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Nutzerorientierte Evaluation zweier altersgerechter Assistenzroboter zur Unterstützung von Alltagsaktivitäten („Ambient Assisted Living-Roboter“) bei älteren Menschen mit funktionellen Einschränkungen: MOBOT-Rollator und I-SUPPORT-Duschroboter

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Gewidmet meiner Familie

In Erinnerung an meinen Vater

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Liste der Manuskripte zur publikationsbasierten Dissertation

Manuskript I
Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62*(6), 644-653. DOI: 10.1159/000444878

Manuskript II
Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2018). A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. *Disability and Rehabilitation: Assistive Technology, 13*(1), 31-39. DOI: 10.1080/17483107.2016.1278470

Manuskript III
Werner, C., Moustris, G. P., Tzafestas, C. S. & Hauer, K. (2018). User-oriented evaluation of a robotic rollator that provides navigation assistance in frail older adults with and without cognitive impairment. *Gerontology, 64*(3), 278-290. DOI: 10.1159/000484663

Manuskript IV
Werner, C., Chalvatzaki, G., Papageorgiou, X. S., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (2019). Assessing the concurrent validity of a gait analysis system integrated into a smart walker in older adults with gait impairments. *Clinical Rehabilitation, 33*(10), 1682-1687. DOI: 10.1177/0269215519852143

Manuskript V
Geravand, M., **Werner, C.,** Hauer, K. & Peer, A. (2016). An integrated decision making approach for adaptive shared control of mobility assistive robots. *International Journal of Social Robotics, 8*(5), 631-648. DOI: 10.1007/s12369-016-0353-z

Manuskript VI
Werner, C. Geravand, M., Korondi, P. Z., Peer, A., Bauer, J. M. & Hauer, K. (2020). Evaluating the sit-to-stand transfer assistance from a smart walker in older adults with motor impairments. *Geriatrics & Gerontology International.* DOI: 10.1111/GGI.13874

Manuskript VII
Werner, C., Dometios, A. C., Maragos, P., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (*submitted*). Evaluating the task effectiveness and user satisfaction with different operation modes for an assistive bathing robot in older adults with bathing disability. Under review in *Assistive Technology*.

Manuskript VIII
Werner, C., Kardaris, N., Koutras, P., Zlatintsi, A., Maragos, P., Bauer, J. M. & Hauer, K. (2020). Improving gesture-based interaction between an assistive bathing robot and older adults via user training on the gestural commands. *Archives of Gerontology and Geriatrics, 87, 103996.* DOI: 10.1016/j.archger.2019.103996

Vorbemerkung

Die vorliegende publikationsbasierte Dissertation ist in der Schnittstelle der Sport- und Bewegungswissenschaft, Geriatrie und Gerontologie sowie Robotik einzuordnen und geht aus den internationalen, multizentrischen und interdisziplinären Forschungsprojekten „MOBOT“ („Intelligent Active MObility Aid RoBOT Integrating Multimodal Communication“, Laufzeit: Februar 2013 – November 2016) und “I-SUPPORT” („ICT-Supported bath robots”, Laufzeit: März 2015 – Februar 2018) hervor. Beides sind von der Europäischen Kommission geförderte Kooperationsprojekte mehrerer europäischer Institutionen, in denen die Forschungsabteilung des AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG / Geriatrisches Zentrum am Klinikum der Universität Heidelberg unter Leitung von Herrn Prof. Dr. Klaus Hauer jeweils als klinischer Partner an der nutzerorientierten Entwicklung und Evaluation eines robotergestützten Rollators (MOBOT) bzw. eines Duschroboters (I-SUPPORT) für ältere Menschen mit funktionellen Einschränkungen beteiligt war.

Der Verfasser dieser Arbeit war im Rahmen dieser Projekte maßgeblich beteiligt an der Konzeption und Planung, an der praktischen Durchführung und Koordination sowie an der Datenerhebung und -analyse der verschiedenen Studien zur Evaluation der entwickelten Assistenzrobotern bei potentiellen Nutzern[1]. Über den Verlauf beider Projekte war er zudem gemeinsam mit Herrn Prof. Hauer federführend an der Erstellung von Zwischen- und Abschlussberichten („Deliverables“) für den Fördermittelgeber beteiligt.

Die Ergebnisse der Vorarbeiten und selbst durchgeführten Evaluationsstudien wurden vom Verfasser auf nationalen und internationalen wissenschaftlichen Kongressen der fachlichen Öffentlichkeit zur Diskussion vorgestellt (siehe S. 79 ff.).

Das in gemeinsamer Erstautorschaft mit Phoebe Ullrich erstellte Manuskript I zur systematischen Literaturanalyse des methodischen Vorgehens bisheriger Evaluationsstudien robotergestützter Rollatoren aus der Nutzerperspektive wurde von der europäischen Fachzeitschrift *Gerontology* (Karger Publishers, Basel, Switzerland) als „Editor’s Choice – Free Access“ ausgezeichnet und in diesem Zusammenhang vom Herausgeber online frei zugänglich publiziert.

[1] Aus Gründen der besseren Lesbarkeit wird in der vorliegenden Dissertationsschrift auf die gleichzeitige Verwendung weiblicher und männlicher Sprachformen verzichtet und das generische Maskulinum verwendet. An dieser Stelle sei jedoch explizit darauf hingewiesen, dass sämtliche Personenbezeichnungen (z. B. Studienteilnehmer, Patient) gleichermaßen für beiderlei Geschlechter gelten.

Kurzdarstellung

Ziel der vorliegenden Arbeit ist die nutzerorientierte Evaluation zweier Prototypen für altersgerechte Assistenzroboter zur Unterstützung von Alltagsaktivitäten („Ambient Assisted Living“ [AAL]-Roboter) bei älteren Menschen mit funktionellen Einschränkungen. Bei den Prototypen handelt es sich dabei um (1) einen robotergestützten Rollator zur Unterstützung der Mobilität (MOBOT) und (2) einen Assistenzroboter zur Unterstützung von Duschaktivitäten (I-SUPPORT).

Manuskript I dokumentiert eine systematische Literaturanalyse des methodischen Vorgehens bisheriger Studien zur Evaluation robotergestützter Rollatoren aus der Nutzerperspektive. Die meisten Studien zeigen erhebliche methodische Mängel, wie unzureichende Stichprobengrößen/-beschreibungen; Teilnehmer nicht repräsentativ für die Nutzergruppe der robotergestützten Rollatoren; keine geeigneten, standardisierten und validierten Assessmentmethoden und/oder keine Inferenzstatistik. Ein generisches methodisches Vorgehen für die Evaluation robotergestützter Rollatoren konnte nicht identifiziert werden. Für die Konzeption und Durchführung zukünftiger Studien zur Evaluation robotergestützter Rollatoren, aber auch anderer AAL-Systeme werden in Manuskript I abschließend Handlungsempfehlungen formuliert.

Manuskript II analysiert die Untersuchungsergebnisse der in Manuskript I identifizierten Studien. Es zeigen sich sehr heterogene Ergebnisse hinsichtlich des Mehrwerts ihrer innovativen Assistenzfunktionen. Im Allgemeinen werden die robotergestützten Rollatoren als positiv von den Nutzern wahrgenommen. Die große Heterogenität und methodischen Mängel der Studien schränken die Interpretierbarkeit ihre Untersuchungsergebnisse stark ein. Insgesamt verdeutlicht Manuskript II, dass die Evidenz zur Effektivität und positiven Wahrnehmung robotergestützter Rollatoren aus der Nutzerperspektive noch unzureichend ist.

Basierend auf den Erkenntnissen und Handlungsempfehlungen der systematischen Literaturanalysen aus Manuskript I und II wurden die nutzerorientierten Evaluationsstudien des MOBOT-Rollators konzipiert und durchgeführt (Manuskript III-VI).

Manuskript III überprüft die Effektivität des in den MOBOT-Rollator integrierten Navigationssystems bei potentiellen Nutzern (= ältere Personen mit Gangstörungen bzw. Rollator als Gehhilfe im Alltag). Es liefert erstmals einen statistischen Nachweis dafür, dass eine solche Assistenzfunktion effektiv ist, um die Navigationsleistung der Nutzer (z. B. geringer Stoppzeit, kürzere Wegstrecke) – insbesondere derjenigen mit kognitiven Einschränkungen – in einem realitätsnahen Anwendungsszenario zu verbessern.

Manuskript IV untersucht die konkurrente Validität des MOBOT-integrierten Ganganalysesystems bei potentiellen Nutzern. Im Vergleich zu einem etablierten Referenzstandard (GAITRite®-System) zeigt es eine hohe konkurrente Validität für die Erfassung zeitlicher,

nicht jedoch raumbezogener Gangparameter. Diese können zwar ebenfalls mit hoher Konsistenz gemessen werden, aber lediglich mit einer begrenzten absoluten Genauigkeit.

Manuskript V umfasst die nutzerorientierte Evaluation der im MOBOT-Rollator integrierten Assistenzfunktion zur Hindernisvermeidung und belegt erstmals die Effektivität einer solchen Funktionen bei potentiellen Nutzern. Unter Verwendung des für den MOBOT-Rollator neu entwickelten technischen Ansatzes für die Hindernisvermeidung zeigten die Teilnehmer signifikante Verbesserungen bei der Bewältigung eines Hindernisparcours (weniger Kollisionen und geringere Annäherungsgeschwindigkeit an die Hindernisse).

Manuskript VI dokumentiert die Effektivität und Zufriedenheit mit der Aufstehhilfe des MOBOT-Rollators von potentiellen Nutzern. Es wird gezeigt, dass die Erfolgsrate für den Sitzen-Stehen-Transfer älterer Personen mit motorischen Einschränkungen durch die Aufstehhilfe signifikant verbessert werden kann. Die Ergebnisse belegen zudem eine hohe Nutzerzufriedenheit mit dieser Assistenzfunktion, insbesondere bei Personen mit höherem Body-Mass-Index.

Manuskript VII untersucht die Mensch-Roboter-Interaktion zwischen dem I-SUPPORT-Duschroboter und seiner potentiellen Nutzer (= ältere Personen mit Problemen bei Baden/Duschen) und überprüft deren Effektivität sowie Zufriedenheit mit drei unterschiedlich autonomen Betriebsmodi. Die Studienergebnisse dokumentieren, dass sich mit zunehmender Kontrolle des Nutzers (= abnehmende Autonomie des Duschroboters) nicht nur die Effektivität für das Abduschen eines definierten Körperbereichs verringert, sondern auch die Nutzerzufriedenheit sinkt.

Manuskript VIII umfasst die Evaluation eines spezifischen Nutzertrainings auf die gestenbasierte Mensch-Roboter-Interaktion mit dem I-SUPPORT-Duschroboter. Es wird gezeigt, dass ein solches Training die Ausführung der Gesten potentieller Nutzer und sowie die Gestenerkennungsrate des Duschroboters signifikant verbessern, was insgesamt auf eine optimierte Mensch-Roboter-Interaktion in Folge des Trainings schließen lässt. Teilnehmer mit der schlechtesten Ausgangsleistung in der Ausführung der Gesten und mit der größten Angst vor Technologien profitierten am meisten vom Nutzertraining.

Insgesamt belegen die Studienergebnisse zur nutzerorientierten Evaluation des MOBOT-Rollators die Effektivität und Gültigkeit seiner innovativen Teilfunktionen. Sie weisen auf ein hohes Potential der Assistenzfunktionen (Navigationssystem, Hindernisvermeidung, Aufstehhilfe) zur Verbesserung der Mobilität älterer Menschen mit motorischen Einschränkungen hin. Vor dem Hintergrund der methodischen Mängel und unzureichenden evidenzbasierten Datenlage hierzu, liefert diese Dissertationsschrift erstmals statistische Belege für den Mehrwert solcher Teilfunktionen bei potentiellen Nutzern und leistet somit einen wichtigen Beitrag zur Schließung der bisherigen Forschungslücke hinsichtlich des nutzerorientierten Wirksamkeits- und Gültigkeitsnachweises robotergestützter Rollatoren und ihrer innovativen Teilfunktionen.

Die Ergebnisse der Studien des I-SUPPORT-Duschroboters liefern wichtige Erkenntnisse hinsichtlich der Mensch-Roboter-Interaktion im höheren Alter. Sie zeigen, dass bei älteren Nutzern für eine effektive Interaktion Betriebsmodi mit einem hohen Maß an Autonomie des Duschroboters notwendig sind. Trotz ihrer eingeschränkten Kontrolle über den Roboter, waren die Nutzer mit dem autonomsten Betriebsmodus sogar am zufriedensten. Darüber hinaus unterstreichen die Ergebnisse hinsichtlich der gestenbasierten Interaktion mit dem I-SUPPORT-Duschroboter, dass zukünftige Entwicklungen von altersgerechten Assistenzrobotern mit gestenbasierter Interaktion nicht nur die Verbesserungen technischer Aspekte, sondern auch die Sicherstellung und Verbesserungen der Qualität der Nutzergesten für die Mensch-Roboter-Interaktion durch geeignete Trainings- oder Schulungsmaßnahmen berücksichtigen sollten. Das vorgestellte Nutzertraining könnte hierfür ein mögliches Modell darstellen.

Abstract

The aim of this publication-based dissertation is the user-oriented evaluation of two prototypes for “Ambient Assisted Living” (AAL) robots in older people with functional impairments. The prototypes consist of (1) a robotic rollator for mobility assistance (MOBOT) and (2) an assistive robot for assistance in bathing/showering activities (I-SUPPORT).

Manuscript I presents a systematic review on the methodology of previous studies evaluating robotic rollators from the user perspective. Most studies showed major methodological shortcomings such as insufficient sample sizes and descriptions, participants not representative of potential users of robotic rollators, lack of appropriate, standardized and validated assessment methods, and/or no inferential statistics. No generic methodology to evaluate robotic rollators from the user perspective could be identified. Manuscript I finally provides recommendations for future studies on the evaluation of robotic rollators and other AAL systems.

Manuscript II analyses the results of the studies identified in manuscript I. It reveals very heterogeneous results regarding the added value of their innovative assistance functionalities. User perception of the robotic rollators was found to be generally positive. The large heterogeneity and methodological shortcomings of the studies severely limit the interpretability of their results. Overall, manuscript II highlights that the evidence on the effectiveness and positive perception of robotic rollators from the user perspective is still insufficient.

Manuscript III examine the effectiveness of the MOBOT-integrated navigation system in potential users (= older persons with gait impairments and/or habitual use of a rollator in daily life) with and without cognitive impairment. It provides for the first time statistical evidence that such assistance functionality can be effective for improving navigation (e.g., reduced stop time and walking distance) within a real-life scenario in potential users, especially in those with cognitive impairment.

Manuscript IV assesses the concurrent validity of the MOBOT-integrated gait analysis system in potential users. It shows that the gait analysis system has good concurrent validity with an established criterion standard (GAITRite® system) for measuring temporal but not spatial gait parameters. Spatial-related gait parameters can also be measured with high consistency, but only with limited absolute accuracy.

Manuscript V includes the user-oriented evaluation of the MOBOT-integrated obstacle avoidance functionality and proves for the first time the effectiveness of such functionality in potential users. Participants showed significant improvements in completing an obstacle course (fewer collisions, lower approaching velocity to the obstacles) when using the obstacle avoidance functionality specifically developed for the MOBOT rollator.

Manuscript VI documents the effectiveness and satisfaction of potential users with the sit-to-stand (STS) assistance system of the MOBOT rollator. It highlights that the success

rate for the STS transfer of older persons with motor impairments can be significantly improved with this assistance functionality. The results also show a high user satisfaction with the STS assistance system, especially among potential users with higher body mass index.

Manuscript VII examines the human-robot interaction (HRI) between the I-SUPPORT bathing robot and its potential users (= older people with difficulty in bathing/showering) and evaluates their effectiveness and satisfaction with three different autonomous operation modes. The results show that with increasing user control (= decreasing robot autonomy) the effectiveness in showering a predefined body area as well as the user satisfaction with the I-SUPPORT bathing robot significantly decreases.

Manuscript VIII includes the evaluation of a specific user training on gesture-based HRI with the I-SUPPORT bathing robot. It highlights that such training is highly beneficial for the quality of older users' gestural commands, leading to a higher command recognition rate of the I-SUPPRT bathing robot, and thus to an overall improved HRI. Participants with the worst gestural performance and higher gerontechnology anxiety benefited most from the training.

Overall, the study results for the user-oriented evaluation of the MOBOT rollator demonstrate the effectiveness and validity of its innovative functionalities. They indicate the high potential of the assistance functionalities for improving the mobility of older people with motor impairments. Taking into account the methodological shortcomings of previous evaluation studies in this research area, this dissertation provides for the first time statistical evidence for the benefit and validity of such functionalities in potential users, and thus a significant contribution to closing the research gap on the user-oriented proof of the effectiveness and validity of robotic rollators and their innovative functionalities.

The results of the studies with the I-SUPPORT bathing robot provide important insights into HRI in old age. They indicate that in older users, operation modes with a high degree of autonomy of the bathing robot are necessary for an effective HRI. Despite their limited control over the robot, the users were most satisfied with the most autonomous operation mode. Furthermore, the results on gesture-based HRI with the I-SUPPORT bathing robot highlights that future developments of gesture-based AAL robots should focus not only on refining technical aspects of the robot but also on improving the quality of a user's input for HRI through appropriate training procedures. The presented user training could provide a model for this.

1 Einleitung und Überblick

Infolge des demographischen Wandels wird sich die Anzahl älterer Menschen in der Bevölkerung westlicher Industriestaaten zukünftig weiter erhöhen. Da mit zunehmendem Alter auch das Risiko für funktionelle Beeinträchtigungen, Krankheit, Behinderung oder Pflegebedürftigkeit ansteigt (Barnett et al., 2012; Ferrucci et al., 2016; Hall et al., 2017; Menning & Hoffmann, 2009), ist davon auszugehen, dass in einer alternden Gesellschaft auch die Anzahl der davon Betroffenen und der Bedarf an Unterstützung, Versorgung und Pflege von Älteren zunehmen wird. Bereits heute stößt die Gesundheits- und Pflegeversorgung jedoch an ihre Grenzen (z. B. Fachkräftemangel in der Pflege) (Bertelsmann Stiftung, 2012; Spasova et al., 2018). Um die Herausforderungen des demographischen Wandels in Zukunft bewältigen zu können, müssen geeignete Bewältigungsstrategien gefunden werden. Hierbei wird das Potential des Einsatzes von technischen Assistenzsystemen diskutiert, die die Funktionsfähigkeit und Selbstständigkeit von älteren Menschen im Alltag erhalten oder verbessern, bestehende Beeinträchtigungen kompensieren und den Bedarf an Gesundheits- und Pflegeleistungen reduzieren sollen (European Commission, 2013d; Robert Koch-Institut, 2015). Während in den letzten Jahren zahlreiche Entwicklungen technischer Assistenzsysteme im Bereich Alltagsunterstützung sowie Gesundheits- und Pflegeversorgung von älteren Menschen durchgeführt wurden, ist der evidenzbasierte Nachweis hinsichtlich ihrer Effektivität meist unzureichend. Häufig erfolgte die Entwicklungen lediglich entlang des technisch Machbaren und potentielle Nutzer der Assistenzsysteme waren nur unzureichend am Entwicklungs- und Evaluationsprozess beteiligt (European Commission, 2013b; Friesdorf, Podtschaske, Stahl, Glende & Nedopil., 2011).

Vor diesem Hintergrund war das übergeordnete Ziel dieser Dissertation die nutzerorientierte Evaluation zweier neu entwickelter altersgerechter Assistenzroboter (robotergestützter Rollator, Duschroboter) zur Unterstützung von Alltagsaufgaben (Mobilität, Baden/Duschen) bei älteren Menschen mit funktionellen Einschränkungen.

Die vorliegende Arbeit ist wie folgt gegliedert: In Kapitel 2 wird zunächst der theoretische Hintergrund beschrieben, der die Relevanz und Aktualität dieser Arbeit begründet. Zu Beginn werden die durch den demographischen Wandel bedingten Herausforderungen an das Gesundheitssystem dargestellt. Dem folgen die Grundlagen und Forschungsinitiativen zu technischen Assistenzsystemen für die Unterstützung ältere Menschen im Alltag als mögliche Bewältigungsstrategie für diese Herausforderungen. Dabei wird u. a. auf die fehlende Nutzerperspektive bisheriger Entwicklungen und Evaluationen altersgerechter Assistenzrobotern eingegangen. Am Ende von Kapitel 2 werden die von der Europäischen Union geförderten Projekte vorgestellt (MOBOT, I-SUPPORT), in denen die beiden zu evaluierenden altersgerechten Assistenzroboter (robotergestützter Rollator, Duschroboter) entwickelt wurden. In Kapitel 3 werden die Fragestellungen und Ziele der in die Dissertation einfließenden Manuskripte formuliert. Kapitel 4 beinhaltet die Zusammenfassungen dieser Manuskripte. Die Einordnung der Studienergebnisse der einzelnen Manuskripte in den Forschungszusammenhang erfolgt in Kapitel 5. Abschließend bietet Kapitel 6 ein Fazit aus der gesamten Arbeit und einen Ausblick auf daraus hervorgehende zukünftige Forschungsfragen.

2 Theoretischer Hintergrund

2.1 Demographischer Wandel als Herausforderung für das Gesundheitswesen

Ein zentrales Merkmal des demographischen Wandels in den westlichen Industriestaaten ist der kontinuierlicher Anstieg der absoluten Anzahl sowie des relativen Anteils älterer Menschen in der Bevölkerung. Lebten z. B. nach Angaben des United Nations Department of Economic and Social Affairs (UN DESA) im Jahr 1950 in Europa noch 43,7 Millionen (8,0 %) Menschen im Alter von 65 Jahren und älter, so erhöhte sich diese Anzahl im Jahr 2015 auf über 130,5 Millionen (17,6 %). Aktuellen Hochrechnungen zufolge wird in den nächsten drei Jahrzehnten die Zahl der älteren Menschen in Europa weiter ansteigen und im Jahr 2050 bei knapp 200 Millionen liegen (vgl. Abbildung 1), was mehr als einem Viertel (27,8 %) der europäischen Gesamtbevölkerung entsprechen wird. (UN DESA, 2019)

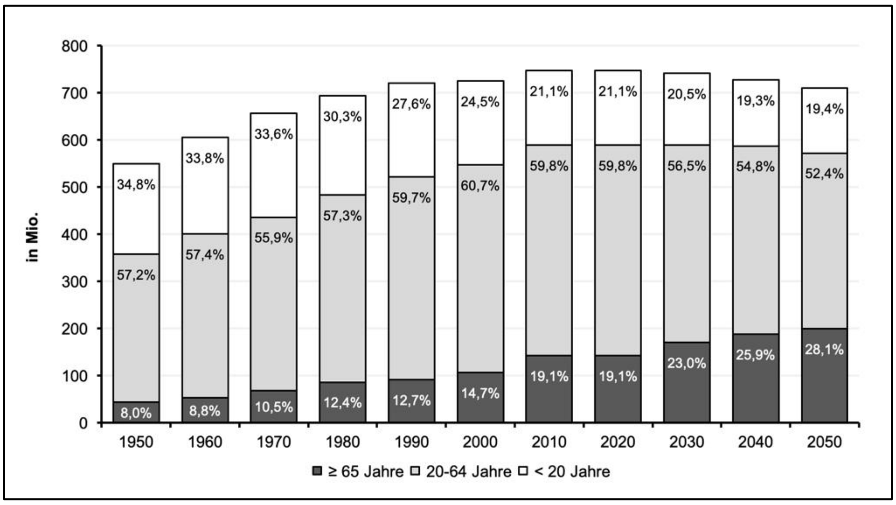

Abb. 1: Altersstruktur und Bevölkerungsentwicklung in Europa in den Jahren 1950 bis 2050 (eigene Darstellung, Datenquelle: UN DESA, 2019, mittlere Variante)

Ein weiterer bemerkenswerter Aspekt der prognostizierten Veränderungen der Bevölkerungsstruktur in Europa betrifft die fortschreitende Alterung der älteren Bevölkerung selbst. Die Altersgruppe der hochbetagten Menschen ab 80 Jahre wächst schneller als jede andere. Während im Jahr 1950 noch 8,0 Millionen (1,0 %) Europäer 80 Jahre oder älter waren, galt dies im Jahr 2015 bereits für 34,7 Millionen (4,7 %). Bis zum Jahr 2050 wird sich diese Anzahl nochmals mehr als verdoppeln und etwa 71,9 Millionen betragen. Jeder zehnte (10,1 %) Einwohner Europas wird demnach 80 Jahre oder älter sein. (UN DESA, 2019)

Vergleichbare Ergebnisse und Hochrechnungen für die zurückliegenden bzw. zukünftigen demographischen Veränderungen liegen auch für Deutschland vor (Statistisches Bundesamt, 2019a; UN DESA, 2019): Aktuell zählt Deutschland innerhalb der Mitgliedstaaten der Europäischen Union (EU) mit einem Altersmedian von 46,0 Jahren sogar zu den Ländern mit dem höchsten Durchschnittsalter und dem größten Anteil von 65-Jährigen und

Älteren in der Bevölkerung (Eurostat, 2019e). Im Jahr 2018 war bereits mehr als jeder fünfte Deutsche (21,5 %, 17,8 Mio.) 65 Jahre oder älter (Statistisches Bundesamt, 2019a). Dieser Anteil wird auch in Deutschland in den nächsten Jahrzehnten weiter deutlich ansteigen (2050: 30,0 %, 24,0 Mio.) (UN DESA, 2019), wobei auch hier der Anteil der hochbetagten Menschen ab 80 Jahren am stärksten anwachsen wird (vgl. Abbildung 2). Die wesentlichen Ursachen für den demographischen Wandel in Deutschland und Europa sind einerseits die langjährig hohen und dann anhaltend niedrigen Geburtenraten. Andererseits ist die Lebenserwartung kontinuierlichen gestiegen, da große Fortschritte in der medizinischen Versorgung erzielt wurden, sich die Lebens- und Arbeitsbedingungen verbessert haben und der allgemein Wohlstand gestiegen ist (Statistisches Bundesamt, 2016).

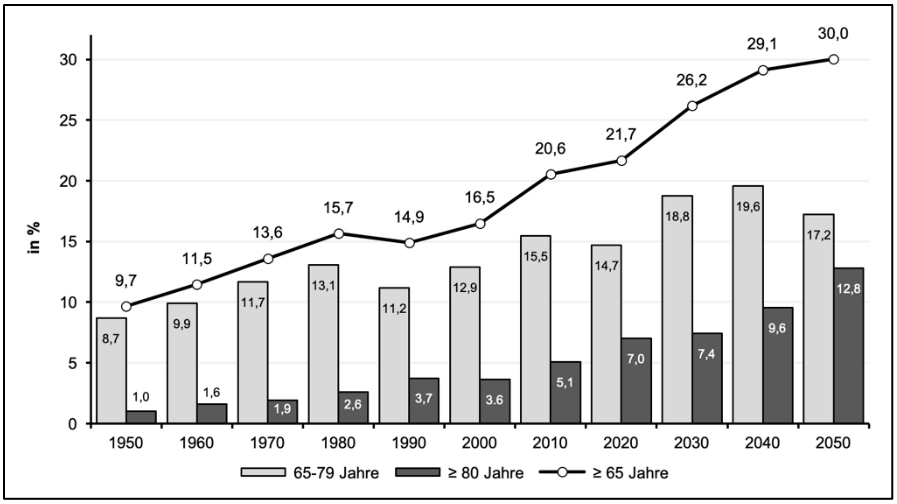

Abb. 2: Anteil und Entwicklung der älteren Menschen (≥ 65 Jahre) an der Gesamtbevölkerung in Europa nach Altersgruppen in den Jahren 1950 bis 2050 (eigene Darstellung, Datenquelle: UN DESA, 2019, mittlere Variante)

Ältere Menschen scheinen heute aufgrund des medizinischen Fortschritts und der verbesserten Lebensumstände weniger in ihrer funktionalen Gesundheit beeinträchtigt zu sein (Christensen, Doblhammer, Rau & Vaupel, 2009; Ziegler & Doblhammer, 2008) und mehr gesunde Lebensjahre zu verbringen als noch frühere Generationen (Eurostat, 2019b; Fries, 1980; Ziegler & Doblhammer, 2008). Dennoch bleibt weiterhin das mit zunehmendem Alter erhöhte Risiko für funktionelle Beeinträchtigungen, Mobilitätseinschränkungen, Krankheit (Multimorbidität), Behinderung oder Pflegebedürftigkeit bestehen (Barnett et al., 2012; Ferrucci et al., 2016; Hall et al., 2017; Menning & Hoffmann, 2009). Dies führt in einer alternden Gesellschaft von immer mehr und immer länger lebenden älteren Menschen zwangsläufig dazu führt, dass auch die Anzahl der davon Betroffenen sowie die damit verbundenen Anforderungen an das Gesundheits- und Pflegewesen zunehmen (Peters, Pritzkuleit, Beske & Katalinic, 2010; Statistisches Bundesamt, 2019b).

2.1.1 Pflegebedürftigkeit

Im Zeitraum von 1999 bis 2017 hat sich die Anzahl von pflegebedürftigen älteren Menschen in Deutschland von 1,6 auf 2,8 Millionen erhöht (vgl. Abbildung 3), was einem prozentualen Anstieg von über 72 % entspricht (Statistisches Bundesamt, 2019b).

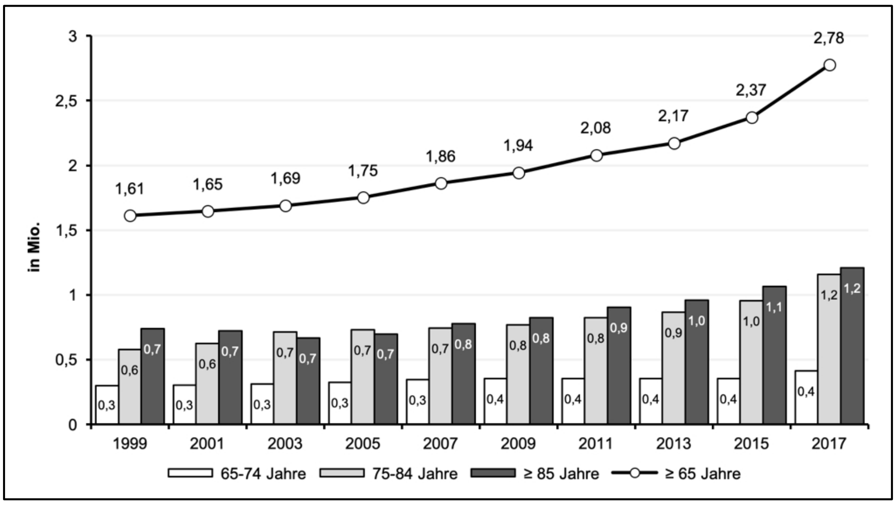

Abb. 3: Anzahl pflegebedürftiger älterer Menschen in Deutschland nach Altersgruppen in den Jahren 1999 bis 2017 (eigene Darstellung, Datenquelle: Statistisches Bundesamt, 2019b)

Auch zukünftig wird infolge der demographischen Veränderungen weiterhin ein deutlicher Anstieg der Anzahl an Pflegebedürftigen für Deutschland (für eine ausführliche Übersicht siehe Nowossadeck, 2013; Robert Koch-Institut, 2015), aber auch für Europa prognostiziert (European Commission, 2013a, 2018). Demgegenüber steht jedoch eine Abnahme des Pflegepotentials in der Gesellschaft. Ein beachtlicher Anteil von Pflegebedürftigen wird zu Hause von Angehörigen ohne weitere professionelle Unterstützung versorgt (Schwinger & Tsiasioti, 2018; Verbakel, 2018). In Europa wird die Zahl der informellen Pflegekräfte (z. B. Familie, Nachbarn, Freunde) mindestens doppelt so hoch eingeschätzt, wie die der formellen, professionellen Pflegekräfte (European Commission, 2013a). Durch die demographische Veränderung der quantitativen Verhältnisse der Generationen zueinander, in denen immer mehr hochaltrige Menschen immer weniger jungen Erwachsenen gegenüberstehen (Eurostat, 2018; Statistisches Bundesamt, 2019a), sinkt auch das demographische Potenzial für die Zahl pflegender Angehöriger. Hinzu kommen weitere Faktoren, wie z. B. veränderte partnerschaftliche Lebensformen, zunehmende Erwerbstätigkeit von Frauen, längere Lebensarbeitszeit oder größere Wohnentfernungen zwischen pflegebedürftigen Eltern und ihren erwachsenen Kindern, die die Möglichkeit der Unterstützung und Versorgung durch Angehörige weiter einschränken (European Commission, 2013a; Robert Koch-Institut, 2015). Aufgrund des rückläufigen familiären Pflegepotentials ist somit anzunehmen, dass zukünftig immer mehr Pflegeleistungen in den Bereich der professionellen Pflege verlagert werden (European Commission, 2018; Nowossadeck, 2013). Bereits heute besteht jedoch sowohl in Deutschland als auch in Europa ein deutlicher Fachkräftemangel in der Pflege, der sich in den kommenden Jahren noch weiter verschärfen wird (Bertelsmann Stiftung, 2012; European Commission, 2012a; Sermeus & Bruyneel, 2019; Spasova et al., 2018; WHO, 2016). Zudem sind arbeitszeitliche, physische sowie psychische Anforderungen und Belastung in allen Bereichen der Pflege bereits jetzt überdurchschnittlich hoch und werden laut Expertenangaben zukünftig eher weiter zu- als abnehmen (Glock et al., 2018). Zu hohe Arbeitsbelastungen können nicht nur negative Auswirkungen auf die Qualität der pflegerischen Versorgung haben, sondern auch auf die Motivation, Zufriedenheit sowie physische und psychische Gesundheit der Beschäftigten in der Pflegebranche (European Commission, 2012a; Rothgang, Fünfstück & Kalwitzki, 2020; Schmucker, 2020; Stordeur et al., 2005). So haben Pflegekräfte beispielsweise in ihrem Berufsalltag mittlerweile nicht mehr ausreichend Zeit für die zwischenmenschliche Zuwendung (Glock et al., 2018), welche als zentrales Handlungsfeld in der pflegerischen Tätigkeit und Qualität erachtet wird. Zudem berichten sie im Vergleich zu anderen Berufsgruppen häufiger von muskuloskelettalen sowie psychovegetativen Beschwerden und zeigen insgesamt überdurchschnittlich hohe krankheitsbedingte Fehlzeiten (BAuA, 2014; Drupp & Meyer, 2020).

2.1.2 Einschränkungen in den Aktivitäten des täglichen Lebens

Die Ausprägung der Einschränkungen in den Aktivitäten des täglichen Lebens („activities of daily living“ = ADLs) bestimmt maßgeblich die personelle, finanzielle und zeitliche Belastung der Pflege (Ku, Chang, Pai & Hsieh, 2019; LaPlante, Harrington & Kang, 2002; Oliva-Moreno et al., 2019; Onder et al., 2009; Reed et al., 2016). ADLs beschreiben die Fähigkeit, grundlegende im Alltag wiederkehrende Tätigkeiten der Pflege und Versorgung der eigenen Person zu leisten, wie z. B. Essen, Bett- und Stuhltransfer, An- und Auskleiden, Toilettengang und Baden oder Duschen (Katz, Ford, Moskowitz, Jackson & Jaffe, 1963). Die Fähigkeit, ADLs ohne Hilfe einer anderen Person durchführen zu können, kann somit als Referenz für die Selbständigkeit einer Person im Alltag angesehen werden. Demgegenüber stellen Einschränkungen in den ADLs wesentliche Ursachen sowie Prädiktoren für die Pflege- und Hilfebedürftigkeit einer Person dar (Cloutier, Penning, Nuernberger, Taylor & MacDonald, 2019; Sjölund, Wimo, Engström & von Strauss, 2015; Wee et al., 2014; Wu et al., 2014).

Laut aktueller Daten des statistischen Amts der EU (Eurostat) benötigen mehr als die Hälfte (53,3 %) der 65- bis 74-jährigen EU-Bürger Hilfe bei den grundlegenden Aktivitäten der Selbstversorgung (Essen, Toilettengang, An-/Auskleiden, Bett-/Stuhltransfer, Baden/Duschen); unter den 75-Jährigen und Älteren sogar deutlich mehr als zwei Drittel (71,4%) (Eurostat, 2019a). Das Baden oder Duschen stellt dabei die ADL dar, welche am häufigsten Probleme bei der selbstständigen Durchführung verursacht. So berichtet etwa jede sechste Person (17,9 %) im Alter zwischen 65 bis 74 Jahre und sogar mehr als jede vierte Person (28,3 %) im Alter von 75 Jahre und älter von Problemen beim Baden oder Duschen (vgl. Abbildung 4).

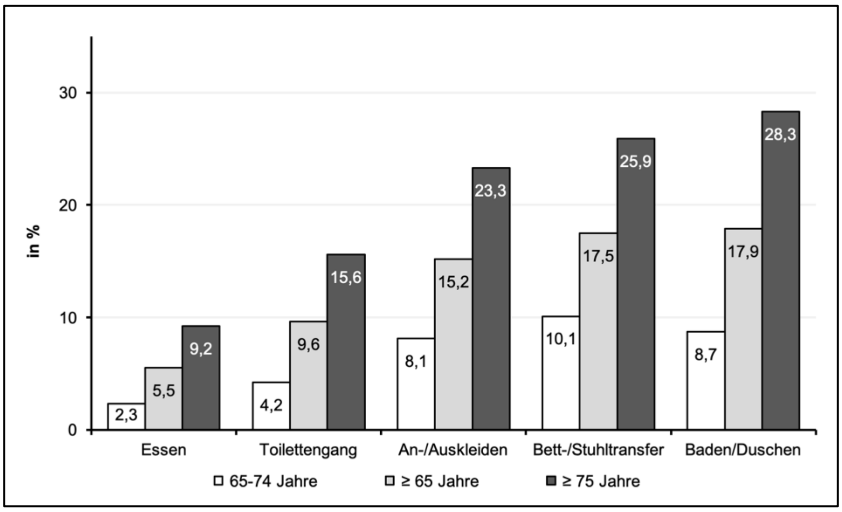

Abb. 4: Anteil der älteren Menschen (≥ 65 Jahre) mit Problemen in grundlegenden Aktivitäten des täglichen Lebens (Essen, Toilettengang, An-/Auskleiden, Bett-/Stuhltransfer, Baden/Duschen) an der Gesamtbevölkerung in den EU-Mitgliedstaaten nach Altersgruppen im Jahr 2014 (eigene Darstellung, Datenquelle: Eurostat, 2019a)

Unter den ADL-Einschränkungen sind diese beim Baden/Duschen diejenigen, welche als erstes während des Alterungsprozesses auftreten (Fong & Feng, 2016; Jagger, Arthur, Spiers & Clarke, 2001; Katz et al., 1963). Darüber hinaus benötigen ältere Personen beim Baden/Duschen häufiger persönliche Hilfe als bei jeder anderen grundlegenden ADL (Wiener, Hanley, Clark & Van Nostrand, 1990). Vor diesem Hintergrund sowie der Annahme konstanter Prävalenzraten dieser Einschränkungen und unveränderter Inanspruchnahme von Hilfeleistungen wird sich in einer alternden Gesellschaft vor allem die Anzahl von älteren Personen mit Einschränkungen und Hilfsbedarf beim Baden/Duschen erhöhen. Demnach scheinen Maßnahmen zur Unterstützung älterer Menschen bei dieser ADL besonders förderlich, um deren Unabhängigkeit möglichst lange im Alterungsprozess aufrechtzuerhalten sowie die personelle, finanzielle und zeitliche Pflegebelastung zu reduzieren (Gill, Guo & Allore, 2006; Naik, Concato & Gill, 2004).

2.1.3 Beeinträchtigung der Mobilität

Mobilität kann als die Fähigkeit der (Fort-)Bewegung in der Umwelt definiert werden (Webber, Porter & Menec, 2010). Mobilitätseinschränkungen einer älteren Person werden dabei häufig anhand ihrer Fähigkeit beurteilt, alltagsrelevante motorisch-funktionelle Leistungen wie z. B. Stehen (Balance), Gehen, Treppensteigen oder Transferleistungen (Aufstehen von einem Stuhl) zu bewältigen (Soubra, Chkeir & Novella, 2019). Aufgrund des biologischen Alterungsprozesses, zunehmender Multimorbidität und häufig auch mangelnder körperlicher Aktivität ist das Altern mit einem Rückgang dieser motorisch-funktionellen Alltagsleistungen verbunden (vgl. Abbildung 5), wodurch Einschränkungen bei der Bewältigung alltagsrelevanter motorisch-funktioneller Leistungen sind unter älteren Menschen weit verbreitet sind. So berichtete nach Angaben von Eurostat im Jahr 2014 mehr als ein Viertel (25.9%) der EU-Bürger im Alter von 75 Jahren von Schwierigkeiten bei alltäglichen Transferleistungen und fast ein Drittel (32,4 %) von erheblichen Schwierigkeiten beim Gehen (Eurostat, 2019a, 2019c). Die besondere Bedeutung von Einschränkungen in diesen motorischen Schlüsselqualifikationen des Alltags ergibt sich daraus, dass sie mit zahlreichen negativen gesundheitsbezogenen Ereignissen assoziiert sind, wie z. B. körperliche Behinderung, Verlust der Unabhängigkeit, Stürzen, reduzierte soziale Teilhabe, geringere Lebensqualität, Institutionalisierung oder vorzeitige Mortalität (Abellan van Kan et al., 2009; Cooper et al., 2010; Davis et al., 2015; Guralnik et al., 1994; Haider et al., 2016; Heiland et al., 2016; Hirvensalo, Rantanen & Heikkinen, 2000; Veronese et al., 2014).

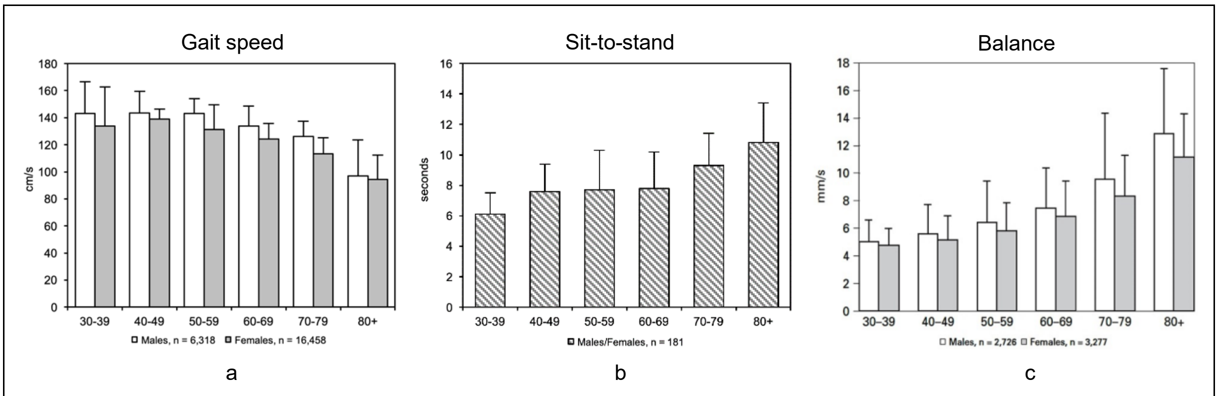

Abb. 5: Motorisch-funktionelle Leistungen nach Altersgruppen (a: habituelle Ganggeschwindigkeit in cm/s, [Bohannon & Williams Andrews, 2011]; b: Zeitdauer für schnellstmögliches, fünfmaliges Aufstehen von einem Stuhl [Bohannon, Bubela, Magasi, Wang & Gershon, 2010]; c: Balance während des normalen Stehens für 30s, gemessen anhand der Geschwindigkeit in mm/s der Bewegungen des Center of Pressure in die anterior-posteriore Richtung [Era et al., 2006]).

Mobilitätseinschränkungen zeichnen sich jedoch nicht nur durch beeinträchtigte motorisch-funktionelle Alltagsleistungen aus, sondern präsentieren sich als multidimensionales Konstrukt, welches das Resultat vieler unterschiedlicher Faktoren und Defizite sein kann (Webber et al., 2010). Eine eingeschränkte Mobilität kann auch mit sensorischen, kognitiven oder psychologischen Beeinträchtigungen zusammenhängen (Crews & Campbell, 2004; Donoghue et al., 2014; Pedersen et al., 2014), die mit zunehmendem Alter vermehrt auftreten (Harada, Natelson Love & Triebel, 2013; Scheffer, Schuurmans, van Dijk, van der Hooft & de Rooij, 2008; Whitson et al., 2018). So können z. B. ein eingeschränktes Sehvermögen (Swenor et al., 2015), Probleme bei der räumlichen Orientierung (Burns, 1999;

Passini, Rainville, Marchand & Joanette, 1995) und Sturzangst (Auais et al., 2017; Scheffer et al., 2008) weitere Barrieren für die Mobilität von Älteren darstellen.

Trotz leicht rückläufiger Prävalenzraten von Einschränkungen der Mobilität bei älteren Personen (Christensen et al., 2009) ist infolge des demographischen Wandels zukünftig weiterhin von einer deutlich ansteigenden Zahl von Älteren mit Beeinträchtigungen in der Mobilität zu rechnen. So ist z. B. anzunehmen, dass sich die Anzahl der EU-Bürger im Alter von 75 Jahren mit selbstberichteten erheblichen Gehschwierigkeiten trotz eines jährlichen Rückgangs der aktuellen Prävalenzrate um 0,25 % von etwa 14,6 Millionen im Jahr 2014 auf über 19,0 Millionen im Jahr 2050 erhöhen wird, was einem prozentualen Anstieg von über 30 % entspricht (eigene Berechnungen, Datenquelle: Eurostat, 2019c, 2019d).

Vor dem Hintergrund, dass die Mobilität einer Person fundamental für deren Gesundheit, Lebensqualität, Selbstständigkeit und sozialen Teilhabe ist, scheint es unerlässlich, geeignete Maßnahmen zur Erhaltung und Förderung der Mobilität älterer Menschen zu finden, um diese demographischen Herausforderungen erfolgreich zu bewältigen (Hirsch et al., 2017).

2.1.4 Mögliche Bewältigungsstrategien

Um die Herausforderungen des demographischen Wandels und den steigenden Bedarf an Unterstützung, Versorgung und Pflege von älteren Menschen bei rückläufigen Ressourcen in der Gesundheits- und Pflegeversorgung bewältigen zu können, müssen geeignete Lösungsansätze gefunden werden. Die hierzu diskutierten Bewältigungsstrategien sind vielfältig (z. B. für eine ausführliche Übersicht siehe Robert Koch-Institut, 2015), zielen jedoch im Wesentlichen auf drei Bereiche ab: (1) die Verringerung der Inzidenz und Gesamtprävalenz von funktionellen Beeinträchtigungen und Behinderung; (2) die Reduzierung der Abhängigkeit, d.h. ältere Menschen dazu befähigen, trotz funktionellen Einschränkungen weiterhin ein unabhängiges Leben führen; (3) die Steigerung der Produktivität (= Maß der erreichten Versorgungsqualität relativ zu den eingesetzten Mitteln) der Pflegeleistungen (European Commission, 2013a). Eine konkret genannte und geförderte Maßnahme hierfür ist die Entwicklung und Implementierung von innovativen technischen Assistenzsystemen in die Gesundheitsversorgung von älteren Menschen (BMBF, 2016, 2018; European Commission, 2013a, 2013d; Glock et al., 2018)

2.2 Technische Assistenzsysteme in der Gesundheitsversorgung

2.2.1 Begriffsbestimmung und Grundlagen

Die World Health Organization (WHO) definiert technische Assistenzsysteme in der Gesundheitsversorgung als „[…] those whose primary purpose is to maintain or improve an individual's functioning and independence, to facilitate participation, and to enhance overall well-being“ (WHO, 2019). Demnach besteht das primäre Ziel eines technischen Assistenzsystems darin, die Funktionsfähigkeit und Selbstständigkeit einer Person zu erhalten oder zu verbessern, die Teilhabe zu erleichtern und das allgemeine Wohlbefinden zu steigern. Technische Assistenzsysteme stellen wesentliche Instrumente dar, um erfolgreiches Altern positiv zu unterstützen; präventiv dem Verlust der Mobilität vorzubeugen, bestehende Beeinträchtigungen zu kompensieren, das Ausmaß der Pflegebedürftigkeit sowie den Bedarf an Gesundheits- und Unterstützungsleistungen oder Langzeitpflege zu reduzieren und Pflegekräften zu Gunsten einer höheren Qualität und Produktivität ihrer pflegerischen Versorgung (z. B. mehr Zeit für pflegerische Betreuung und persönliche Zuwendung) zu unterstützen und zu entlasten (Doblhammer, Georges & Barth, 2015; Executive Board, 2017). Hierzu existiert eine Vielzahl von unterschiedlichen technischen Assistenzsysteme. So listet z. B. das Informationsportal REHADAT – ein vom Bundesministerium für Arbeit und Soziales gefördertes Projekt des Instituts der Deutschen Wirtschaft – über 13.000 mögliche Hilfsmittel und technische Assistenzsysteme zur Unterstützung von Menschen mit Behinderungen (www.rehadat-hilfsmittel.de). Die meisten dieser Assistenzsysteme lassen sich nach Angaben der WHO grob in die in Tabelle 1 aufgeführten Kategorien einordnen.

Tab. 1: Kategorien und Beispiele für technische Assistenzsysteme (WHO, 2014)

Kategorie	**Beispiele**
Kognitive Funktionen	Speichergeräte, Global Positioning Systeme (GPS), Erinnerungshelfer für Medikamente
Sensorische Funktionen	Brillen, Lupen, Hörgeräte
Orthesen & Prothesen	Prothesen, Wirbelsäulenorthesen, Halskrausen
Persönliche Mobilität	Gehstöcke, Rollatoren, Rollstühle
Aktivitäten des täglichen Lebens inkl. Körperpflege und Sicherheit	Toiletten-/Duschstühle, Pflegeroboter, Sturzmatten
Kommunikations- & Kompetenztraining	Geräte für Sprach-/Sprechtraining, Bildschirmlesegeräte, Brailledisplays
Freizeit & Sport	modifizierte Sportausrüstung, Kamerahalterung, audio-taktiles Schachbrett
Verbesserung von Wohnen, Arbeit und Umwelt	Hausmodifikationen, Handläufe oder Haltegriffe, kontrollierte Beleuchtung

Technische Assistenzsysteme können auch anhand ihrer Interaktion und Vernetzung in drei unterschiedliche Generationen eingeteilt werden. Die erste Generation beinhaltet etablierte Systeme ohne Informationsaustausch, wie z. B. Seh- und Hörgeräte, Mobilitäts- und Haushaltshilfen, Trainingsgeräte und Hebe-/Tragesysteme in stationären Einrichtungen. Zur zweiten Generation zählen Systeme mit Informationsaustausch, wie z. B. Serviceroboter oder passive Monitoring-Systeme, die von Menschen kontrolliert werden. Die dritte Generation umfasst vernetzte, umgebungsintelligente Systeme, die mit dem Nutzer direkt interagieren und z. T. eigenständig (re-)agieren sowie Aufgaben erledigen (Fachinger, 2017).

Ein theoretischer Rahmen für die Bedeutung technischer Assistenzsysteme zur Erhaltung und Verbesserung der Funktionsfähigkeit bildet die von der WHO herausgegebene „International Classification of Functioning, Disability and Health“ (ICF) (WHO, 2001) (vgl. Abbildung 4).

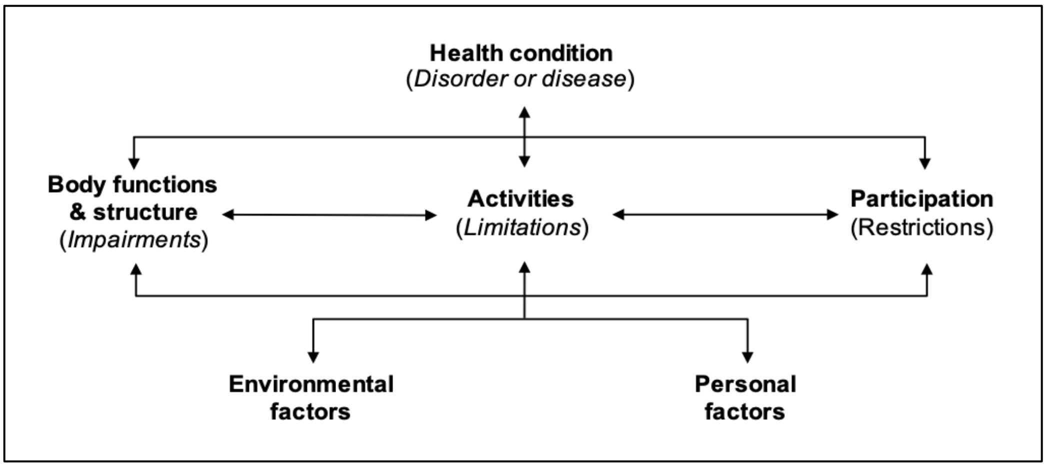

Abb. 6: International Classification of Functioning, Disability and Health (WHO, 2001)

Technische Assistenzsysteme werden in der ICF als Förderfaktoren innerhalb der Umweltfaktoren (= environmental factors) klassifiziert, die Körperfunktionen (einschließlich des mentalen Bereichs) und -strukturen (= body functions & structure) ersetzen (z. B. Prothesen) bzw. wiederherstellen, erweitern oder kompensieren (z. B. Brillen, Hörgeräte, Rollstühle). Körperfunktionen/-strukturen stehen in einer direkten Wechselwirkung mit der Aktivität (= activity) und der Partizipation [Teilhabe] einer Person (= participation). Deren Verbesserung durch ein technisches Assistenzsystem reduziert oder verhindert die aus den Funktionsstörungen oder Strukturschäden (= impairments) resultierenden Beeinträchtigungen der Aktivität (= limitations) und Einschränkungen der Partizipation (= restrictions), indem sie die tatsächliche Leistung[2] einer Person bei der Bewältigung einer Aufgabe/Handlung trotz des eigentlich bestehenden Problems in der Leistungsfähigkeit (Kapazität)[3] verbessert und somit eine Grundvoraussetzung für ihre Teilhabe in verschiedenen Lebensbereichen schafft. Z. B. kann einem Pflegeheimbewohner mit eingeschränkter Gehfähigkeit ein Rollator zur Verfügung gestellt werden, um dadurch seine Beeinträchtigung beim Gehen (= body function) zu reduzieren und es ihm so zu ermöglichen, trotz bestehender Probleme in seiner eigentlichen Leistungsfähigkeit, den Gang zum Aufenthaltsraum (= activity) mit Hilfe des Rollators selbstständig zurückzulegen und dort an den sozialen Angeboten des Pflegeheims teilzunehmen (= participation). Ein technisches Assistenzsystem kann somit

[2] Leistung ist die konkrete Durchführung einer Aufgabe oder Handlung einer Person in der gegenwärtigen, tatsächlichen Umwelt, d.h. unter Einbezug aller Aspekte der materiellen, sozialen und einstellungsbezogenen Gegebenheiten.

[3] Leistungsfähigkeit (Kapazität) ist das höchstmögliche Niveau der Funktionsfähigkeit, welches eine Person in einem bestimmten Lebensbereich zu einem bestimmten Zeitpunkt in einer standardisierten Umwelt erreichen kann (z. B. im Rahmen von standardisierten Testverfahren).

einen positiven Einfluss auf alle Komponenten der Funktionsfähigkeit einer Person (Körperfunktionen-/strukturen, Aktivitäten, Partizipation [Teilhabe]) haben.

Neben dem unmittelbaren Nutzen für die Funktionsfähigkeit und Selbständigkeit einer Person können auch versorgende Angehörige, Pflegekräfte sowie das Gesundheits- und Pflegewesen im Allgemeinen von technischen Assistenzsystemen profitieren. Technische Assistenzsysteme können die Notwendigkeit an persönlicher Betreuung und Pflege zeitlich hinauszögern oder sogar verhindern sowie pflegerische Tätigkeiten unterstützen, erleichtern oder ganz übernehmen. So können diese insgesamt zu einer Reduktion des personellen, finanziellen und zeitlichen Aufwands in der Gesundheits- und Pflegeversorgung beitragen (Fachinger, 2017; Hülsken-Giesler, 2015; Kunze & König, 2017; WHO, 2014). Z. B. könnte eine pflegebedürftige Person, die beim Duschen oder Baden auf persönliche Hilfe eines Angehörigen oder einer Pflegekraftangewiesen ist, durch einen Duschroboter so unterstützt werden, dass sie diese ADL wieder selbständig ausführen kann. Die pflegedürftige Person wird somit unmittelbar in ihrer Selbständigkeit unterstützt, der Bedarf an persönlicher Hilfe bei dieser ADL entfällt, die Angehörigen oder Pflegekräfte werden entlastet und personelle sowie zeitliche Ressourcen werden geschont.

Hinsichtlich der Effektivität von technischen Assistenzsystemen bei älteren Personen bemängeln zahlreiche Übersichtarbeiten die bisher noch fehlende Evidenz (Anttila, Samuelsson, Salminen & Brandt, 2012; Connell, Grealy, Olver & Power, 2011; Khosravi & Ghapanchi, 2016; Martin, Kelly, Kernohan, McCreight & Nugent, 2008; Topo, 2009). Häufig wurden sie lediglich anhand ihrer technischen Machbarkeit und/oder Akzeptanz bei den Nutzern bewertet. Um den tatsächlichen Mehrwert eines technischen Assistenzsystems für die Verbesserung der Funktionsfähigkeit, Selbstständigkeit, soziale Teilhabe oder des allgemeinen Wohlbefindens potentieller Nutzer aufzeigen zu können, muss jedoch auch deren Effektivität hierfür überprüft werden (Fuhrer, Jutai, Scherer & DeRuyter, 2003; Khosravi & Ghapanchi, 2016).

2.2.2 Ambient Assisted Living

Unter dem Begriff „Ambient Assisted Living“ (AAL) können Forschungsarbeiten zu technisch innovativen Assistenzsystemen im Bereich Alltagsunterstützung, Pflege und Gesundheitsversorgung von älteren Menschen beschrieben werden (Knols, Stoller & de Bruin, 2018). AAL-Systeme lassen sich dabei als „altersgerechte Assistenzsysteme für ein gesundes und unabhängiges Leben“ definieren (BMBF, 2008), die ältere Menschen durch den Einsatz innovativer Informations- und Kommunikationstechnologien (ICT) in die Gegenstände des täglichen Lebens und das unmittelbare Wohnumfeld bei der selbstständigen Bewältigung alltäglicher Aktivitäten in ihrer gewohnten und vertrauen Umgebung proaktiv, situationsabhängig und unaufdringlich unterstützen sollen, um ihnen so zu mehr Lebensqualität und Selbstbestimmung zu verhelfen (Berndt et al., 2009; BMBF/VDE Innovationspartnerschaft AAL, 2011; Knols et al., 2018; Varnai, Farla, Glasgow, Romeo & Simmonds, 2018). Die gewohnte und vertraue Umgebung umfasst dabei nicht nur das eigene Zuhause, sondern auch andere Lebenswelten (Pudane, Petrovica, Lavendelis & Ekenel, 2019). Durch diese prinzipiell weitgefasste Ausrichtung können AAL-Systeme nicht nur zur Förderung der Lebensqualität und Unterstützung der Selbstständigkeit in der eigenen Häuslichkeit eingesetzt werden, sondern auch im Falle von Hilfe- und Pflegebedürftigkeit in institutionalisierten Settings wie z. B. Alten- sowie Pflegeheime und können so die Belastung für die Pflege reduzieren (Fachinger, 2017; Krings, Böhle, Decker, Nierling & Schneider, 2014). Technisch betrachtet lassen sich AAL-Systeme als „Multi-Engineering-Systeme“ beschreiben, die aus unterschiedlichen Komponenten wie z. B. Sensoren, Aktoren, Computerhardware, Software oder Kommunikationsnetzwerke verschiedenster technischer Bereiche wie Gerätefertigung, Elektrotechnik, Robotik, Informatik und Telekommunikation bestehen (Memon, Wagner, Pedersen, Beevi & Hansen, 2014).

Innerhalb des AAL-Forschungsfelds haben in den letzten Jahren vor allem altersgerechte Assistenzroboter (AAL-Roboter) zunehmend an Bedeutung gewonnen. So initiierte z. B. die Europäische Kommission im Zeitraum von 2004 bis 2015 insgesamt 48 Forschungsprojekte im Bereich von AAL-Roboter (Payr, Werner & Werner, 2015b). Ein AAL-Roboter kann dabei als Roboter definiert werden, welcher (1) ältere Nutzer (und Nutzer mit Behinderung) als Zielgruppe hat, (2) diese Zielgruppe in den ADLs unterstützt und (3) deren Unabhängigkeit verbessert oder erhält (modifiziert nach (Payr, Werner & Werner, 2015a). Ein Roboter wird innerhalb dieser Definition als Mechanismus verstanden, der über Sensoren und Aktuatoren verfügt, sensorische Entscheidungen trifft und zu visuell erkennbaren Bewegungen fähig ist.

Altersgerechte Assistenzroboter lassen sich anhand ihres Anwendungsbereichs und der durch sie unterstützenden Aktivität in unterschiedliche Kategorien einteilen (Payr et al., 2015a). Tabelle 2 beschreibt diese Kategorien und fasst die Aktivitäten zusammen, welche die jeweiligen Kategorien von AAL-Robotern unterstützen (sollen).

Tab. 2: Kategorien von Ambient Assisted Living-Robotern nach Anwendungsbereich und unterstützte Aktivitäten (Payr et al., 2015a)

Kategorie	Beschreibung	Unterstützung			
		BADLs	**IADLs**	**EADLs**	**Sonstige**
Primäre Mobilitätshilfen	Direkte Unterstützung der Mobilität der Nutzer, indem ihre Fortbewegung oder Navigation zwischen Standorten verbessert wird (z. B. Rollstühle, Exoskelette für untere Extremitäten, robotische Gehhilfen [Rollatoren])	alle	Kochen Einkaufen Putzen	alle	Stabilität
Sekundäre Mobilitätshilfen	Unterstützung der Nutzer, indem deren Notwendigkeit zur Mobilität verringert wird (z. B. Hol- und Trageroboter)	-	Tragen Einkaufen	-	-
Manipulationshilfen	Unterstützung der Nutzer bei allen Aktivitäten, die Hand-/Armkraft oder -geschicklichkeit erfordern (z. B. Exoskelette für obere Extremitäten oder Roboterarme)	alle	alle	Hobbys Arbeit	-
Roboter für die Körperpflege	Unterstützung der Nutzer bei spezifischen Aktivitäten zur Körperpflege (z. B. Duschroboter, Toilettenroboter)	Essen Trinken Baden Toilettengang	-	-	-
Haushaltsroboter	Unterstützung der Nutzer bei hauswirtschaftlichen Aktivitäten wie Putzen und Kochen (z. B. Reinigungsroboter, Saugroboter, Fensterputzroboter)	-	Putzen Kochen	-	-
Begleitroboter, Telepräsenzroboter	Unterstützung der Nutzer bei der Kommunikation, Integration, Kognition (Erinnerung); soziale Unterstützung, Überwachung der Gesundheit, Warnung vor Sicherheitsbedrohungen	-	Management (Gesundheit, Verwaltung) Nutzung von Dienstleistungen, Transportmitteln (Tele-)Shopping	Lernen Kognitives Training Lesen Schreiben Teilhabe Unterhaltung Soziale Aktivitäten	Sicherheit Körperliches Training Unternehmung
Emotionale Roboter	Emotionale Unterstützung der Nutzer (meist in Pflegeeinrichtungen od. häuslicher Pflege); repräsentieren typischerweise Tierroboter (z. B. Katzen, Hunde, Robbe); Vorteile leiten sich aus der tiergestützten Therapie ab	-	-	Unterhaltung Kognitives Training	Unternehmung

BADLs = grundlegende Aktivitäten des täglichen Lebens zur Selbstversorgung (Trinken und Essen, Toilettengang, An-/Auskleiden, Körperpflege, Baden/Duschen, Bett-/Stuhltransfer, Gehen); IADLs = instrumentelle, kognitive und teilweise körperlich komplexere Aktivitäten des täglichen Lebens, wie das Zubereiten von Nahrungsmitteln, Einkaufen, Haushaltsführung, Verwalten von Finanzen, Bedienen des Telefons, Benutzung von Transportmitteln; EADLs = erweitere Aktivitäten des täglichen Lebens zur Teilnahme am sozialen Leben, wie Hobbys oder ehrenamtliche Arbeiten.

2.2.3 Fördermaßnahmen im Bereich Ambient Assisted Living

In den letzten Jahren gab es große Anstrengungen und Initiativen im Bereich der Forschungsförderung von AAL-Systemen, sowohl auf nationaler als auch internationaler Ebene. So förderte das Bundesministerium für Bildung und Forschung (BMBF) in Kooperation mit VDI/VDE (Verein Deutscher Ingenieure / Verband der Elektrotechnik Elektronik Informationstechnik e. V.) Innovation + Technik GmbH im Zeitraum von 2008 bis 2013 insgesamt 18 Forschungsprojekte im Bereich „altersgerechte Assistenzsysteme für ein gesundes und unabhängiges Leben“ mit einer Fördersumme von insgesamt 45 Millionen Euro

(AAL Deutschland, 2016). Auf europäischer Ebene beschloss die Europäische Kommission mit ihrem Aktionsplan „Aging Well in the Information Society“ für den Zeitraum von 2007 bis 2013 mehr als 1 Milliarde Euro für die Förderung von Forschung und Innovationen zu ICT-basierter Technologien für die alternde Gesellschaft („ICT for Aging Well“) in Europa bereitzustellen (European Commission, 2010a). Innerhalb des 7. EU-Rahmenprogramms für Forschung, technologische Entwicklung und Demonstration (FP7, 2007-2013) wurden hierfür rund 400 Millionen investiert; weitere 600 Millionen wurden darauf verwendet, das mit 23 europäischen Ländern im Jahr 2007 gemeinsam gegründete Forschungs- und Innovationsprogramm „AAL-Joint Programme“ (AAL-JP) zu fördern (European Commission, 2012b). Dessen Hauptziel ist es, innovative ICT-basierte Lösungen für Assistenzsysteme zur Verbesserung der Autonomie, sozialen Teilhabe und funktionellen Fähigkeit älterer Erwachsener zu entwickeln (AAL Association, 2013). Auch innerhalb des aktuellen EU-Rahmenprogramms für Forschung und Innovation „Horizon 2020“ (2014-2020) wird das AAL-JP gemeinsam mit 17 Ländern bis 2020 mit einem Budget von weiteren 600 Millionen Euro gefördert (European Commission, 2016a). Bis heute wurden im AAL-JP über 220 Forschungsprojekte im Bereich AAL mit einer Fördersumme von insgesamt mehr als 1,2 Milliarden Euro unterstützt (AAL Association, 2019). Neben dem AAL-JP fördert die Europäische Kommission mit dem Horizon 2020-Rahmenprogramm zusätzlich weitere Forschungs- und Innovationsprojekte zu „ICT for Aging Well“. Im Arbeitsprogramm „Societal Challenges 1 – Health, Demographic Change and Wellbeing“ werden für den Bereich „Personalising Health and Care” seit 2015 weitere 24 Forschungsprojekte zu ICT-basierten Assistenzsystemen bzw. AAL-Systemen für ältere Menschen mit mehr als 95 Millionen Euro gefördert (European Commission, 2016b).

Nach Bewertung der ersten AAL-JP bzw. ICT-Fördermaßnahmen von 2007 bis 2013 sah die Europäische Kommission besonderen Bedarf hinsichtlich der verstärkten Einbindung potentieller Nutzer in zukünftige Forschungsprojekte. Zwar konnte für diesen Zeitraum z. B. innerhalb der geförderten AAL-JP-Projekte etwa 30% der beteiligten Organisationen eine gewisse Form von Nutzerrolle zugeschrieben werden (European Commission, 2010b, 2013c), dennoch waren potentielle Nutzer nur unzureichend an den Forschungs-, Entwicklungs- und Innovationsprozessen aktiv beteiligt. Zudem wurden die Nutzer zu ungenau definiert und ihren persönlichen Eigenschaften im Hinblick auf die Akzeptanz der AAL-Systeme wurde zu wenig Aufmerksamkeit geschenkt (European Commission, 2013b). An zukünftig geförderte Projekte stellte die Europäische Kommission daher die Forderung, die Perspektive der potentiellen Nutzer von AAL-Systemen zu stärken. In nachfolgenden Förderprogrammen sollten die Beteiligung von Organisationen zur Vertretung der Nutzer deutlicher unterstützt, die potentiellen Nutzer enger in alle Phase der Programmgestaltung/-

durchführung miteingebunden sowie vermehrt Demonstrationen und Pilotprojekte unter realistischen, alltagsnahen Bedingungen durchgeführt werden (European Commission, 2013b, 2013c).

Auf nationaler Ebene kam die vom BMBF im Rahmen der AAL-Begleitforschung in Auftrag gegebene Studie zur Analyse der 18 geförderten Forschungsprojekte im Bereich „altersgerechte Assistenzsysteme für ein gesundes und unabhängiges Leben“ im Jahr 2011 zu einem vergleichbaren Fazit. Sie bemängelt eine oftmals fehlende Nutzerperspektive in der Entwicklung von AAL-Systemen. Vielmehr waren diese bisher stark technologiegetrieben und nicht bzw. nur sehr wenig auf die Bedürfnisse älterer Nutzer abgestimmt (Friesdorf et al., 2011). Eine vom Bundesministerium für Gesundheit (BMG) beauftragte Studie zur Unterstützung der Pflegebedürftigkeit durch technische Assistenzsysteme im Jahr 2013 hebt zusätzlich hervor, dass der evidenzbasierte Nachweis hinsichtlich der Wirksamkeit und des Nutzens von AAL-Systemen unter realistischen Bedingungen noch unzureichend ist (BMG, 2013).

2.2.4 Nutzerzentrierter Entwicklungsprozess

Definitionsgemäß sind ältere Menschen die Zielgruppe von AAL-Systemen (BMBF, 2008), welche jedoch häufig wenig Erfahrung mit neuartigen Technologien zeigen (Czaja et al., 2006; Lee et al., 2019). Bei AAL-Systemen kommen für diese Zielgruppe meist unbekannte Technologie zum Einsatz, die bei unzureichender Passung mit den vorhandenen Ressourcen zu Stress, Ängstlichkeit, Überforderung, Gefährdung oder gar Ablehnung führen können (Hauer, 2018). Für eine erfolgreiche Entwicklung, Implementierung und Nutzung von AAL-Systemen ist daher eine gezielte und frühzeitige Ableitung und Einbindung von Anforderungen, Bedürfnissen und Wünschen der zukünftigen Nutzergruppe im Sinne eines nutzerzentrierten Entwicklungsprozesses von entscheidender Bedeutung. Nur so kann eine gezielte Anpassung der Entwicklung an die Kompetenzen der zukünftigen Nutzer gewährleistet werden und ein nutzerfreundliches sowie gebrauchstaugliches AAL-System entstehen (Friesdorf et al., 2011; Manzeschke, Weber, Rother & Fangerau, 2013). Bei der Zielgruppe von AAL-Systemen kann es sich außerdem häufig um ältere Personen handeln, welche die Aufgaben des Alltags bisher ohne Unterstützung solcher Technologien gelöst haben. Es ist daher essentiell, dass vom Gebrauch eines AAL-Systems auch ein Mehrwert für die Nutzer erkennbar wird, um deren Akzeptanz und Zustimmung für die neue Technologie zu erreichen. Fester Bestandteil eines nutzerzentrierten Entwicklungsprozesses stellt somit die Evaluation des tatsächlich entwickelten AAL-Systems bei potentiellen Nutzern dar, in der überprüft werden soll, ob die entwickelten Lösungen auch den zu Beginn festgelegten Nutzeranforderungen entsprechen und in einem bestimmten Nutzungskontext von der Zielgruppen effektiv, effizient und zufriedenstellend genutzt werden können (Lindwedel-Reime et al., 2016).

Insgesamt wird auf nationaler wie auch internationaler Ebene bei der zukünftigen Entwicklung von AAL-Systemen eine stärkere Berücksichtigung der Nutzerperspektive über den gesamten Entwicklungsprozess hinweg gefordert (BMG, 2013; European Commission, 2013b, 2013c; Friesdorf et al., 2011).

2.3 MOBOT – Intelligent Active Mobility Aid RoBOT Integrating Multimodal Communication

Das MOBOT-Projekt war ein von der Europäischen Kommission innerhalb des FP7 gefördertes Forschungsprojekt, das im Zeitraum von Februar 2013 bis Juli 2016 als Kooperationsprojekt von zehn europäische Institutionen aus den Fachbereichen Informatik, Ingenieurwissenschaft, Elektro- und Computertechnik, Mathematik, Robotik und (geriatrische) Rehabilitation durchgeführt wurde (www.cordis.europa.eu/project/id/600796). Ziel dieses Projektes war es u.a., einen altersgerechten Assistenzroboter auf Basis eines Rollators zu entwickeln, welches die Mobilität älterer Menschen mit Gangstörungen proaktiv, nutzerangepasst sowie kontext- und situationsabhängig unterstützt.

Der Prototyp des MOBOT-Rollators (vgl. Anhang: Manuskript III, Fig. 1, S. 146) integriert vielfältige, innovative und „smarte“ Teilfunktionen, welche den primären Fokus der körperlichen Mobilitätsunterstützung eines herkömmlichen Rollators (Gehen, Balance) deutlich erweitern. Hierzu ist der MOBOT-Rollator mit zahlreichen unterschiedlichen Sensoren (z. B. Laser-Entfernungssensoren, Kraftsensoren, Kinect-Kamera, Mikrophone, optische Encoder, inertiale Messeinheiten) ausgestattet, mit deren Hilfe die Aktivität und Bewegung des Nutzers zu jedem Zeitpunkt analysiert, seine Absichten interpretiert und das Verhalten des MOBOT-Rollators entsprechend daran angepasst werden soll. Außerdem kann der über Gestik und/oder Sprache ohne Körperkontakt gesteuert werden. Tabelle 3 fasst die während des Projekts entwickelten und implementierten Teilfunktionen des MOBOT-Rollators zusammen. Eine ausführlichere Beschreibung der für diese Dissertationsschrift relevanten Funktionen (Navigationssystem, Ganganalysesystem, Aufstehhilfe) ist in den angehängten Manuskripten III-VI zu finden.

Innerhalb des MOBOT-Projekts nahm das AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG die Rolle des führenden klinischen Partners ein. Dabei bestand die Hauptaufgabe darin, die Nutzerperspektive über den gesamten Entwicklungsprozess des MOBOT-Rollators (Planung, Entwicklung und Evaluation) sicherzustellen. Hierzu zählte u.a. die Überprüfung des Forschungsstands zu robotergestützten Rollatoren; die Analyse und Definition typischer Anwendungsfälle sowie der Zielgruppe des MOBOT-Rollators inkl.

ihrer Anforderungen und Bedürfnisse; die Identifikation und Entwicklung geeigneter objektiver und subjektiver Leistungsparameter für die Evaluation der innovativen Funktionen des MOBOT-Rollators; die Studienplanung, -durchführung und -auswertung zur Evaluation der innovativen Teilfunktionen des MOBOT-Rollators mit potentiellen Nutzern.

Tab. 3: Innovative Teilfunktionen des MOBOT-Rollators

Funktion	**Beschreibung**
Lokalisierung & Navigation (Manuskript III)	Basierend auf hinterlegten Gebäudeplänen (Karten), den Daten der integrierten Sensortechnik (optische Encoder, inertiale Messeinheiten, Laser-Entfernungsmesser) und etablierten Algorithmen aus dem Bereich der Lokalisierung mobiler Roboter ermöglicht der MOBOT-Rollator eine sprachgesteuerte Navigationshilfe innerhalb von fremden Gebäuden.
Ganganalyse (Manuskript IV)	Räumlich-zeitliche Gangparameter des Nutzers werden basierend auf den Daten eines an der Rückseite des MOBOT-Rollators angebrachten Laser-Entfernungssensor bestimmt.
Hindernisvermeidung (Manuskript V)	Hindernisse in der Umgebung werden durch einen Laser-Entfernungssensor an der Vorderseite des MOBOT-Rollators erkannt und die interaktive Steuerungsarchitektur des MOBOT-Rollators verhindert die Kollision und unterstützt das Umfahren der Hindernisse.
Aufstehhilfe (Manuskript VI)	Der MOBOT-Rollator besitzt zwei hydraulisch parallel angetriebene (aktuierte) Roboterarme mit Handgriffen, an denen sich der Nutzer aktiv festhält. Basierend auf nutzerspezifischen, nach vorne/oben gerichtete Bewegungsbahnen (Trajektorien) der Handgriffe, wird der Nutzer aktiv über eine Hebekraft beim Aufstehen unterstützt.
Sprach-/Gestensteuerung (Efthimiou et al., 2016)	Die integrierte(n) Kinect-Kamera und Mikrophone ermöglichen eine Steuerung des MOBOT-Rollators über festgelegte Sprachbefehle oder Gesten ohne direkten körperlichen Kontakt (z. B. MOBOT-Rollator herbeirufen oder in die Parkposition schicken)
„Vorausfahrende" Folgefunktion (Moustris & Tzafestas, 2016)	Basierend auf den Daten der Laser-Entfernungssensoren an der Rück- und Vorderseite des MOBOT-Rollators und einer interaktiven Antriebsarchitektur ermöglicht der MOBOT-Rollator ein Vorausfahren nah vor dem Nutzer, jedoch ohne direkten körperlichen Kontakt.

2.4 I-SUPPORT – ICT-Supported bath robots

Das I-SUPPORT-Projekt war ebenfalls ein von der Europäischen Kommission gefördertes Forschungsprojekt. Es wurde innerhalb des Horizon 2020-Rahmenprogramms im Zeitraum von März 2015 bis Februar 2018 als multidisziplinäres Kooperationsprojekt (Robotik, Informatik, Ingenieurwissenschaft, Elektro- und Computertechnik, geriatrische und neuromotorische Rehabilitation, angewandte Gesundheits- und Sozialwissenschaft) durchgeführt (www.cordis.europa.eu/project/id/643666). Ziel des I-SUPPORT-Projekts war es einen innovativen, modularen, ICT-gestützten Duschroboter zu entwickeln, welcher ältere Menschen mit Einschränkungen beim Baden/Duschen dabei unterstützt diese grundlegende ADL erfolgreich, sicher und selbstständig durchzuführen.

Der Prototyp des I-SUPPORT-Duschroboters (vgl. Anhang: Manuskript VII: Figure 1, S. 209) besteht aus einem motorisierten Stuhl zur Unterstützung des Sitzen-Stehen-Transfers und des Übergangs in und aus dem Duschbereich, einem robotergestützten Softarm für die spezifischen Bade/-Duschaktivitäten (z. B. Abspülen, Einseifen, Schrubben, Abtrocknen), visuelle und auditive Sensoren (Kinect-Kameras und Mikrophone) für eine sprach-/gestenbasierte Mensch-Roboter-Interaktion und ein multisensorisches, kontextbewusstes System zur Überwachung der Umgebung (Wasserfluss/-temperatur, Lufttemperatur, Feuchtigkeit und Beleuchtung) und Nutzerinformationen (Smartwatch zur Nutzeridentifikation und Aktivitätsüberwachung).

Auch innerhalb des I-SUPPORT-Projekts bestand die Hauptaufgabe des AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG darin, als klinischer Partner den nutzerzentrierten Entwicklungsprozess des I-SUPPORT-Duschroboters sicherzustellen. Entsprechende Projektaufgaben umfassten hierbei u.a. die Definition der typischen Anwendungsfälle und Nutzer(-anforderungen) des I-SUPPORT-Duschroboters (Werle & Hauer, 2016), die Ausarbeitung eines geeigneten Evaluationsplan inkl. -kriterien zur Überprüfung der Übereinstimmung des I-SUPPORT-Duschroboters mit den Nutzeranforderungen und -bedürfnissen sowie die Durchführung und Auswertung von Studien zur Evaluation der Bedienbarkeit und Akzeptanz des I-SUPPORT-Duschroboter unter realistischen Bedingungen mit potentiellen Nutzern.

3 Fragestellungen und Ziele

Das übergeordnete Ziel dieser Dissertation war es, die in den Projekten „MOBOT“ und „I-SUPPORT“ neu entwickelten altersgerechten Assistenzroboter (MOBOT-Rollator, I-SUPPORT-Duschroboter) aus der Perspektive potentieller Nutzer zu evaluieren.

Im Rahmen des MOBOT-Projekts wurde hierfür zunächst eine systematische Literaturanalyse von Studien zur Evaluation robotergestützter Rollatoren aus der Nutzerperspektive durchgeführt (Manuskript I & II). Sie diente in einem ersten Schritt dazu, einen umfassenden Überblick zur methodischen Vorgehensweise bisheriger Studien in diesem Themenbereich zu erhalten, um daraus wertvolle Erkenntnisse und Handlungsempfehlungen für die nutzerorientierten Evaluationsstudien des MOBOT-Rollators sowie von anderen robotergestützten Rollatoren, aber auch von altersgerechten Assistenzrobotern (AAL-Roboter) im Allgemeinen abzuleiten (Manuskript I). In einem zweiten Schritt wurden die Untersuchungsergebnisse der in der systematischen Literaturanalyse identifizierten Studien mit dem Ziel analysiert, daraus die derzeitige Evidenz zur Effektivität und positiven Wahrnehmung der robotergestützten Rollatoren bei potentiellen Nutzern zu ermitteln und den weiteren Forschungsbedarf in diesem Themenbereich aufzuzeigen (Manuskript II). Zusammenfassend wurden anhand der systematischen Literaturanalyse folgende Fragestellungen bearbeitet:

- Mit welcher methodischen Vorgehensweise wurden bisherige Studien zur Evaluation von robotergestützten Rollatoren aus der Perspektive der Nutzer durchgeführt und lassen sich daraus Handlungsempfehlungen für zukünftige Evaluationsstudien ableiten? (Manuskript I)
- Welche Untersuchungsergebnisse zeigen bisherige Studien zur Effektivität und positiven Wahrnehmung von robotergestützten Rollatoren aus der Perspektive der Nutzer? (Manuskript II)

Aufbauend auf den Erkenntnissen und Handlungsempfehlungen der systematischen Literaturanalyse wurden die nutzerorientierten Evaluationsstudien des MOBOT-Rollators konzipiert und durchgeführt (Manuskript III-VI). Ein wesentliches Ziel dabei war, die in der systematischen Literaturanalyse aufgedeckten methodischen Defizite bisheriger Evaluationsstudien von robotergestützten Rollatoren zu vermeiden und anhand methodisch hochwertiger Evaluationsstudien innerhalb des MOBOT-Projekts, einen Beitrag zur Schließung der noch bestehenden Forschungslücken in diesem Bereich zu leisten. Die eigens konzipierten und durchgeführten Evaluationsstudien fokussierten sich jeweils auf eine spezifisch zu evaluierende Teilfunktion des MOBOT-Rollators, wobei folgende Fragestellungen bearbeitet wurden:

- Kann das MOBOT-integrierte Navigationssystem die Navigationsleistung von potentiellen Nutzer mit und ohne kognitive Einschränkungen verbessern? (Manuskript III)

- Kann das MOBOT-integrierte Ganganalysesystem räumlich-zeitliche Gangparameter bei potentiellen Nutzern valide erfassen? (Manuskript IV)
- Kann die MOBOT-integrierte Assistenzfunktion zur Hindernisvermeidung Gefahrensituationen mit Hindernissen in der Umgebung bei potentiellen Nutzern reduzieren? (Manuskript V)
- Kann die MOBOT-integrierte Aufstehhilfe den Sitzen-Stehen-Transfer bei potentiellen Nutzern effektiv unterstützen? (Manuskript VI)

Im Rahmen des I-SUPPORT-Projekts wurden vor dem Hintergrund der Entwicklung und Implementierung einer erfolgreichen Mensch-Roboter-Interaktion zwei Studien durchgeführt mit dem Ziel, (1) die Effektivität und Zufriedenheit mit unterschiedlich autonomen Betriebsmodi des I-SUPPORT-Duschroboters (Manuskript VII) sowie (2) die Effekte eines spezifischen Nutzertrainings auf die Mensch-Roboter-Interaktion bei potentiellen Nutzern des I-SUPPORT-Duschroboters zu evaluieren (Manuskript VIII). Die Hauptfragestellungen dieser Studien lauteten demnach wie folgt:

- Hat der Automatisationsgrad der unterschiedlichen Betriebsmodi des I-SUPPORT-Duschroboters (autonomer, roboterassistierter oder telemanipulativer Modus) bei potentiellen Nutzern Auswirkungen auf die Effektivität und Zufriedenheit mit dem I-SUPPORT-Duschroboter? Und wenn ja, mit welchem Betriebsmodus wird die höchste Effektivität und Zufriedenheit erreicht? (Manuskript VII)
- Führt ein spezifisches Training der für die gestenbasierte Interaktion mit dem I-SUPPORT-Duschroboter notwendigen Gesten zu einer verbesserten Mensch-Roboter-Interaktion bei potentiellen Nutzern? (Manuskript VIII)

Darüber hinaus wurden zusätzlich nachfolgende Nebenfragestellungen bearbeitet:

- Haben persönliche Eigenschaften der Nutzer einen Einfluss auf deren Zufriedenheit mit den unterschiedlichen autonomen Betriebsmodi des I-SUPPORT-Duschroboters? (Manuskript VII)
- Haben persönliche Eigenschaften der Nutzer einen Einfluss auf die gestenbasierte Mensch-Roboter-Interaktion mit dem I-SUPPORT-Duschroboter bzw. auf die Trainingseffekte? (Manuskript VII)
- Gibt es einen Zusammenhang zwischen der Ausführung der Gesten und der Gestenerkennungsrate des I-SUPPORT-Duschroboters? (Manuskript VIII)

Die einzelnen Manuskripte werden nachfolgend in Kapitel 4 anhand einer gängigen Abstract-Gliederung (Hintergrund und Zielstellung, Methodik, Ergebnisse, Diskussion und Schlussfolgerung) zusammengefasst. Die publizierten oder eingereichten („pre-prints“) Originaldokumente befinden sich im Anhang dieser Dissertationsschrift (Anhang B).

4 Publikationsübersicht und Zusammenfassungen

4.1 Manuskript I: Systematische Literaturanalyse des methodischen Vorgehens von Studien zur Evaluation von robotergestützten Rollatoren aus der Nutzerperspektive

Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62*(6), 644-653. DOI: 10.1159/000444878

Hintergrund und Zielsetzung

Im Rahmen der Forschungs- und Entwicklungsaktivitäten zu altersgerechten Assistenzsystemen entstand durch den Einsatz robotischer Systeme in den letzten beiden Jahrzehnten eine neue Art von smarten Hightech-Rollatoren (Martins, Santos, Frizera-Neto & Ceres, 2012). Die Entwicklung solcher robotergestützten Rollatoren erfolgte in diesem Zeitraum häufig entlang des technisch Machbaren. Auch deren bisherige Evaluation scheint hauptsächlich von technischen Zielen bestimmt gewesen zu sein und fokussierte sich überwiegend auf die Überprüfung ihrer technischen Funktionsfähigkeit (Martins, Santos, Frizera & Ceres, 2015). Für die erfolgreiche Entwicklung von Assistenzsystemen ist jedoch nicht nur die Bewertung ihrer technischen Funktionsfähigkeit, sondern vor allem auch die ihrer Brauchbarkeit und Effektivität für die vorgesehene Nutzergruppe von entscheidender Bedeutung. Nur durch eine kontinuierliche Einbindung und Berücksichtigung der Nutzerperspektive in den fortlaufenden Entwicklungs- und Evaluationsprozess kann überprüft werden, ob ein Assistenzsystem den Bedürfnissen, Anforderungen und Erwartungen ihrer Nutzer gerecht wird und einen Mehrwert für sie bietet (Choi & Sprigle, 2011; Kensing & Blomberg, 1998; Schulz et al., 2015; Tsui, Feil-Seifer, Matarić & Yanco, 2009). Daher hat sich der geforderte Forschungs- und Entwicklungsschwerpunkt bei altersgerechten Assistenzrobotern in den letzten Jahren zunehmend Richtung der Mensch-Roboter-Interaktion und der Nutzerperspektive im Speziellen verlagert (AAL Association, 2014; Beckerle et al., 2017; BMBF, 2018). Eine Verlagerung von einer technischen hin zu einer nutzerorientieren Perspektive könnte allerdings bei der Evaluation von altersgerechten Assistenzrobotern mit speziellen Herausforderungen hinsichtlich des methodischen Vorgehens verbunden sein (Tsui et al., 2009). Etablierte Standards oder Empfehlungen insbesondere zur Evaluation von robotergestützten Rollatoren aus der Perspektive der Nutzer sowie systematische Übersichtarbeiten zu diesem Themengebiet fehlen jedoch bislang. Vor diesem Hintergrund wurde in Manuskript I eine systematische Literaturanalyse mit dem Ziel durchgeführt, das methodische Vorhergehen bisheriger Studien zur Evaluation von robotergestützten Rollatoren zu analysieren und aus den daraus gewonnenen Erkenntnissen konkrete Handlungsempfehlung sowohl für die Evaluationsstudien innerhalb des eigenen MOBOT-Projekts als auch für zukünftige Evaluationsstudien anderer robotergestützter Rollatoren abzuleiten.

Methodik

Die systematische Literaturrecherche erfolgte nach den Standards der Cochrane Collaboration (Higgins & Green, 2011) in den elektronischen Datenbanken PubMed und IEEE Xplore. Die verwendete Suchstrategie basierte auf standardisiertem Vokabular der Datenbanken (MeSH terms, IEEE terms) und freien Textwörtern zu den Bereichen „assistive mobility device“, „robotic functionality“, „gait/mobility support“ und „evaluation measure“. Eingeschlossen wurden Studien zur nutzerorientierten Evaluation der Interaktion zwischen Mensch und robotergestütztem Rollator unabhängig von der Art der hierfür verwendeten Assessmentmethoden. Es wurden keine Einschränkungen in Bezug auf Alter oder Gesundheitsstatus der Studienteilnehmer gemacht. Ausgeschlossen wurden Einzelfallstudien und Studien, in denen ausschließlich Monitoring-Funktionen, nicht jedoch nutzerorientiere Assistenzfunktionen oder die subjektive Nutzererfahrung evaluiert wurden. Die Suche war begrenzt auf englischsprachige Artikel, die bis zum 31. Dezember 2014 publiziert wurden.

Ergebnisse

Insgesamt konnten 28 Studien identifiziert werden, die den Einschlusskriterien der Literaturrecherche entsprachen. Diese Studien zeigten hinsichtlich der Nutzergruppen, der Stichproben sowie der verwendeten Studiendesigns und Assessmentstrategien eine große Heterogenität. So wurde die potentielle Nutzergruppe der robotergestützten Rollatoren überwiegend anhand generischer (z. B. ältere Personen, Menschen mit Behinderung) oder settingspezifischer Kriterien (z. B. Pflegeheimbewohner) bzw. anhand von Krankheitskategorien (z. B. Morbus Parkinson, Hemiplegie) oder unspezifischen funktionellen Kriterien (z. B. Mobilitätsprobleme, kognitive Einschränkungen) definiert. Nur vereinzelte Studien verwendeten präzise Kriterien basierend auf etablierten Screening- oder Assessmentmethoden, um die spezifischen funktionellen Beeinträchtigungen der potentiellen Nutzergruppe zu definieren. Die Stichproben unterschieden sich erheblich in Bezug auf ihre Größe (Spannweite = 2-60 Teilnehmer) und dem Alter (Spannweite = 14-97 Jahre) sowie den Beeinträchtigungen der Teilnehmer (gesunde junge Personen – hochbetagte Personen mit kognitiven und motorischen Einschränkungen). Es wurden drei unterschiedliche Studiendesigns identifiziert: Beobachtungs-, Vergleichs- (z. B. robotergestützter Rollator vs. konventioneller Rollator, aktivierte vs. nicht-aktivierte Assistenzfunktion) und Interventionsstudien. Zudem kamen insgesamt fünf unterschiedliche Kategorien von Assessmentmethoden in den Studien zum Einsatz: (1) klinisch etablierte, funktionelle Testverfahren (z. B. Timed „Up and Go“-Test, Podsiadlo & Richardson, 1991;4-Meter-Gehtes, Guralnik et al., 1994); (2) „maßgeschneiderte“ Assessmentmethoden in Form von selbst entworfenen, leistungsbasierten Testverfahren, die speziell auf die zu evaluierende Assistenzfunktion des robotergestützten

Rollators zugeschnitten waren (z. B. Hindernisparcours → Assistenzfunktion: Hindernisvermeidung); (3) Assessmentmethoden zur Beurteilung der körperlichen Beanspruchung während der Verwendung des robotergestützten Rollators (z. B. Respirometrie, Elektromyografie); (4) Instrumente zur subjektiven Erfassung der Nutzererfahrung (z. B. Befragungen, selbst entworfene Fragebögen) und (5) Assessmentmethoden zur Überprüfung der technischen Funktionsfähigkeit. Ein generisches methodisches Vorgehen bei der Evaluation von robotergestützter Rollatoren aus der Nutzerperspektive konnte nicht identifiziert werden. Insgesamt zeigten die meisten Studien vielmehr erhebliche methodische Mängel: Stichprobenbeschreibungen und -größen waren unzureichend, die Teilnehmer waren für die potentielle Nutzergruppe der robotergestützten Rollatoren nicht repräsentativ, geeignete, standardisierte und validierte Assessmentmethoden sowie inferentielle statistische Analysen fehlten.

Diskussion und Schlussfolgerung
Manuskript I bietet erstmals einen systematischen Überblick über die Studien zur Evaluation robotergestützter Rollatoren aus der Nutzerperspektive. Neben der großen Heterogenität der Studien hinsichtlich ihres methodischen Vorgehens war festzustellen, dass ein eklatanter Mangel an methodisch hochwertigen Evaluationsstudien besteht. Basierend auf der systematischen Literaturanalyse konnten für zukünftige Evaluationsstudien folgende Empfehlungen formulierte werden: (1) klare Definition der Nutzergruppe anhand von spezifischen und validen Kriterien zur Bewertung ihrer Einschränkungen; (2) angemessene Auswahl der Teilnehmer entsprechend der definierten Nutzergruppe; (3) Vergleich mit anderen (konventionellen) Mobilitätshilfen; (4) Evaluation der habituellen Verwendung im fortgeschrittenen Entwicklungsprozess des robotergestützten Rollators; (5) Auswahl von standardisierten und validierten Assessmentmethoden; (6) Umsetzung einer spezifisch auf die zu evaluierende Assistenzfunktion des robotergestützten Rollators zugeschnittene Assessmentstrategie und (7) statistische Überprüfung der Studienergebnisse. Diese Empfehlungen können im Allgemeinen auch für die nutzerorientierte Evaluation von anderen AAL-Systemen angewendet werden.

4.2 Manuskript II: Systematische Literaturanalyse der Ergebnisse von Studien zur Evaluation von robotergestützten Rollatoren aus der Nutzerperspektive

Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2018). A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. *Disability and Rehabilitation: Assistive Technology*, *13*(1), 31-39. DOI: 10.1080/17483107. 2016.1278470

Hintergrund und Zielsetzung

Die Evaluation von altersgerechten Assistenzrobotern aus der Nutzerperspektive ist mit signifikanten methodischen Herausforderungen verbunden (Tsui et al., 2009). Manuskript I bestätigt dies für robotergestützte Rollatoren und zeigt auf, dass bisherige Evaluationsstudien hierzu nicht nur eine große Heterogenität im methodischen Vorgehen, sondern auch erhebliche methodische Mängel aufweisen (Werner, Ullrich, Geravand, Peer & Hauer, 2016). Es ist anzunehmen, dass die Evidenz für die Effektivität und positive Wahrnehmung der robotergestützten Rollatoren dadurch wesentlich beeinflusst worden sind. Da sich Manuskript I auf das methodische Vorgehen der Evaluationsstudien, nicht jedoch auf deren Ergebnisse fokussierte, wurde diese Annahme in Manuskript I noch nicht überprüft. Andere systematische Übersichtsarbeiten zur Effektivität und positiven Wahrnehmung von robotergestützten Rollatoren aus der Nutzerperspektive wurden bislang ebenfalls noch nicht durchgeführt. Manuskript II hatte daher zum Ziel, die Ergebnisse der in Manuskript I identifizierten Studien hinsichtlich der Effektivität und Nutzerwahrnehmung von robotergestützten Rollatoren zu evaluieren.

Methodik

Die identifizierten Studien der systematischen Literaturanalyse in Manuskript I wurden nochmals gescreent und anhand folgender Einschlusskriterien auf ihre Eignung überprüft: (1) Evaluation der Interaktion zwischen Mensch und robotergestütztem Rollator aus der Nutzerperspektive, (2) Verwendung standardisierter Assessmentmethoden und (3) quantitative Darstellung der Studienergebnisse.

Ergebnisse

Nach dem erneuten Screeningprozess entsprachen 17 Studien den Einschlusskriterien. Aufgrund der klinischen und methodischen Heterogenität der Studien wurde eine narrative Synthese der Studienergebnisse durchgeführt. Insgesamt zeigten sich kontroverse Studienergebnisse hinsichtlich der Effektivität der robotergestützten Rollatoren. Manche Studien deuteten auf eine gesteigerte körperliche, kognitive oder sensorische Leistung der Nutzer (z. B. Gang-, Navigations- oder Präzisionsleistung) oder eine verringerte körperliche Beanspruchung (z. B. Kraftaufwand, kardiorespiratorische Belastung) unter Verwendung der innovativen Assistenzfunktionen der robotergestützten Rollatoren im Vergleich zu Bedingungen ohne deren Unterstützung oder auch zu anderen konventionellen Mobilitätshilfen. Andere Studien berichteten hingegen von einer geringeren Nutzerleistung oder einer höheren körperlichen Beanspruchung mit den robotergestützten Rollatoren innerhalb dieser Vergleiche. In 14 von 17 Studien (82.4%) basierten die Studienergebnisse jedoch nur auf deskriptiven Statistiken und es fehlten inferentielle statistische Analysen. Die Ergebnisse zur subjektiven Wahrnehmung zeigten, dass die robotergestützten Rollatoren im Allgemeinen positiv wahrgenommen wurden.

Diskussion und Schlussfolgerung

Manuskript II verdeutlicht, dass die Datenlage und Evidenz zur Effektivität und positiven Wahrnehmung von robotergestützten Rollatoren aus der Nutzerperspektive noch unzureichend sind. Hierzu publizierte Ergebnisse basieren hauptsächlich auf subjektiven Bewertungen der Studienautoren und weniger auf geeignete statistische Analysen. Dieses methodische Vorgehen ist eher mit Beschreibungen von Anwendungsfällen vergleichbar und erlaubt keine evidenzbasierten Aussagen. Es bleibt somit unklar, ob die fehlende Evidenz auf die mangelnde Eignung der robotergestützten Rollatoren oder die teilweise erheblichen methodischen Defizite bisheriger Evaluationsstudien zurückzuführen ist. Insgesamt ist die Durchführung methodisch hochwertiger Evaluationsstudien notwendig, um die geringe Datenlage qualitativ zu erweitern und evidenzbasierte Aussagen zum Mehrwert von robotergestützten Rollatoren und deren innovativen Assistenzfunktionen für potentielle Nutzer sowie zur positiven Nutzerwahrnehmung treffen zu können.

4.3 Manuskript III: Evaluation des im MOBOT-integrierten Navigationssystems bei älteren Personen mit und ohne kognitiver Einschränkung

Werner, C., Moustris, G. P., Tzafestas, C. S. & Hauer, K. (2018). User-oriented evaluation of a robotic rollator that provides navigation assistance in frail older adults with and without cognitive impairment. *Gerontology, 64*(3), 278-290. DOI: 10.1159/000484663

Hintergrund und Zielsetzung

Die Fähigkeit der räumlichen Orientierung und Navigation nimmt mit zunehmendem Alter ab (Kirasic, 1991; Moffat, 2009). Dieser Rückgang ist vor allem bei älteren Personen mit kognitiven Einschränkungen zu beobachten (Cushman, Stein & Duffy, 2008; Hort et al., 2007). Räumliche Orientierungsschwierigkeiten in unbekannten und vertrauen Umgebungen zählen zudem zu den ersten Symptomen einer Demenz (Chiu et al., 2004; Pai & Jacobs, 2004). Da der Verlust der räumlichen Orientierung und Navigationsfähigkeit zu einer eingeschränkten Mobilität, Autonomie und Unabhängigkeit führen kann (Burns, 1999;

Passini et al., 1995), könnte die Unterstützung bei Orientierungs- und Navigationsproblemen durch geeignete Assistenzsysteme von großem Nutzen für gebrechliche ältere Menschen mit solchen Problemen sein. Vor diesem Hintergrund wurde bei der Entwicklung von robotergestützten Rollatoren teilweise Assistenzsysteme verbaut, die ihre Nutzer bei der räumlichen Orientierung und Navigation unterstützen sollen. Die technische Implementierung dieser Navigationssysteme basiert dabei auf ganz unterschiedlichen Konzepten. Manche robotergestützten Rollatoren führen ihre Nutzer eher passiv zu einem vorher festgelegten Ziel, indem sie ausschließlich Routeninformationen in Form von Sprachhinweisen (z. B. „Biegen Sie rechts ab.“), visuellen Anweisungen (z. B. Richtungspfeil auf einem Bildschirm) oder haptischen Richtungssignalen (z. B. Vibrationen am linken oder rechten Handgriff) geben, während der Nutzer jedoch jederzeit die volle Bewegungskontrolle über den Rollator behält (Glover et al., 2003; Kulyukin, Kutiyanawala, LoPresti, Matthews & Simpson, 2008; Wachaja et al., 2017). Andere robotergestützten Rollatoren unterstützen den Nutzer aktiver, indem sie ihre eigene Bewegungsrichtung über virtuelle Kräfte, die Steuerung der Lenkwinkel der Vorderräder oder die Verlangsamung der Geschwindigkeit beeinflussen, um so den Nutzer bei zu großen Abweichungen auf der vorher festgelegten Route zu halten (Morris et al., 2003; Palopoli et al., 2015; Rodriguez-Losada, Matia, Jimenez, Galan & Lacey, 2005; Yu, Spenko & Dubowsky, 2003). Unabhängig von ihrer technischen Implementierung ist die Evidenz für die Effektivität der Navigationssysteme von robotergestützten Rollatoren bei potentiellen Nutzern noch unzureichend. Die Ergebnisse der systematischen Literaturanalyse in Manuskript II deuten zwar darauf hin, dass sie hilfreich für die Steigerung der Navigationsleistung ihrer Nutzer sein könnten, jedoch die Evidenz für deren Mehrwert für die Nutzer durch die erheblichen methodischen Mängel bisheriger Evaluationsstudien noch sehr gering ist (Werner et al., 2018). Ziel von Manuskript III war es daher zu überprüfen, ob das für den MOBOT-Rollator entwickelte Navigationssystem die Navigationsleistung von potentiellen Nutzern mit und ohne kognitiven Einschränkungen in einem realitätsnahen Anwendungsszenario verbessern kann.

Methodik

In Anlehnung an die Kriterien der definierten Nutzergruppe des MOBOT-Rollators wurden 42 ältere Personen im Alter von mindestens 65 Jahren aus geriatrischen Gesundheitseinrichtungen rekrutiert (Akut- und Rehabilitationsstationen des AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG, Pflegeheim [AGAPLESION MARIA VON GRAIMBERG, AGAPLESION LINDENHOF], Verein für Rehabilitationssport in der Geriatrie [REGE e.V.]), die keine (Mini-Mental State Examination [MMSE] Score > 26 Pkt., Folstein, Folstein & McHugh, 1975) oder leichte bis moderate kognitive Einschränkungen (MMSE Score = 17-26 Pkt.) hatten und auf einen Rollator als Gehilfe in ihrem Alltag angewiesen waren. Die

Teilnehmer wurden nach ihrem kognitiven Status gematcht und zufällig einer von zwei Testbedingungen zugeordnet, in der sie den MOBOT-Rollator entweder mit aktiviertem oder deaktiviertem Navigationssystem verwendeten. Alle Teilnehmer absolvierten einmalig einen zweigeteilten Navigationskurs in einer für den MOBOT-Rollator anwendungsnahen (geriatrisches Krankenhaus), aber für sie nicht vertrauten Umgebung. Die Teilnehmer mit aktiviertem Navigationssystem wurden während des Navigationskurses durch Sprachhinweise an kritischen Wegpunkten bei der Zielfindung unterstützt. Die Teilnehmer mit deaktiviertem Navigationssystem erhielten keine Sprachhinweise und mussten den Navigationskurs mit Hilfe der Orientierung an den herkömmlichen Hinweisschildern und Wegweisern des Krankenhauses absolvieren. Die Parameter zur Bewertung der Navigationsleistung umfassten die Erfolgsrate, Durchführungszeit, Anzahl der Stopps, Stoppzeit, Wegstrecke sowie Ganggeschwindigkeit und wurden – mit Ausnahme der Erfolgsrate, welche durch den Testleiter aufgezeichnet wurde – basierend auf den Daten der im Rollator integrierten Sensortechnik (optische Encoder, inertiale Messeinheiten, Laser-Entfernungsmesser) über etablierte Algorithmen aus dem Bereich der Positionsbestimmung von mobilen Robotern (z. B. Monte-Carlo-Lokalisation, Thrun, Fox, Burgard & Dellaert, 2001) berechnet.

Ergebnisse

Die Erfolgsraten für die Bewältigung der zwei Teile des Navigationskurses war sowohl in der Gesamtstichprobe als auch in den beiden Gruppen der kognitiv eingeschränkten und kognitiv nicht eingeschränkten Teilnehmer jeweils unabhängig von der Testbedingung (aktiviertes vs. deaktiviertes Navigationssystem) ($p > 0.999$). Für die Durchführungszeit, Anzahl der Stopps und Stoppzeit zeigte sich jedoch eine signifikante Wechselwirkung zwischen der Testbedingung und dem kognitiven Status der Teilnehmer ($p = 0.002\text{-}0.040$, $\eta_p^2 = 0.115\text{-}0.235$). Demnach führte die Unterstützung des Navigationssystems bei der kognitiv eingeschränkten, nicht jedoch bei der kognitiv nicht eingeschränkten Gruppe ($p = 0.165\text{-}0.925$) in beiden Teilen des Navigationskurses zu einer signifikant kürzeren Durchführungszeit ($p = 0.001\text{-}0.003$), in Teil 1 zu einer signifikant kürzeren Stoppzeit ($p = 0.014$) und in Teil 2 zu signifikant weniger Stopps ($p < 0.001$). Für den komplexeren, zweiten Teil des Navigationskurses zeigte sich ein signifikanter Effekt der Testbedingung auf die Stoppzeit und Gehstrecke ($p = 0.014\text{-}0.016$, $\eta_p^2 = 0.162\text{-}0.171$), wobei Teilnehmer, die mit Hilfe des Navigationssystems den Navigationskurs absolvierten, unabhängig von ihrem kognitiven Status kürzer stoppten und eine kürzere Wegstrecke zurücklegten als diejenigen Teilnehmer, die sich mit Hilfe der Hinweisschilder und Wegweiser orientieren mussten.

Diskussion und Schlussfolgerung

Die Studienergebnisse belegen, dass die Navigation von potenzielle Nutzern eines robotergestützten Rollators – insbesondere von denjenigen mit kognitiver Einschränkung – in einer für sie unbekannten Umgebung durch ein in den Rollator integriertes Navigationssystem verbessert werden kann. Um die methodischen Defizite bisheriger Evaluationsstudien von robotergestützten Rollatoren zu vermeiden, wurde in der vorliegenden Untersuchung eine angemessene Anzahl von potentiellen Nutzern entsprechend der definierten Nutzergruppe des robotergestützten Rollators eingeschlossen, ein komparatives Studiendesign (aktiviertes vs. deaktiviertes Navigationssystem) mit einer auf das Navigationssystem spezifisch ausgerichtete Assessmentstrategie verwendet und die erfassten Daten mit statistischen Methoden analysiert. Manuskript III kann damit als erste Studie betrachtet werden, die eine statistische Evidenz für die Effektivität eines in einem robotergestützten Rollator integrierten Navigationssystem zur Verbesserung der Navigationsleistung von potentiellen Nutzern des Rollators liefert.

4.4 Manuskript IV: Überprüfung der konkurrenten Validität des MOBOT-integrierten Ganganalysesystems bei älteren Personen mit Gangstörungen

Werner, C., Chalvatzaki, G., Papageorgiou, X. S., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (2019). Assessing the concurrent validity of a gait analysis system integrated into a smart walker in older adults with gait impairments. *Clinical Rehabilitation, 33*(10), 1682-1687. DOI: 10.1177/0269215519852143

Hintergrund und Zielsetzung

Die Ganganalyse ist ein wichtiges klinisches sowie Forschungsinstrument zur Identifikation von Gangstörungen, Beurteilung des Sturzrisikos, Auswahl geeigneter Therapiemaßnahmen und Überprüfung sowie Dokumentation von Interventionseffekten. Optische 3D-Bewegungsanalysesysteme, Kraftmessplatten oder elektronische Gangmatten gelten als Goldstandard für die klinische Erfassung von Gangparametern (Najafi, Khan & Wrobel, 2011), sind jedoch mit einem hohen instrumentellen, personellen, zeitlichen oder finanziellen Aufwand verbunden und auf Labormessungen beschränkt. Da insbesondere unter standardisierten Laborbedingungen gemessene Gangparameter nicht das natürliche Gangbild einer Person im Alltag widerspiegeln (Brodie et al., 2016; Rispens et al., 2016; Takayanagi et al., 2019) und von möglichen Reaktivitätseffekten (z. B. Hawthorne-Effekt) beeinflusst werden können (Robles-Garcia et al., 2015), fokussieren sich jüngste technologische Entwicklungen in der Ganganalyse auf ambulante, am Körper getragene Sensoren (z. B. inertiale Messeinheiten), welche eine unaufdringliche und kontinuierliche Erfassung des Gangbilds außerhalb des Labors im Alltag ermöglichen sollen (Chen, Lach, Lo & Yang, 2016; Muro-de-la-Herran, Garcia-Zapirain & Mendez-Zorrilla, 2014). Solche Sensoren erfordern jedoch die Bereitschaft einer Person diese auch zu tragen und können – je nach Platzierung – als störend und unangenehm empfunden werden. Darüber hinaus ist deren Validität für die Erfassung von räumlich-zeitlichen Gangparametern bei älteren Personen mit Rollatoren meist nicht bekannt. Vor dem Hintergrund, dass Patienten während der geriatrischen Rehabilitation routinemäßig Rollatoren verordnet bekommen und viele andere ältere Erwachsene mit Mobilitätseinschränkungen diese ebenfalls als Gehhilfe im Alltag verwenden, besteht weiterhin ein Bedarf an validen Systemen, die auch bei diesen Personengruppen eine unaufdringliche und kontinuierliche Erfassung von räumlich-zeitlichen Gangparametern im alltäglichen Kontext ermöglichen. Ein möglicher Lösungsansatz hierfür könnten robotergestützte Rollatoren darstellen, die mittels eines integrierten Ganganalysesystems die Gangleistung ihrer Nutzer kontinuierlich während des Gehens erfassen. In manche robotergestützten Rollatoren wurden solche Ganganalysesysteme basierend auf unterschiedlichen technischen Konzepte (z. B. optische Sensoren, inertiale Messeinheiten, Kraftsensoren) bereits integriert (Ballesteros, Urdiales, Martinez & Tirado, 2017; Paulo, Peixoto & Nunes, 2017; Wang et al., 2016). Deren Validität für die Erfassung von räumlich-zeitlichen Gangparametern bleibt jedoch aufgrund der mangelnden methodischen Qualität ihrer Validierungsstudien (kleine Stichproben, Teilnehmer nicht repräsentativ für die potentielle Nutzergruppe der robotergestützten Rollatoren, kein Vergleich mit einem Referenzstandard und/oder fehlende statistische Analysen) bislang unklar integriert (Ballesteros et al., 2017; Paulo et al., 2017; Wang et al., 2016). Vor diesem Hintergrund war das Ziel von Manuskript IV, die konkurrente Validität des im MOBOT-Rollator integrierten Ganganalysesystems mittels eines etablierten Referenzstandards in einer geeigneten Anzahl von potentiellen Nutzern des Rollators statistisch zu überprüfen.

Methodik

Insgesamt wurde 25 potentielle Nutzer des MOBOT-Rollators (≥ 65 Jahre, MMSE Score ≥ 17 Pkt. (Folstein et al., 1975), moderate Gangstörungen = Verwendung eines Rollators als Gehhilfe im Alltag und/oder habituelle Ganggeschwindigkeit < 0,6 m/s) eingeschlossen. Alle Teilnehmer absolvierten mit Hilfe des MOBOT-Rollators eine mit dem GAITRite®-System (CIR Systems Inc., Havertown, PA, USA; (Bilney, Morris & Webster, 2003; Webster, Wittwer & Feller, 2005) ausgestattete 7,8 m Gehstrecke. Räumlich-zeitliche Gangparameter (Zyklus-, Schwung- und Standzeit, Schreitlänge, Ganggeschwindigkeit) wurden dabei gleichzeitig mittels des GAITRite®-Systems und des MOBOT-integrierten Ganganalysesystems erfasst. Das Ganganalysesystem des MOBOT-Rollators basiert auf einem Laser-Entfernungsmesser (UBG-04LX-F01; Hokuyo Automatic Co., Ltd, Osaka, Japan), der an der Rückseite des Rollators auf einer Höhe von 35 cm mit Blick Richtung der Beine des Nutzers angebracht ist, aus dessen Daten mittels probalistischer Datenassoziationen, Partikelfilter und Hidden Markov Modellen räumlich-zeitliche Gangparameter des Nutzers extrahiert wurden (Chalvatzaki, Papageorgiou & Tzafestas, 2017). Ein zukünftiges Ziel bei der Entwicklung des Ganganalysesystems ist es, auf Grundlage einer validen, kontinuierlichen Erfassung der räumlich-zeitlichen Gangparameter des Rollator-Nutzers im Alltag, einen kontextbewussten, robotergestützten Rollator zu entwickeln, welcher sein Verhalten in Echtzeit an das aktuell erfasste Gangbild des Nutzers anpasst. Die konkurrente Validität wurde mittels der Bland-Altman-Methode (mittlere Differenzen, 95%-Übereinstimmungsgrenzen) (Bland & Altman, 1986), prozentualen Fehlern (klinisch akzeptabel < 30 %) (Critchley & Critchley, 1999), Intra-Klassen-Korrelationskoeffizienten (ICC) für die Konsistenz ($ICC_{3,1}$) und absolute Übereinstimmung ($ICC_{2,1}$) zwischen den beiden Messinstrumenten bewertet.

Ergebnisse

Für die Zyklus-, Schwung- und Standzeit zeigten sich zwischen den Messinstrumenten mittlere Differenzen von -0,04 bis 0,04 s und klinisch akzeptable Fehler (8,7–23,0 %). Deutlich höhere mittlere Differenzen und nicht akzeptable prozentuale Fehler ergaben sich für die Schreitlänge (0,20 ± 0,11 m; 31,3 %) und die Ganggeschwindigkeit (0,19 ± 0,13 m/s, 42,3 %). Auch die 95%-Übereinstimmungsgrenzen waren deutlich schmaler für die zeitlichen (Zykluszeit: -0,10-0,11 s; Schwungzeit: -0,07-0,16 s; Standzeit: -0,12-0,20 s) als für die raumbezogenen (Schreitlänge: -0,02-0,42 m, Ganggeschwindigkeit = -0,07-0,44 m/s) Gangparameter. Für alle Gangparameter zeigte sich eine gute bis exzellente Konsistenz zwischen den Messinstrumenten ($ICC_{3,1}$ = 0.72–0.97). Die absolute Übereinstimmung für alle zeitlichen Gangparameter war ebenfalls gut bis exzellent ($ICC_{3,1}$ = 0.72-0.97), jedoch nur gering bis mittelmäßig für die raumbezogenen Gangparameter ($ICC_{2,1}$ = 0.37-0.52).

Diskussion und Schlussfolgerung

Manuskript IV repräsentiert die erste Studie, welche die Validität eines in einen robotergestützten Rollator integrierten Ganganalysesystems mittels eines etablierten Referenzstandards (GAITRite®) in einer angemessenen Anzahl potentieller Rollator-Nutzern statistisch überprüft. Die Studienergebnisse zeigen, dass das MOBOT-integrierte Ganganalysesystem gegenüber dem GAITRite®-System eine hohe konkurrente Validität für die Erfassung von zeitlichen (Zyklus-, Schwung-, Standzeit), nicht jedoch von raumbezogenen (Schreitlänge, Ganggeschwindigkeit) Gangparametern aufweist. Die Schreitlänge und Ganggeschwindigkeit können zwar ebenfalls mit hoher Konsistenz gemessen werden, aber lediglich mit einer begrenzten absoluten Genauigkeit. Insgesamt stellt Manuskript IV einen wichtigen Entwicklungsschritt für die valide, kontinuierliche Erfassung der Gangleistung von Rollator-Nutzern im Alltag sowie für die Entwicklung eines kontextbewussten, adaptiven robotergestützten Rollators dar.

4.5 Manuskript V: Evaluation der MOBOT-integrierten Assistenzfunktion zur Hindernisvermeidung bei älteren Personen mit motorischen Einschränkungen

Geravand, M., **Werner, C.,** Hauer, K. & Peer, A. (2016). An integrated decision making approach for adaptive shared control of mobility assistive robots. *International Journal of Social Robotics, 8*(5), 631-648. DOI: 10.1007/s12369-016-0353-z

Manuskript V entstand federführend durch Mitarbeiter des Lehrstuhls für Steuerungs- und Regelungstechnik der Technischen Universität München (Dr. Milad Geravand) und des Bristol Robotics Laboratory, University of the West of England (Prof. Dr. Angelika Peer). Der Fokus dieses Manuskripts liegt daher auf dem technischen Konzept sowie der technischen Implementierung und Validierung der Steuerungsarchitektur des MOBOT-Rollators („adaptive shared control"). Manuskript V beinhaltet jedoch auch die Beschreibung der nutzerorientierten, klinischen Evaluationsstudie der im MOBOT-Rollator integrierten Assistenzfunktion zur Hindernisvermeidung (siehe Anhang: Manuskript V, S. 169 ff., 6.2 User Study), die am AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG durchgeführt wurde und an deren Konzeption, Durchführung, Auswertung und Veröffentlichung der Verfasser dieser Dissertation maßgeblich beteiligt war. Die nachfolgende Zusammenfassung bezieht sich daher lediglich auf die klinische Perspektive dieser Assistenzfunktion und die in Manuskript V unter Punkt 6.2 beschriebene Evaluationsstudie.

Hintergrund und Zielsetzung

Stürze bei älteren Menschen sind häufig bedingt durch Probleme mit räumlichen Hindernissen (Tinetti, Speechley & Ginter, 1988). Hindernissen während des Gehens auszuweichen oder sie angemessen überwinden zu können, stellt somit eine wichtige Fähigkeit für die sichere Fortbewegung im Alltag dar. Mit zunehmendem Alter nimmt diese Fähigkeit jedoch ab (Chen, Ashton-Miller, Alexander & Schultz, 1991, 1994; Weerdesteyn, Nienhuis & Duysens, 2005), was ein möglicher Grund für die erhöhte Sturzrate von älteren Menschen sein könnte (Di Fabio, Kurszewski, Jorgenson & Kunz, 2004; McFadyen & Prince, 2002). Manche Studien zeigen, dass Rollatoren die Balance und Mobilität ihrer Nutzer verbessern sowie Stürze reduzieren können (American Geriatrics Society, British Geriatrics Society & American Academy of Orthopaedic Surgeons Panel on Falls Prevention, 2001; Bateni & Maki, 2005; Graafmans, Lips, Wijlhuizen, Pluijm & Bouter, 2003; Jensen, Lundin-Olsson, Nyberg & Gustafson, 2002; Salminen, Brandt, Samuelsson, Toytari & Malmivaara, 2009), wobei wiederum andere Studien von einem erhöhten Sturzrisiko mit Rollatoren berichten (Bateni, Heung, Zettel, McLlroy & Maki, 2004; Mann, Hurren, Tomita & Charvat, 1995). Eines der Hauptprobleme von Rollatoren ist, dass eine Person mehr Platz benötigt, um sich mit ihm fortzubewegen. Dies kann schnell zu Schwierigkeiten und Kollisionen mit Hindernissen in der Umgebung führen, die wiederum Stürze verursachen können. Umfragen zu möglichen Problemen und zur Nutzerzufriedenheit mit Rollatoren zeigen zudem, dass das

Überwinden und Umgehen von Hindernissen mit einem Rollator ein häufig genanntes Problem ist (Lindemann et al., 2016) und dass Kollisionen mit Hindernissen in der Umgebung zu Frustration sowie Ärger führen können (Brandt, Iwarsson & Stahl, 2003). In robotergestützte Rollatoren sind daher häufig Assistenzfunktionen zur Hindernisevermeidung integriert, mit dem Ziel, mögliche Gefahrensituationen mit Hindernissen in der Umgebung zu vermeiden und das damit verbunden Sturzrisiko zu reduzieren (Martins et al., 2015; Werner et al., 2016). Der Nachweis für die Effektivität dieser Assistenzfunktionen bei der Hindernisvermeidung von Nutzern eines robotergestützten Rollators ist aufgrund der methodischen Defizite bisheriger Evaluationsstudien hierzu jedoch noch unzureichend geklärt (Werner et al., 2018). Vor diesem Hintergrund war ein Ziel von Manuskript III, die Effektivität der im MOBOT-intergierten Assistenzfunktion zur Hindernisvermeidung zu überprüfen und dabei die methodischen Defizite bisheriger Evaluationsstudien zu vermeiden.

Methodik

Entsprechend der Definition der Nutzergruppe des MOBOT-Rollators wurden 35 Personen im Alter von ≥ 65 Jahre ohne schwere kognitive Einschränkungen (MMSE Score ≥ 17 Pkt., Folstein et al., 1975) eingeschlossen, die alle auf einen Rollator als Gehilfe in ihrem Alltag angewiesen waren. Die Teilnehmer absolvierten mit Hilfe des MOBOT-Rollators einen selbst entworfenen, ca. 40 m langen Hindernisparcours unter drei unterschiedlichen, randomisierten Testbedingungen: (B1) deaktivierte Hindernisvermeidung, (B2) aktivierte Hindernisvermeidung basierend auf einem in der Literatur bereits vorhandenen technischen Ansatz (Hirata, Hara & Kosuge, 2007) und (B3) aktivierte Hindernisvermeidung basierend auf dem in Manuskript V vorgestellten, neu entwickelten Ansatz. Zur Bewertung der Leistung im Hindernisparcours wurde die Anzahl der Kollisionen und die Annährungsgeschwindigkeit an die Hindernisse über die integrierte Sensortechnik des MOBOT-Rollators erfasst sowie die Durchführungszeit vom Testleiter dokumentiert.

Ergebnisse

Die unterschiedlichen Testbedingungen zeigten keinen signifikanten Effekt auf die Durchführungszeit (p = 0.286), jedoch auf die Anzahl der Kollisionen und die Annäherungsgeschwindigkeit an die Hindernisse (p = 0.033). Im Vergleich zur Testbedingung, in der die Hindernisvermeidung deaktiviert war, reduzierte sich die Anzahl der Kollisionen und die Annäherungszeiten an die Hindernisse signifikant mit der aktivierten, neu entwickelten Hindernisvermeidung (B1 vs. B2: p = 0.003-0.049). Weitere signifikanten Unterschiede zwischen den Testbedingungen wurden nicht festgestellt (B2 vs. B1 / B3: p = 0.074-0.999).

Diskussion und Schlussfolgerung

Die in Manuskript V beschriebenen Ergebnisse zur nutzerorientierten Evaluationsstudie zeigen, dass durch die Verwendung der Assistenzfunktion für die Hindernisvermeidung des MOBOT-Rollators die Leistung von potentiellen Nutzern des MOBOT-Rollators in einem Hindernisparcours signifikant verbessert werden kann. Der neu entwickelte technische Ansatz für diese Assistenzfunktion führte zu einer geringeren Anzahl von Kollisionen und einer niedrigeren Annäherungsgeschwindigkeit an die Hindernisse, ohne dass dabei die Durchführungszeit erhöht wurde. Die unveränderte Durchführungszeit spricht dafür, dass der vorgeschlagene technische Ansatz für die sensorische Unterstützung der Rollator-Nutzer die normale Aktivität mit dem MOBOT-Rollator nicht beeinträchtigt, dabei aber gleichzeitig Gefahrensituationen (Kollisionen mit Hindernissen) mit einem Rollator reduziert bzw. ein sicheres Herantreten an Hindernisse gewährleistet. In Anbetracht der methodischen Defizite bisheriger Evaluationsstudien von robotergestützten Rollatoren, liefert Manuskript V erstmals einen statistischen Nachweis für die Effektivität der Hindernisvermeidung eines solchen Rollators bei potentiellen Nutzern von robotergestützten Rollatoren.

4.6 Manuskript VI: Evaluation der MOBOT-integrierten Aufstehhilfe bei älteren Personen mit motorischen Einschränkungen

Werner, C. Geravand, M., Korondi, P. Z., Peer, A., Bauer, J. M. & Hauer, K. (2020). Evaluating the sit-to-stand transfer assistance from a smart walker in older adults with motor impairments. *Geriatrics & Gerontology International.* DOI: 10.1111/GGI.13874

Hintergrund und Zielsetzung

Der Transfer von einer sitzenden in eine stehende Körperposition stellt eine motorische Schlüsselqualifikation des Alltags dar. Ältere Personen zeigen jedoch häufig Probleme beim Sitzen-Stehen-Transfer (STS) (Guralnik et al., 1994; Williamson & Fried, 1996), die mit einem erhöhten Sturzrisiko sowie einem Verlust der Mobilität, Selbstständigkeit und Lebensqualität assoziiert sind (Fusco et al., 2012; Guralnik et al., 1994). Ein altersgerechtes Assistenzsystem zur Unterstützung des STS dieser Personen könnte dazu beitragen, deren Sturzrisiko zu verringern sowie deren Mobilität, Unabhängigkeit und Lebensqualität zu fördern. Manche robotergestützten Rollatoren besitzen daher Assistenzfunktionen, die ihre Nutzer auch beim STS unterstützen sollen (Martins et al., 2015; Page, Saint-Bauzel, Rumeau & Pasqui, 2017; Werner et al., 2016). Da bisherige Evaluationsstudien von robotergestützten Rollatoren mit integrierten Aufstehhilfen jedoch erhebliche methodische Defizite aufweisen (kleine Stichproben, Teilnehmer nicht repräsentativ für die potentielle Nutzergruppe der robotergestützten Rollatoren, keine spezifisch auf die Aufstehhilfe ausgerichteten Assessmentstrategien, keine Erhebung der Nutzerzufriedenheit, keine inferentielle statistische Analysen), existiert bislang keine ausreichende Evidenz für deren Effektivität und Nutzerzufriedenheit (Werner et al., 2018). Die in Manuskript VI beschriebene Studie hatte daher zum Ziel, die methodischen Defizite von bisherigen Evaluationsstudien zu vermeiden und eine möglichst aussagekräftige und methodisch hochwertige Überprüfung der Effektivität und Nutzerzufriedenheit mit der Aufstehhilfe des MOBOT-Rollators zu gewährleisten. Zudem wurde eine Prädiktorenanalyse durchgeführt, um potentielle Einflussfaktoren von Nutzercharakteristika auf die Effektivität und Nutzerzufriedenheit zu identifizieren.

Methodik

Potentielle Nutzer (n = 33) des MOBOT-Rollators (≥ 65 Jahre, MMSE Score ≥ 17 Pkt. (Folstein et al., 1975), Verwendung eines Rollators als Gehhilfe im Alltag) absolvierten einen fünftmaligen Aufstehtest zunächst ohne und anschließend mit der Aufstehhilfe des MOBOT-Rollators. Anhand der erfolgreich durchgeführten STS wurden Erfolgsraten (in %) für beide Testbedingungen berechnet. Die Nutzerzufriedenheit mit der Aufstehhilfe wurde mittels des Telehealthcare Satisfaction Questionnaire – Wearable Technology (TSQ-WT, Spannweite = 0-80 Pkt.) erfasst (Chiari, van Lummel, Pfeiffer, Lindemann & Zijlstra, 2009). Demographische, anthropometrische, funktionelle, körperliche, kognitive und psychologische Eigenschaften der Teilnehmer wurden als Prädiktoren für die Erfolgsrate und Nutzerzufriedenheit mit der Aufstehhilfe analysiert.

Ergebnisse

Die Erfolgsrate mit der MOBOT-integrierten Aufstehhilfe (93,3 ± 12,9 %) war signifikant höher ($p < 0.001$) als die ohne jegliche Hilfe (54,5 ± 50,6 %). Mit einem TSQ-WT Score von 62,5 ± 11,2 Pkt. zeigte sich eine hohe Nutzerzufriedenheit. Die Erfolgsrate mit der Aufstehhilfe war mit keiner der untersuchten Eigenschaften der Teilnehmer signifikant assoziiert (p = 0.183-0.999). Ein höherer Body-Mass-Index als signifikanter, unabhängiger Prädiktor für eine höhere Nutzerzufriedenheit identifiziert ($\beta = 0.48$, $R^2 = 0.23$, $p = 0.005$).

Diskussion und Schlussfolgerung

Manuskript VI belegt, dass bei motorisch eingeschränkten, älteren Personen die Erfolgsrate für den Transfer von einer sitzenden in eine stehende Position signifikant durch die Aufstehhilfe des MOBOT-Rollators verbessert werden kann. Es ist es somit erstmals gelungen, einen statistischen Nachweis für die Effektivität der Aufstehhilfe eines robotergestützten Rollators in repräsentativen Nutzergruppe eines solchen Rollators zu erbringen. Die Ergebnisse zeigen zudem eine hohe Zufriedenheit mit der Aufstehhilfe bei möglichen Rollator-Nutzern, insbesondere bei denjenigen, die einen höheren Body-Mass-Index aufweisen. Manuskript VI deutet auf das Potenzial eines robotergestützten Rollators mit integrierter Aufstehhilfe hin, bei älteren Personen mit motorischen Beeinträchtigungen das Sturzrisiko zu reduzieren und die Mobilität, Unabhängigkeit und Lebensqualität zu fördern.

4.7 Manuskript VII: Bewertung der Effektivität und Nutzerzufriedenheit mit unterschiedlichen Betriebsmodi eines Duschroboters bei älteren Personen mit Einschränkungen beim Duschen

Werner, C., Dometios, A. C., Maragos, P., Tzafestas, C. S., Bauer, J. M. & Hauer, K. Evaluating the task effectiveness and user satisfaction with different operation modes for an assistive bathing robot in older adults with bathing disability. Under review in *Assistive Technology*.

Hintergrund und Zielsetzung

Ältere Menschen haben meist wenig Erfahrung mit neuen Technologien und tuen sich oft schwer mit deren Bedienung. Eine der größten Herausforderungen bei der Entwicklung von altersgerechten Assistenzrobotern für ältere Menschen besteht daher darin, die Mensch-Roboter-Interaktion so einfach wie möglich zu gestalten (Ka, Ding & S., 2015). Ein möglicher Ansatz zur Vereinfachung dieser Interaktion besteht darin, die kognitive Anforderung für den Nutzer zu reduzieren, indem die Autonomie des Assistenzroboters erhöht wird. Frühere Studien mit z. B. Telemedizin-Robotern oder robotergestützten Gehhilfen/Rollstühlen deuten darauf hin, dass mit zunehmender Autonomie von robotergestützten Assistenzsystemen auch deren Effektivität bei der Bewältigung der für sie vorgesehenen Aufgabe(n) ansteigt (Erdogan & Argall, 2017; Kim et al., 2012; Koceska, Koceski, Beomonte Zobel, Trajkovik & Garcia, 2019; Werner et al., 2018; Yu et al., 2003). Demgegenüber zeigt sich jedoch auch, dass die autonomsten Betriebsmodi mit der höchsten Effektivität nicht immer diejenigen sind, die bei den Nutzern auf die größte Zufriedenheit stoßen und sie es eher bevorzugen, bei der Interaktion so viel Kontrolle wie möglich über den Assistenzroboter zu haben (Cooper et al., 2012; Kim et al., 2012; Yu et al., 2003). Für altersgerechte Assistenzroboter, die eine so sensible und intime ADL wie das Baden/Duschen unterstützen sollen, fehlen jedoch bislang Kenntnisse hinsichtlich der Effektivität und Nutzerzufriedenheit mit unterschiedlich autonomen Betriebsmodi. Das primäre Ziel der in Manuskript VIII beschriebenen Studie bestand daher darin, die Effektivität und Nutzerzufriedenheit mit drei unterschiedlich autonomen Betriebsmodi für den I-SUPPORT-Duschroboter (autonomer, roboterassistierter und telemanipulativer Modus) innerhalb eines Duschszenarios bei potentiellen Nutzern zu untersuchen. Ein sekundäres Ziel war es, die Nutzerzufriedenheit mit den Betriebsmodi auf mögliche Wechselwirkungen mit bestimmten Nutzercharakteristika zu überprüfen.

Methodik

Die Studie wurde im Messwiederholungsdesign („within subject“-Design) durchgeführt, wobei 25 ältere Personen mit Problemen beim Baden/Duschen (Barthel Index, Item „Baden/Duschen“ = 0 Pkt., Mahoney & Barthel, 1965) und keinen schweren kognitiven Einschränkungen (MMSE Score > 17 Pkt. Folstein et al., 1975) ein Duschszenario für einen definierten Körperbereich (oberer Rücken) mit jeweils drei unterschiedlichen Betriebsmodi des I-SUPPORT-Duschroboters absolvierten. Die unterschiedlichen Betriebsmodi umfassten (1) einen vollständig vom Roboter kontrollierten, autonomen Modus; (2) einen vom Teilnehmer kontrollierten, aber vom Roboter assistierten Modus („shared control") und (3) einen vollständig vom Teilnehmer kontrollierten, telemanipulativen Modus. Die Effektivität mit den Betriebsmodi wurde anhand des erfolgreich abgeduschten, prozentualen Anteils des oberen Rückenbereichs innerhalb eines standardisierten Zeitraums bewertet, welcher objektiv basierend auf den aufgezeichneten Daten der im Duschroboter integrierten Sensortechnik (Kinect v2 Kamera) und Bewegungssteuerung (Dometios, Papageorgiou, Arvanitakis, Tzafestas & Maragos, 2017) berechnet wurden. Der After-Scenario-Questionnaire (ASQ, Spannweite = 1-7 Pkt., Lewis, 1995) wurde verwendet, um die Benutzerzufriedenheit mit den drei unterschiedlichen Betriebsmodi zu erfassen (Lewis, 1995). Eine geringere Punktzahl im ASQ deuten dabei auf eine höhere Nutzerzufriedenheit. Demographische, klinische, funktionelle, körperliche, kognitive und psychologische Eigenschaften der Teilnehmer wurden auf mögliche Wechselwirkungen mit der Nutzerzufriedenheit untersucht.

Ergebnisse

Der Betriebsmodus des Duschroboters hatte einen signifikanten Effekt auf die Effektivität innerhalb des Duschszenarios ($p < 0.001$). Im autonomen Modus wurde bei allen Teilnehmern der gesamte obere Rückenbereich (100,0 ± 0,0 %) erfolgreich abgeduscht. Im Vergleich dazu war die Effektivität in den beiden von den Teilnehmern kontrollierten Modi signifikant geringer (roboterassistierter Modus = 79,4 ± 18,2 %, $p = 0.001$; telemanipulativer Modus = 64,4 ± 19,4 %, $p < 0.001$). Beim Vergleich der beiden von den Teilnehmern kontrollierten Modi untereinander zeigte sich eine signifikant höhere Effektivität mit dem roboterassistierten Modi ($p = 0.009$). Auch auf die Zufriedenheit der Teilnehmer hatte der Betriebsmodus einen signifikanten Effekt ($p = 0.037$). Für den autonomen Modus war die Nutzerzufriedenheit (ASQ = 2,0 ± 1,0) signifikant bzw. tendenziell höher als mit dem telemanipulativen (ASQ = 2,5 ± 1,5, $p = 0.003$) und roboterassistierten Modus (ASQ = 3,0 ± 1,4, $p = 0.070$). Signifikante Wechselwirkungen zwischen der Nutzerzufriedenheit und den persönlichen Eigenschaften der Teilnehmer wurden nicht festgestellt ($p = 0.491$-0.826).

Diskussion und Schlussfolgerung

Die Studienergebnisse von Manuskript VIII zeigen, dass der autonome Betriebsmodus des I-SUPPORT-Duschroboters sehr effektiv und zuverlässig war, um einen definierten Körperbereich abzuduschen. Eine deutlich geringere Effektivität wurde für die Betriebsmodi beobachtet, in denen der Duschroboter hauptsächlich von den Teilnehmern kontrolliert wurde. Je geringer dabei die Unterstützung des Duschroboters war, desto niedriger war auch die

Effektivität. Mit zunehmender Kontrolle der Teilnehmer über den Duschroboter verringerte sich jedoch nicht nur die Effektivität, sondern auch die Nutzerzufriedenheit. Präferenzen für einen bestimmten Betriebsmodus wurden bei den verschiedenen Untergruppen von Teilnehmern nicht beobachtet. Insgesamt deuten die Studienergebnisse darauf hin, dass es für eine effektive und höchst zufriedenstellende Interaktion zwischen einem Duschroboter und potenziellen, älteren Nutzern notwendig zu sein scheint, Betriebsmodi mit einem hohen Maß an Autonomie auf Seiten des Roboters zu implementieren, welche ein Minimum an Nutzereingaben erfordern.

4.8 Manuskript VIII: Verbesserung der gestenbasierten Interaktion zwischen einem Duschroboter und älteren Personen durch ein Nutzertraining

Werner, C., Kardaris, N., Koutras, P., Zlatintsi, A., Maragos, P., Bauer, J. M. & Hauer, K. (2020). Improving gesture-based interaction between an assistive bathing robot and older adults via user training on the gestural commands. *Archives of Gerontology and Geriatrics,* 87, 103996. DOI: 10.1016/j.archger.2019.103996.

Hintergrund und Zielsetzung

Um eine erfolgreiche Zusammenarbeit von älteren, meist Technik unerfahrenen Menschen und robotergestützten Assistenzsystemen zu ermöglichen, sollte deren Mensch-Roboter-Interaktion möglichst auf einer natürlichen, intuitiven und einfachen Bedienbarkeit beruhen. Da sie als die natürlichste und einfachste Form der Kommunikation zwischen Menschen gilt, basiert die Interaktion zwischen Mensch und Roboter häufig auf verbaler Kommunikation, bei der der Roboter anhand von Sprachbefehlen des Nutzers bedient und gesteuert wird (Mavridis, 2015). In realen Anwendungsszenarien von robotergestützten Assistenzsystemen können Sprachbefehle jedoch durch Rauschen, Nachhall und andere störende Schallquellen beeinträchtigt werden (Alameda-Pineda & Horaud, 2015). Angesichts der Störquellen für die verbale Mensch-Roboter-Interaktion und der Tatsache, dass Gesten ebenfalls eine zentrale Rolle in der natürlichen menschlichen Kommunikation spielen (Goldin-Meadow & Alibali, 2013), ist die gestenbasierte Steuerung zu einem Kernelement bei der Entwicklung von natürlich, intuitiv und einfach zu bedienenden Robotern geworden (Hernandez-Belmonte & Ayala-Ramirez, 2016). Die Entwicklung im Bereich gestenbasierter Mensch-Roboter-Interaktion scheint sich dabei bislang häufig auf die Verbesserung in der Erkennung und Interpretation der Gesten durch die Integration neuer Hardwareentwicklungen bzw. die Entwicklung neuer Softwarealgorithmen konzentriert zu haben (Guler et al., 2016; Liu & Wang, 2018; Wang, Kläser, Schmid & Cheng-Lin, 2011). Eine erfolgreiche gestenbasierte Mensch-Roboter-Interaktion ist jedoch nicht nur eine Frage der technischen Leistungsfähigkeit des im Roboter integrierten Gestenerkennungssystems, sondern auch der Bewegungsausführung und Qualität der Gesten des Nutzers. Insbesondere bei älteren

Menschen mit funktionellen Einschränkungen (= primäre Nutzergruppen von altersgerechten, robotergestützten Assistenzsystemen), die häufig auch Einschränkungen in den für die Ausführung von Gesten beteiligten kognitiven Fähigkeiten (z. B. Aufmerksamkeitskontrolle, Informationsverarbeitung, Exekutivfunktion, räumlich-visuelle Fähigkeiten) aufweisen (Gure, Langa, Fisher, Piette & Plassman, 2013; Häkkinen et al., 2007; Harada et al., 2013), kann die Bewegungsausführung der Gesten erheblich beeinträchtigt sein. Um eine ausreichende Qualität der Gesten für eine erfolgreiche Mensch-Roboter-Interaktion in dieser Personengruppe zu gewährleisten, scheint es daher sinnvoll, Trainingsprogramme oder Schulungen mit den älteren Nutzern durchzuführen, in denen die Interaktion mit dem Roboter trainiert wird. Solche Nutzertrainings sind dabei nicht nur wichtig für eine ausreichende Qualität der Nutzereingabe, sondern auch für den Abbau von negativen Emotionen und die Steigerung der Akzeptanz des Nutzers gegenüber den Assistenzrobotern (Louie, McColl & Nejat, 2014; Tacken, Marcellini, Mollenkopf, Ruoppila & Széman, 2005). Die in Manuskript VII beschriebene Studie hatte primär zum Ziel, die Effekte eines spezifischen Nutzertrainings auf die gestenbasierte Mensch-Roboter-Interaktion zwischen dem I-SUPPORT-Duschroboter und dessen potentiellen Nutzern zu untersuchen. Sekundäre Studienziele waren (1) die Überprüfung von potentiellen Einflussfaktoren bestimmter Nutzercharakteristika auf die initiale Bewegungsausführung der Gesten sowie auf die Trainingseffekte und (2) die Überprüfung des Zusammenhangs zwischen der Bewegungsausführung der Gesten und der Gestenerkennungsrate des I-SUPPORT-Duschroboters.

Methodik

Insgesamt 25 ältere Personen mit Problemen beim Baden/Duschen (Barthel Index, Item „Baden/Duschen“ = 0 Pkt., Mahoney & Barthel, 1965) und keinen schweren kognitiven Einschränkungen (MMSE Score > 17 Pkt., Folstein et al., 1975) nahmen an der quasi-experimentellen Eingruppen-Prä-Post-Studie teil. Nach einer kurzen Einführung in die gestenbasierte Interaktion mit dem I-SUPPORT-Duschroboter wurde jeder Teilnehmer aufgefordert diesen mittels der in der Einführung vorgestellten Gesten zu steuern. Direkt im Anschluss absolvierte jeder Teilnehmer eine 10- bis 15-minütige spezifische Trainingseinheit zur Verbesserung der Bewegungsausführung dieser Gesten. Hierfür wurden spezifische Lehrmethoden angewandt und Übungsbedingungen geschaffen (Spiegeltechnik, Verknüpfung von Bewegungen mit bestimmten Assoziationen, haptische Unterstützung, hohe Wiederholungszahlen), die sich bereits als effektiv für das motorische Lernen bei älteren Menschen mit kognitiven Einschränkungen erwiesen haben (van Halteren-van Tilborg, Scherder & Hulstijn, 2007; Werner et al., 2017). Nach der Trainingseinheit wurden die Teilnehmer aufgefordert den I-SUPPORT-Duschroboter erneut mittels der Gesten zu steuern. Die Ausführung der Gesten vor und nach der Trainingseinheit wurde per Video aufgezeichnet und anhand eines standardisierten klinischen Tests zur Bewertung von Gesten (Test of Upper Limb Apraxia [TULIA], Vanbellingen et al., 2010) beurteilt (TULIA Gesamtscore, Spannweite = 0-5 Pkt.). Weitere Parameter zur Bewertung der Gesten umfassten technisch hinterlegte Leistungswerte („sensor-based gestural performance" [SGP] Gesamtscore, Spannweite = 0-1 Pkt.), die über etablierte Algorithmen aus den aufgezeichneten Daten des Gestenerkennungssystems des I-SUPPORT-Duschroboters bestimmt wurden (Platt, 2000; Schuldt, Laptev & Caputo, 2004; Wang et al., 2011), und die Gestenerkennungsrate des I-SUPPORT-Duschroboters („command recognition rate" [CRR], Spannweite = 0-100 %). Persönliche Eigenschaften der Teilnehmer wurden auf mögliche Zusammenhänge mit der Bewegungsausführung der Gesten sowie den Trainingseffekten analysiert.

Ergebnisse

Vor der Trainingseinheit war die Ausführung der Gesten und die Gestenerkennungsrate eher schlecht bis mittelmäßig (Prä-Test: TULIA, Median [Interquartilsbereich, IQR] = 2,4 Pkt. [IQR 1,8-2,9], SGP = 0,60 Pkt. [IQR 0,47-0,67], CRR = 85,7 % [IQR 50,0-85,7]). Eine höhere initiale Bewegungsqualität der Gesten war signifikant mit höheren kognitiven Leistungen ($r = 0.68$, $p < 0.001$) und einer geringeren Angst vor Technologien assoziiert ($r = 0.41\text{-}0.59$, $p = 0.002\text{-}0.041$). Sowohl die Ausführung der Gesten als auch die Gestenerkennungsrate verbesserten sich signifikant ($p < 0.001\text{-}0.003$) über die Trainingseinheit (Post-Test: TULIA = 3,6 Pkt. [IQR 2,9-3,9], SGP = 0,80 Pkt. [IQR 0,60-0,87], CRR = 100,0 % [IQR 71,4-100,0]). Diese Verbesserungen waren dabei sehr hoch miteinander assoziiert ($r = 0.80\text{-}0.81$, $p < 0.001$). Die größten Verbesserungen in der Ausführung der Gesten zeigte sich bei den Teilnehmern, welche die größte Angst vor Technologien hatten ($r = -0.41$, $p = 0.041$) und die Gesten vor der Trainingseinheit am schlechtesten durchführten ($r = 0.52\text{-}0.67$, $p < 0.001\text{-}0.008$).

Diskussion und Schlussfolgerung

Die Studienergebnisse von Manuskript VIII zeigen zunächst, dass die kurze Einführung in die gestenbasierte Interaktion mit einem robotergestützten Assistenzsystem bei älteren, potentiellen Nutzern dieser Systeme nicht ausreichend war, um eine angemessene Mensch-Roboter-Interaktion zu gewährleisten. Die notwendige Bewegungsqualität der Gesten scheint hierfür initial zu schlecht gewesen zu sein. Durch die 10- bis 15-minütige, spezifisch an die Bedürfnisse der Nutzergruppe angepasste Trainingseinheit konnte jedoch die Ausführung der Gesten und sowie die Gestenerkennungsrate signifikant verbessert werden. Diese Verbesserungen waren dabei miteinander hoch assoziiert, was insgesamt auf eine verbesserte Mensch-Roboter-Interaktion in Folge des Nutzertrainings schließen lässt. Erfreulicherweise profitierten insbesondere diejenigen Teilnehmer, welche anfänglich die schlechteste Leistung bei der Ausführung der Gesten zeigten und die größte Angst vor Technologien hatten. Insgesamt unterstreichen die Ergebnisse, dass zukünftige Entwicklungen im Bereich der gestenbasierten Interaktion zwischen altersgerechten Assistenzrobotern und potentiellen Nutzern nicht nur die Verbesserung der technischen Aspekte, sondern auch die Verbesserung der Qualität der Nutzereingabe (d.h. Ausführung der Gesten) durch angemessene Trainings- oder Schulungsmaßnahmen berücksichtigen sollten.

5 Einordnung der Studienergebnisse in den Forschungszusammenhang

Die wesentlichen Ergebnisse dieser Dissertation sind, dass (1) ein Bedarf an methodisch hochwertigen Studien zur nutzerorientierten Evaluation von robotergestützten Rollatoren besteht (Manuskript I); (2) die Evidenz zur Effektivität und positiven Wahrnehmung von robotergestützten Rollatoren aus der Nutzerperspektive noch unzureichend ist (Manuskript II); (3) das MOBOT-integrierte Navigationssystem die Navigationsleistung von potentiellen Nutzern (= ältere Personen mit Gangstörungen bzw. Rollator als Gehhilfe im Alltag) – insbesondere derjenigen mit zusätzlicher kognitiver Einschränkung – in einem realitätsnahen Anwendungsszenario verbessern kann (Manuskript III); (4) das MOBOT-integrierte Ganganalysesystem eine hohe konkurrente Validität zur Erfassung von zeitlichen Gangparametern bei älteren Personen aufweist (Manuskript IV); (5) die MOBOT-integrierte Assistenzfunktion zur Hindernisvermeidung potentielle Nutzer effektiv unterstützen kann, Gefahrensituationen mit Hindernissen in der Umgebung zu reduzieren (Manuskript V); (6) die Aufstehhilfe des MOBOT-Rollators den Sitzen-Stehen-Transfer von potentiellen Nutzern effektiv und mit hoher Zufriedenheit unterstützen kann (Manuskript VI); (7) für eine effektive und höchst zufriedenstellende Interaktion zwischen dem I-SUPPORT-Duschroboter und seiner potentiellen Nutzer (= ältere Personen mit Problemen bei Baden/Duschen) Betriebsmodi mit einem hohen Maß an Autonomie des Duschroboters notwendig sind (Manuskript VII); (8) durch ein spezifisches Nutzertraining die gestenbasierte Interaktion zwischen dem I-SUPPORT-Duschroboter und seiner potentiellen Nutzer effektiv verbessert werden kann (Manuskript VIII).

Bislang zeigten Studien zur Evaluation von robotergestützten Rollatoren aus der Nutzerperspektive erhebliche methodische Mängel. Zumeist fehlte es ihnen an spezifischen Definitionen der Nutzer und die robotergestützten Rollatoren wurden in kleinen, unspezifisch beschriebenen Studienkollektiven mit oftmals unpassenden Teilnehmern; nicht geeigneten, standardisierten und validierten Assessmentmethoden sowie ohne inferentielle statistische Analysen evaluiert (Manuskript I). Es blieb dadurch bislang unklar, ob die fehlende Evidenz von robotergestützten Rollatoren auf deren mangelnde Eignung oder die methodischen Defizite früherer Evaluationsstudien zurückzuführen ist (Manuskript II). Ein besonderer Schwerpunkt in den vorliegenden Studien des MOBOT-Rollators (Manuskript III-VI) wurde daher auf deren Untersuchungsdesign und -methodik gelegt. Im Gegensatz zu früheren Evaluationsstudien wurde eine spezifische Definition der Nutzergruppe des MOBOT-Rollators basierend auf klinisch etablierten Kriterien für funktionelle Einschränkungen vorgenommen (Manuskript III) und alle nutzerorientierten Evaluationsstudien des MOBOT-Rollators mit Teilnehmern durchgeführt (Manuskript III-VI), die diesen Kriterien entsprachen. Zudem wurde im Vergleich zu den geringen Stichprobengrößen bisheriger Studien von durchschnittlich weniger als acht Teilnehmern eine deutlich höhere und angemessene Anzahl an

Teilnehmern in die jeweiligen Evaluationsstudien des MOBOT-Rollators eingeschlossen (Spannweite = 25-42 Teilnehmer). Es wurde ein komparatives Untersuchungsdesign (Manuskript III: aktiviertes vs. deaktiviertes MOBOT-Navigationssystem; Manuskript IV: MOBOT-Ganganalysesystem vs. GAITRite®; Manuskript V: MOBOT-Hindernisvermeidung vs. früherer Ansatz für die Hindernisvermeidung vs. deaktivierte Hindernisvermeidung; Manuskript VI: MOBOT-Aufstehhilfe vs. ohne Unterstützung) mit einer jeweils auf die zu evaluierende Teilfunktion des MOBOT-Rollators spezifisch ausgerichteten Assessmentstrategie verwendet. Darüber hinaus wurden die erhobenen Daten mit geeigneten statistischen Methoden analysiert. Durch dieses untersuchungsmethodische Vorgehen ist es in den Teilstudien des MOBOT-Rollators erstmals gelungen, die statistische Evidenz für die Effektivität bzw. Gültigkeit innovativer Teilfunktionen eines robotergestützten Rollators bei potentiellen Nutzern zu belegen.

Die Verwendung des MOBOT-integrierten Navigationssystems verbesserte signifikant die Navigationsleitung von potentiellen Nutzern des MOBOT-Rollators – insbesondere von denjenigen mit kognitiver Einschränkung – innerhalb einer für sie unbekannten Umgebung. Einen ähnlich positiven Effekt eines in einen robotergestützten Rollator integrierten Navigationssystems wurde in einer früheren Studie berichtet (Graf, 2009). Sie stellte fest, dass potentielle Nutzer mit Hilfe des Navigationssystems eines robotergestützten Rollators eine kürzere Gehstrecke für die Bewältigung eines Navigationskurses benötigen als mit einem konventionellen Rollator. Allerdings basierte diese Feststellung ausschließlich auf der Beschreibung einzelner Anwendungsfälle und keiner statistischen Analyse (Graf, 2009).

Das MOBOT-integrierte Ganganalysesystem erwies sich verglichen dem GAITRite®-System für die Erfassung zeitlicher Gangparameter seiner potentiellen Nutzer als valide. Für die Erfassung raumbezogener Gangparameter zeigte sich zwar lediglich eine begrenzte absolute Genauigkeit, jedoch konnten sie mit einer hohen Konsistenz (= relative Genauigkeit) gegenüber dem Referenzstandard erfasst werden. Entgegen früherer Validierungsstudien von Ganganalysesystemen eines robotergestützten Rollators, die mit kleinen Stichproben, mit nicht repräsentativen Rollator-Nutzern, ohne Referenzstandard und/oder ohne statistische Datenanalyse durchgeführt wurden (Ballesteros et al., 2017; Paulo et al., 2017; Wang et al., 2016), ist es erstmals gelungen, die konkurrente Validität eines solchen Ganganalysesystems mit einer angemessenen Anzahl potentieller Nutzer eines robotergestützten Rollators, anhand eines Vergleichs mit einem etablierten Referenzstandard und durch geeignete statistische Methoden zu dokumentieren.

Der positive Effekt der Assistenzfunktion zur Hindernisvermeidung des MOBOT-Rollators auf die Leistung potentieller Nutzer in einem Hindernisparcours (weniger Kollisionen, geringere Annäherungsgeschwindigkeit an die Hindernisse) bestätigt Beobachtungen früherer Evaluationsstudien (Graf, 2009; Rentschler, Simpson, Cooper & Boninger, 2008;

Yu et al., 2003). Diese berichten für die Bewältigung eines Hindernisparcours oder Navigationskurses tendenziell ebenfalls von einer geringeren Anzahl von Kollisionen und/oder größeren Abständen zu den Hindernissen mit aktivierter Hindernisvermeidung anderer robotergestützten Rollatoren im Vergleich zu Bedingungen mit deaktivierter Hindernisvermeidung bzw. zu herkömmlichen Mobilitätshilfen. Allerdings zeigten diese Studien deutlich kleinere Stichproben (Spannweite = 6-17 Teilnehmer) und es wurden keine inferentielle statistischen Analysen durchgeführt (Graf, 2009; Yu et al., 2003) oder die Teststärke war zu gering, um einen statistisch signifikanten Effekt der Hindernisvermeidung zu erzielen (Rentschler et al., 2008).

Frühere Studien zur Evaluation von Aufstehhilfen robotergestützter Rollatoren wurden mit kleinen Stichproben, nicht spezifisch auf die Aufstehhilfe zugeschnittenen Assessmentstrategien, ohne Erfassung der Nutzerzufriedenheit und/oder ohne inferentielle statistische Analysen durchgeführt (Chugo, Asawa, Kitamura, Songmin & Takase, 2009; Geravand, Korondi, Werner, Hauer & Peer, 2017; Rumeau, Pasqui & Vigourou, 2012). Analysen zu potentiellen Faktoren, welche mit der Effektivität und Nutzerzufriedenheit solcher Aufstehhilfen assoziiert sein könnten, fehlten in vorangegangen Studien gänzlich. Im Gegensatz hierzu basieren die vorliegenden Studienergebnisse zur Aufstehhilfe des MOBOT-Rollators auf einer angemessenen Anzahl von repräsentativen Rollator-Nutzern, einem vergleichenden Studiendesign (Sitzen-Stehen-Transfer ohne vs. mit Aufstehhilfe) mit einer speziell auf die Aufstehhilfe ausgerichtete Assessmentstrategie zur Überprüfung ihres spezifischen Effekts auf den Sitzen-Stehen-Transfer, einem multidimensionalen Fragebogen zur Erfassung der Nutzerzufriedenheit sowie geeigneten statistischen Analysen. Zudem wurden potentielle Zusammenhänge zwischen den Eigenschaften der Teilnehmer und der Effektivität sowie Nutzerzufriedenheit analysiert. Auf Grundlage dieses methodischen Vorgehens konnte somit erstmals belegt werden, dass durch die Aufstehhilfe eines robotergestützten Rollators die Erfolgsrate für den Sitzen-Stehen-Transfer bei einem breiten Spektrum von potentiellen Nutzern signifikant gesteigert werden kann. Die vorliegenden Studienergebnisse zeigen zudem erstmals anhand eines umfassenden Fragebogens eine hohe Zufriedenheit der Nutzer – insbesondere derjenigen mit höherem Body-Mass-Index – mit der Aufstehhilfe für mehrere Dimensionen.

Frühere Studien zur Mensch-Roboter-Interaktion zwischen Telemedizin-Robotern bzw. robotergestützten Mobilitätshilfen und älteren Personen berichten von einer zunehmenden Effektivität mit zunehmender Autonomie solcher Assistenzroboter (Erdogan & Argall, 2017; Kim et al., 2012; Koceska et al., 2019; Yu et al., 2003). Demgegenüber zeigten die autonomsten Betriebsmodi dabei nicht die höchste Nutzerzufriedenheit. Bisherige Ergebnisse deuteten vielmehr darauf hin, dass ältere Nutzer es eher bevorzugen, möglichst viel Kontrolle über Assistenzroboter während der Interaktion mit ihnen zu haben (Cooper et al., 2010; Kim et al., 2012; Yu et al., 2003). Die vorliegenden Studienergebnisse zum I-SUPPORT-Duschroboter bestätigen zunächst die Ergebnisse früherer Studien (Erdogan & Argall, 2017; Kim et al., 2012; Koceska et al., 2019; Yu et al., 2003) und belegen, dass mit zunehmender Autonomie des Duschroboters auch die Effektivität der Interaktion für den Duschprozess signifikant zunimmt. Im Gegensatz zu früheren Beobachtungen verbesserte sich jedoch mit zunehmender Autonomie des Duschroboters nicht nur die Effektivität, sondern überraschenderweise auch die Nutzerzufriedenheit für die Mensch-Roboter-Interaktion. Diese Ergebnisse zeigen, dass ältere Menschen für die Interaktion mit einem I-SUPPORT-Duschroboter, trotz ihrer sehr eingeschränkten Kontrolle, eher autonome Betriebsmodi bevorzugen, die ein Minimum an Nutzereingaben erfordern.

Die Studienergebnisse zur gestenbasierten Interaktion mit dem I-SUPPORT-Duschroboter bestätigen zunächst Beobachtungen früherer Studien, die von einer geringen Bewegungsqualität der Gesten sowie niedrigen Gestenerkennungsraten für die gestenbasierten Mensch-Roboter-Interaktion zwischen funktionell eingeschränkten älteren Menschen und einem robotergestützten Rollator berichten (Efthimiou et al., 2016; Hauer, 2018). Sie belegen jedoch die Effektivität der spezifisch an die Bedürfnisse der Studienteilnehmer angepassten Trainingseinheit zur Verbesserung der Nutzergesten sowie der Gestenerkennungsrate des I-SUPPORT-Duschroboters und somit der gestenbasierten Mensch-Roboter-Interaktion insgesamt. Kognitive Einschränkungen wurden in vorangegangenen Studien negativ mit trainingsinduzierten motorischen Leistungs-/Lernzugewinnen assoziiert (Ghisla et al., 2007; Ren, Wu, Chan & Yan, 2013; Wu, Chan & Yan, 2016). Durch die Verwendung von Lehrmethoden und Schaffung von Übungsbedingungen, welche sich bereits als effektiv für das motorische Lernen älteren Menschen mit kognitiven Einschränkungen erwiesen haben (van Halteren-van Tilborg et al., 2007; Werner et al., 2017), scheint es in der vorliegenden Studie jedoch gelungen zu sein, dass Studienteilnehmer unabhängig von ihren kognitiven Einschränkungen vom Nutzertraining profitieren. Entsprechend etablierter Trainingsprinzipien und des Phänomens der Ratenabhängigkeit (Dews, 1977; Haskell, 1994; Snider, Quisenberry & Bickel, 2016) zeigten sich stattdessen signifikante Zusammenhänge zwischen den Trainingszugewinnen und der Bewegungsausführung der Gesten vor der Trainingseinheit, wobei diejenigen Teilnehmer mit der initial schlechtesten Ausführung die größten Verbesserungen aufwiesen. Zusätzlich war eine größere Angst vor Technologien mit höheren Trainingszugewinnen assoziiert. Insgesamt unterstreichen die vorliegenden Ergebnisse die bereits in früheren Studien diskutierte Wichtigkeit von Nutzertrainings für eine erfolgreiche Mensch-Roboter-Interaktion im höheren Alter (Efthimiou et al., 2016; Louie et al., 2014; Tacken et al., 2005).

6 Fazit und Ausblick

Die vorliegende Arbeit kommt der Forderung nach, die Nutzerperspektive innerhalb des gesamten Entwicklungsprozesses von altersgerechten Assistenzsystemen stärker zu berücksichtigen. Die gewonnenen Erkenntnisse leisten hierbei einen wichtigen Beitrag für die nutzerorientierte Bewertung der Mensch-Roboter-Interaktion zwischen älteren Menschen mit funktionellen Einschränkungen und einem robotergestützten Rollator bzw. einem Duschroboter.

Die Entwicklung von Handlungsempfehlungen für die Evaluation von robotergestützten Rollatoren innerhalb dieser Arbeit stellt eine wichtige Grundlage hierfür dar. Diese liefern den methodischen Rahmen für die Konzeption von qualitativ hochwertigen Studien zur nutzerorientierten Evaluation von nicht nur robotergestützten Rollatoren, sondern auch von anderen altersgerechten Assistenzsystemen. Da auf nationaler wie internationaler Ebene bislang keine solchen Handlungsempfehlungen existieren, legt die vorliegende Arbeit einen wichtigen Grundstein für die Konzeption, Durchführung und Auswertung zukünftiger nutzerorientierter Evaluationsstudien von altersgerechten Assistenzrobotern.

Die positiven Studienergebnisse zur Effektivität der innovativen Assistenzfunktionen des MOBOT-Rollators (Navigationssystem, Hindernisvermeidung, Aufstehhilfe) weisen – im Gegensatz zur bislang wenig nutzerorientierten und evidenzbasierten Diskussion – auf das hohe Potential solcher Funktionen für die Verbesserung der Mobilität von motorischen eingeschränkten älteren Menschen hin. Da die Mobilität einer Person fundamental für deren Selbstständigkeit, sozialen Teilhabe, körperliche Aktivität und Lebensqualität ist, könnten robotergestützte Rollatoren mit solchen Assistenzfunktionen hierauf ebenfalls einen positiven Effekt haben und indirekt auch den Hilfebedarf von Angehörigen oder Pflegenden verringern. Da solche Effekte u.a. aufgrund des Prototypen-Status des MOBOT-Rollators innerhalb dieser Arbeit nicht untersucht werden konnten, erscheint deren Evaluation im Rahmen zukünftiger Studien mit weiter fortgeschrittenen Entwicklungsstufen des robotergestützten Rollators nach einer längeren Gebrauchsdauer in natürlichen Umgebungen naheliegend und sinnvoll.

Die Validierungsstudie des MOBOT-integrierten Ganganalysesystems stellt einen ersten wichtigen Schritt in Richtung der unaufdringlichen und kontinuierlichen Erfassung der habituellen Gangleistung von Rollator-Nutzern im Alltag dar. Bislang existieren hierfür noch keine validen Messinstrumente. Ferner bildet sie die Grundlage für die zukünftige Weiterentwicklung hin zu einem kontextbewussten, adaptiven robotergestützten Rollator, der in Echtzeit unterstützende Aktionen (z. B. Distanz-/Geschwindigkeitsanpassungen) entsprechend der aktuell erfassten Gangleistung der Nutzer generiert und dadurch kritische Situationen (z. B. Stürze) vermeiden soll. Die Ergebnisse belegen, dass durch das Ganganalysesystem des MOBOT-Rollators die Gangparameter seiner Nutzer unauffällig und ohne am

Körper fixierte Sensoren valide (zeitliche Parameter) bzw. konsistent (raumbezogene Parameter) erfasst werden können. Vor dem Hintergrund, dass in der vorliegenden Studie die Validität des Ganganalysesystems lediglich anhand einer kurzen sowie geraden Gehstrecke und unter kontrollierten Laborbedingungen bewertet wurde, bedarf es zukünftig an Studien, welche die Validität des Systems für ein Langzeit-Monitoring der habituellen Gangleistung in natürlichen Umgebungen überprüfen. Zukünftige Entwicklungsschritte sollten zudem die absolute Messgenauigkeit für die raumbezogenen Gangparameter verbessern.

Die Erkenntnisse aus den Studien des I-SUPPORT-Duschroboters leisten einen wichtigen Beitrag für die zukünftige Entwicklung und Implementierung von geeigneten Betriebsmodi für solche Assistenzroboter bei älteren Menschen mit funktionellen Einschränkungen. Die Studienergebnisse verdeutlichen, dass Betriebsmodi, welche überwiegend auf Nutzereingaben beruhen, für diese Zielgruppe ungeeignet sind, um eine hohe Effektivität der Mensch-Roboter-Interaktion zu gewährleisten. Die Studienergebnisse sprechen dafür, dass für eine effektive Interaktion vielmehr ein Betriebsmodus mit einem sehr hohen Maß an Autonomie auf Seiten des Roboters notwendig ist. Zudem zeigen die Ergebnisse, dass durch einen solchen Betriebsmodus trotz der sehr eingeschränkten Nutzerkontrolle die höchste Zufriedenheit erreicht wird, was zusätzlich für eine zukünftige Implementierung möglichst autonomer Betriebsmodi für solche Assistenzroboter bei älteren Menschen mit funktionellen Einschränkungen spricht.

Die vorliegenden Ergebnisse zum Nutzertraining mit dem I-SUPPORT-Duschroboter sind für eine erfolgreiche gestenbasierte Mensch-Roboter-Interaktion mit altersgerechten Assistenzrobotern hochrelevant. Sie untermauern die Notwendigkeit und den Nutzen geeigneter Training- oder Schulungsmaßnahmen für die gestenbasierte Mensch-Roboter-Interaktion bei älteren Menschen mit funktionellen Einschränkungen. Die Wichtigkeit solcher Maßnahmen für die Mensch-Roboter-Interaktion im höheren Alter wurde zwar bereits in früheren Studien diskutiert; es existieren allerdings bislang keine Empfehlungen für deren Durchführung. Das vorgestellte Nutzertraining könnte ein mögliches Modell für die Sicherstellung der notwendigen Bewegungsqualität der Nutzergesten für eine erfolgreiche gestenbasierte Mensch-Roboter-Interaktion zwischen funktionell eingeschränkten älteren Menschen und der für sie entwickelten Assistenzroboter darstellen. Zukünftig gilt es zu klären, ob eine solche Nutzergruppe in der Lage ist, die gelernten Gesten auch noch nach einem längeren Zeitraum abzurufen und korrekt auszuführen; oder ob wiederholte Trainingsmaßnahmen notwendig sind, um eine ausreichende Bewegungsqualität für eine langfristig erfolgreiche gestenbasierte Mensch-Roboter-Interaktion zu gewährleisten.

Literaturverzeichnis

AAL Association (2013). *Ambient Assisted Living (AAL) Joint Programme. Call for proposals 2013 AAL-2013-6. ICT-based solutions for supporting occupation in life of older adults*. Verfügbar unter: http://www.aal-europe.eu/wp-content/up-loads/2013/03/AAL-2013-6-call-text-20130326.pdf [Zugriff: 11.12.2019].

AAL Association (2014). *Guide for applicants - Active and Assistive Living programme call 2014*. Verfügbar unter: http://www.aal-europe.eu/wp-content/uploads/2015/03/AAL-2015-Guide_for_Applicants_20150306.pdf [Zugriff: 12.12.2019].

AAL Association (2019). *Projects*. Verfügbar unter: http://www.aal-europe.eu/projects-main/ [Zugriff: 11.12.2019].

AAL Deutschland (2016). *Förderprogramme für Ambient Assisted Living*. Verfügbar unter: http://www.aal-deutschland.de/deutschland/bekanntmachung-altersgerechte-assistenzsysteme [Zugriff: 10.12.2019].

Abellan van Kan, G., Rolland, Y., Andrieu, S., Bauer, J., Beauchet, O., Bonnefoy, M. et al. (2009). Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force. *Journal of Nutrition, Health and Aging, 13*(10), 881-889.

Alameda-Pineda, X. & Horaud, R. (2015). Vision-guided robot hearing. *International Journal of Robotics Research, 34*(4-5), 437-456.

American Geriatrics Society, British Geriatrics Society & American Academy of Orthopaedic Surgeons Panel on Falls Prevention. (2001). Guideline for the prevention of falls in older persons *Journal of the American Geriatrics Society, 49*(5), 664-672.

Anttila, H., Samuelsson, K., Salminen, A. & Brandt, A. (2012). Quality of evidence of assistive technology interventions for people with disability: An overview of systematic reviews. *Technology and Disability, 24*(1), 9-48.

Auais, M., Alvarado, B., Guerra, R., Curcio, C., Freeman, E. E., Ylli, A. et al. (2017). Fear of falling and its association with life-space mobility of older adults: a cross-sectional analysis using data from five international sites. *Age and Ageing, 46*(3), 459-465.

Ballesteros, J., Urdiales, C., Martinez, A. B. & Tirado, M. (2017). Automatic assessment of a rollator-user's condition during rehabilitation using the i-walker platform. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 25*(11), 2009-2017.

Barnett, K., Mercer, S. W., Norbury, M., Watt, G., Wyke, S. & Guthrie, B. (2012). Epidemiology of multimorbidity and implications for health care, research, and medical education: A cross-sectional study. *Lancet, 380*(9836), 37-43.

Bateni, H., Heung, E., Zettel, J., McLlroy, W. E. & Maki, B. E. (2004). Can use of walkers or canes impede lateral compensatory stepping movements? *Gait & Posture, 20*(1), 74-83.

Bateni, H. & Maki, B. E. (2005). Assistive devices for balance and mobility: Benefits, demands, and adverse consequences. *Archives of Physical Medicine and Rehabilitation, 86*(1), 134-145.

BAuA (2014). *Arbeit in der Pflege – Arbeit am Limit? Arbeitsbedingungen in der Pflegebranche. Factsheet 10.* Dortmund: BAuA.

Beckerle, P., Salvietti, G., Unal, R., Prattichizzo, D., Rossi, S., Castellini, C. et al. (2017). A human-robot interaction perspective on assistive and rehabilitation robotics. *Frontiers in Neurorobotics, 11*, 24-24.

Berndt, E., Wichert, R., Schulze, E., Oesterreich, D., Böhm, U., Gothe, H. et al. (2009). *Marktpotenziale, Entwicklungschancen, Gesellschaftliche, gesundheitliche und ökonomische Effekte der zukünftigen Nutzung von Ambient Assisted Living (AAL)-Technologien.* Rostock, Darmstadt, Berlin: Fraunhofer-Publica.

Bertelsmann Stiftung. (2012). *Themenreport „Pflege 2030“: Was ist zu erwarten – Was ist zu tun?* Gütersloh: Bertelsmann Stiftung.

Bilney, B., Morris, M. & Webster, K. (2003). Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. *Gait & Posture, 17*(1), 68-74.

Bland, J. M. & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet, 1*(8476), 307-310.

BMBF (2008). *Bekanntmachung des Bundesministeriums für Bildung und Forschung von Richtlinien zur Förderung von Forschung und Entwicklung auf dem Gebiet „Altersgerechter Assistenzsysteme für ein gesundes und unabhängiges Leben – AAL“*. Verfügbar unter: https://www.bmbf.de/foerderungen/bekanntmachung-337.html [Zugriff: 10.12.2019].

BMBF (2016). Richtlinien zur Durchführung des Wettbewerbs „Zukunft der Pflege: Mensch-Technik-Interaktion für die Praxis“. *Bundesanzeiger AT 24.08.2016 B4*.

BMBF (2018). Richtlinie zur Förderung von Forschung und Entwicklung auf dem Gebiet „Robotische Systeme für die Pflege“. *Bundesanzeiger AT 14.11.2018 B5*.

BMBF/VDE Innovationspartnerschaft AAL (Hrsg.). (2011). *Ambient Assisted Living (AAL): Komponenten, Projekte, Services - eine Bestandsaufnahme*. Berlin: VDE-Verlag.

BMG (2013). *Abschlussbericht zur Studie: Unterstützung Pflegebedürftiger durch technische Assistenzsysteme*. Verfügbar unter: https://vdivde-it.de/system/files/-pdfs/unterstuetzung-pflegebeduerftiger-durch-technische-assistenzsysteme.pdf [Zugriff: 10.12.2019]

Bohannon, R. W., Bubela, D. J., Magasi, S. R., Wang, Y.-C. & Gershon, R. C. (2010). Sit-to-stand test: Performance and determinants across the age-span. *Isokinetics and exercise science, 18*(4), 235-240.

Bohannon, R. W. & Williams Andrews, A. (2011). Normal walking speed: A descriptive meta-analysis. *Physiotherapy, 97*(3), 182-189.

Brandt, A., Iwarsson, S. & Stahl, A. (2003). Satisfaction with rollators among community-living users: A follow-up study. *Disability & Rehabilitation, 25*(7), 343-353.

Brodie, M. A., Coppens, M. J., Lord, S. R., Lovell, N. H., Gschwind, Y. J., Redmond, S. J. et al. (2016). Wearable pendant device monitoring using new wavelet-based methods shows daily life and laboratory gaits are different. *Medical & Biological Engineering & Computing, 54*(4), 663-674.

Burns, P. C. (1999). Navigation and the mobility of older drivers. *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences, 54*(1), S49-55.

Chalvatzaki, G., Papageorgiou, X. S. & Tzafestas, C. S. (2017, September). *Towards a user-adaptive context-aware robotic walker with a pathological gait assessment system: First experimental study.* Paper presented at the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, Canada.

Chen, H. C., Ashton-Miller, J. A., Alexander, N. B. & Schultz, A. B. (1991). Stepping over obstacles: Gait patterns of healthy young and old adults. *Journal of Gerontology, 46*(6), M196-203.

Chen, H. C., Ashton-Miller, J. A., Alexander, N. B. & Schultz, A. B. (1994). Effects of age and available response time on ability to step over an obstacle. *Journal of Gerontology, 49*(5), M227-233.

Chen, S., Lach, J., Lo, B. & Yang, G. (2016). Toward pervasive gait analysis with wearable sensors: A systematic review. *IEEE Journal of Biomedical and Health Informatics, 20*(6), 1521-1537.

Chiari, L., van Lummel, R., Pfeiffer, K., Lindemann, U. & Zijlstra, W. (2009). *Deliverable 2.2: Classification of the user's needs, characteristics and scenarios - Update*. [Unpublished report from the EU project (6th Framework Program, IST contract no. 045622) sensing and action to support mobility in ambient assisted living] Department of Health (2009) Prevention Package for Older People. 2009.

Chiu, Y. C., Algase, D., Whall, A., Liang, J., Liu, H. C., Lin, K. N. et al. (2004). Getting lost: Directed attention and executive functions in early Alzheimer's disease patients. *Dementia and Geriatric Cognitive Disorders, 17*(3), 174-180.

Choi, Y. M. & Sprigle, S. H. (2011). Approaches for evaluating the usability of assistive technology product prototypes. *Assistive Technology, 23*(1), 36-41.

Christensen, K., Doblhammer, G., Rau, R. & Vaupel, J. W. (2009). Ageing populations: The challenges ahead. *Lancet, 374*(9696), 1196-1208.

Chugo, D., Asawa, T., Kitamura, T., Songmin, J. & Takase, K. (2009, Oktober). *A motion control of a robotic walker for continuous assistance during standing, walking and seating operation.* Paper presented at the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), St. Louis, USA.

Cloutier, D. S., Penning, M. J., Nuernberger, K., Taylor, D. & MacDonald, S. (2019). Long-term care service trajectories and their predictors for persons living with dementia: Results from a Canadian study. *Journal of Aging and Health, 31*(1), 139-164.

Connell, J., Grealy, C., Olver, K. & Power, J. (2011). *Comprehensive scoping study on the use of assistive technology by frail older people living in the community June 2008*. Verfügbar unter: https://apo.org.au/node/23803 [Zugriff: 12.12.2019].

Cooper, R., Kuh, D., Hardy, R., Mortality Review, G., Falcon & Teams, H. A. S. (2010). Objectively measured physical capability levels and mortality: Systematic review and meta-analysis. *BMJ (Clinical research ed.), 341*, c4467-c4467.

Cooper, R. A., Grindle, G. G., Vazquez, J. J., Xu, J., Wang, H., Candiotti, J. et al. (2012). Personal mobility and manipulation appliance - Design development, and initial testing. *Proceedings of the IEEE, 100*(8), 2505-2511.

Crews, J. E. & Campbell, V. A. (2004). Vision impairment and hearing loss among community-dwelling older Americans: Implications for health and functioning. *American Journal of Public Health, 94*(5), 823-829.

Critchley, L. A. & Critchley, J. A. (1999). A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. *Journal of Clinical Monitoring and Computing, 15*(2), 85-91.

Cushman, L. A., Stein, K. & Duffy, C. J. (2008). Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. *Neurology, 71*(12), 888-895.

Czaja, S. J., Charness, N., Fisk, A. D., Hertzog, C., Nair, S. N., Rogers, W. A. et al. (2006). Factors predicting the use of technology: Findings from the Center for Research and Education on Aging and Technology Enhancement (CREATE). *Psychology and Aging, 21*(2), 333-352.

Davis, J. C., Bryan, S., Li, L. C., Best, J. R., Hsu, C. L., Gomez, C. et al. (2015). Mobility and cognition are associated with wellbeing and health related quality of life among older adults: a cross-sectional analysis of the Vancouver Falls Prevention Cohort. *BMC Geriatrics, 15*, 75.

Dews, P. B. (1977). Rate-dependency hypothesis. *Science, 198*(4322), 1182-1183.

Di Fabio, R. P., Kurszewski, W. M., Jorgenson, E. E. & Kunz, R. C. (2004). Footlift asymmetry during obstacle avoidance in high-risk elderly. *Journal of the American Geriatrics Society, 52*(12), 2088-2093.

Doblhammer, G., Georges, D. & Barth, A. (2015). *Einschränkungen in Mobilität und Sensorik als Risikofaktoren für Demenzerkrankung, Pflegebedarf und Sterblichkeit. Eine Grundlagenstudie für das Potenzial technischer Assistenzsysteme zur Erhöhung von Lebensdauer und Lebensqualität. Arbeitspakete 1 bis 3 des Projektes TEMOA: Teilhabe und Mobilität für Gesundheit im Alter*. Verfügbar unter: https://www.isd.uni-rostock.de/storages/uni-rostock/Alle_WSF/ISD/Publikationen/Gabriele_Doblhammer_UA_-_Einschraenkungen_In_Mobilitaet_Und_Sensorik_Als_Risikofaktoren.pdf [Zugriff: 11.12.2019].

Dometios, A. C., Papageorgiou, X. S., Arvanitakis, A., Tzafestas, C. S. & Maragos, P. (2017, September). *Real-time end-effector motion behavior planning approach using online point-cloud data towards a user adaptive assistive bath robot.* Paper presented at the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, Canada.

Donoghue, O. A., Ryan, H., Duggan, E., Finucane, C., Savva, G. M., Cronin, H. et al. (2014). Relationship between fear of falling and mobility varies with visual function among older adults. *Geriatrics & Gerontology International, 14*(4), 827-836.

Drupp, M. & Meyer, M. (2020). Belastungen und Arbeitsbedingungen bei Pflegeberufen – Arbeitsunfähigkeitsdaten und ihre Nutzung im Rahmen eines Betrieblichen Gesundheitsmanagements. In K. Jacobs, A. Kuhlmey, S. Greß, J. Klauber & A.

Schwinger (Hrsg.), *Pflege-Report 2019: Mehr Personal in der Langzeitpflege - aber woher?* (S. 23-47). Berlin, Heidelberg: Springer Berlin Heidelberg.

Efthimiou, E., Fotinea, S.-E., Goulas, T., Dimou, A.-L., Koutsombogera, M., Pitsikalis, V. et al. (2016). The MOBOT Platform – Showcasing multimodality in human-assistive robot interaction. In: Antona M. & Stephanidis C. (Hrsg.), *Universal access in human-computer interaction. Interaction techniques and environments*. UAHCI 2016. Lecture Notes in Computer Science, vol 9738. Springer, Cham.

Era, P., Sainio, P., Koskinen, S., Haavisto, P., Vaara, M. & Aromaa, A. (2006). Postural Balance in a Random Sample of 7,979 Subjects Aged 30 Years and Over. *Gerontology, 52*(4), 204-213.

Erdogan, A. & Argall, Brenna D. (2017). The effect of robotic wheelchair control paradigm and interface on user performance, effort and preference: An experimental assessment. *Robotics and Autonomous Systems, 94*, 282-297.

European Commission (2010a). *Digital agenda: Review shows strong SME interest and government backing for ICT to assist the elderly*. Verfügbar unter: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_10_1726/IP_10_1726_EN.pdf [Zugriff: 11.12.2019].

European Commission (2010b). *Interim evaluation of the ICT research in the 7th Framework Programme. Catalysing European Competitiveness in a Globalising World*. Verfügbar unter: https://ec.europa.eu/research/evaluations/pdf/archive/fp7-evidence-base/other_fp7_panel_evaluations/catalysing_european_competitive-ness.pdf [Zugriff: 11.12.2019].

European Commission (2012a). *Commission staff working document on an action plan for the EU health workforce*. Verfügbar unter: https://ec.europa.eu/health/sites/health/-files/workforce/docs/staff_working_doc_healthcare_workforce_en.pdf [Zugriff: 10.12,2019].

European Commission (2012b). *Overview of the European strategy in ICT for ageing well*. Verfügbar unter: https://ec.europa.eu/eip/ageing/file/339/down-load_en?token=jdgQXE_L [Zugriff: 11.12.2019].

European Commission (2013a). *Commission staff working document: Long-term care in ageing societies - Challenges and policy options*. Verfügbar unter: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2013:0041:FIN:EN:PDF [Zugriff: 11.12.2019].

European Commission (2013b). *Final Evaluation of the Ambient Assisted Living Joint Programme*. Verfügbar unter: http://www.aal-europe.eu/wp-content/up-loads/2015/05/Final-report-of-the-AAL-Busquin-2013.pdf [Zugriff: 11.12.2019].

European Commission (2013c). *Report from the Commission to the European Parliament and the Council. Final evaluation of the Ambient Assisted Living Joint Programme*. Verfügbar unter: https://ec.europa.eu/transparency/regdoc/rep/1/2013/EN/1-2013-898-EN-F1-1.Pdf [Zugriff: 11.12.2019].

European Commission (2013d). *Tackling the demographic challenge to create growth and jobs - Commission proposal for a renewed Ambient Assisted Living Joint Programme (AAL JP)*. Verfügbar unter: https://ec.europa.eu/digital-single-market/en/news/tackling-demographic-challenge-create-growth-and-jobs-commission-proposal-renewed-ambient [Zugriff: 09.12.2019].

European Commission (2016a). *AAL programme: Funding for Active and Assisted Living*. Verfügbar unter: https://ec.europa.eu/digital-single-market/en/active-and-assisted-living-joint-programme-aal-jp [Zugriff: 11.12.2019].

European Commission (2016b). *EU-funded projects in ICT for aging well*. Verfügbar unter: https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=14564 [Zugriff: 11.12.2019].

European Commission (2018). *The 2018 ageing report: Economic & budgetary projections for the 28 EU member states (2016-2070)*. Verfügbar unter: https://ec.eu-ropa.eu/info/sites/info/files/economy-finance/ip079_en.pdf [Zugriff: 13.12.2019].

Eurostat (2018). *Record high old-age dependency ratio in the EU*. Verfügbar unter: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20180508-1 [Zugriff: 08.12.2019].

Eurostat (2019a). *Difficulties in personal care activities by sex, age and educational attainment level [hlth_ehis_pc1e]*. Verfügbar unter: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hlth_ehis_pc1e&lang=en [Zugriff: 10.12.2019].

Eurostat (2019b). *Healthy life years and life expectancy at age 65 by sex [tepsr_sp320]*. Verfügbar unter: https://ec.europa.eu/eurostat/databrowser/view/tepsr_sp320/default/table?lang=en [Zugriff: 07.12.2019].

Eurostat (2019c). *Physical and sensory functional limitations by sex, age and educational attainment level [hlth_ehis_pl1e]*. Verfügbar unter: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hlth_ehis_pl1e&lang=en [Zugriff: 08.12.2019].

Eurostat (2019d). *Population on 1st January by age, sex and type of projection*. Verfügbar unter: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=proj_18naasfr&lang=en [Zugriff: 08.12.2019].

Eurostat (2019e). *Population structure and ageing*. Verfügbar unter: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_structure_and_ageing - The_share_of_elderly_people_continues_to_increase [Zugriff: 03.12.2019].

Executive Board (2017). *Improving access to assistive technology: Report by the Director-General*. Verfügbar unter: https://apps.who.int/iris/handle/10665/274140 [Zugriff: 12.12.2019].

Fachinger, U. (2017). Technikeinsatz bei Pflegebedürtigen. In K. Jacobs, A. Kuhlmey, S. Greß, J. Klauber & A. Schwinger (Hrsg.), *Pflegereport 2017. Schwerpunkt: Die Versorgung der Pflegebedürftigen* (S. 83-93). Stuttgart: Schattauer.

Ferrucci, L., Cooper, R., Shardell, M., Simonsick, E. M., Schrack, J. A. & Kuh, D. (2016). Age-related change in mobility: Perspectives from life course epidemiology and geroscience. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 71*(9), 1184-1194.

Folstein, M. F., Folstein, S. E. & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189-198.

Fong, J. H. & Feng, J. (2016). Patterns of functional disability in the oldest adults in China. *Journal of the American Geriatrics Society, 64*(9), 1890-1894.

Fries, J. F. (1980). Aging, natural death, and the compression of morbidity. *New England Journal of Medicine, 303*(3), 130-135.

Friesdorf, W., Podtschaske, B., Stahl, M., Glende, S. & Nedopil., C. (2011). *Nutzerabhängige Innovationsbarrieren im Bereich altersgerechter Assistenzsysteme. 1. Studie im Rahmen der AAL-Begleitforschung des Bundesministeriums für Bildung und Forschung*. Berlin: Technische Universität Berlin, Fachgebiet Arbeitswissenschaft und Produktergonomie (AwB), YOUSE GmbH.

Fuhrer, M. J., Jutai, J. W., Scherer, M. J. & DeRuyter, F. (2003). A framework for the conceptual modelling of assistive technology device outcomes. *Disability & Rehabilitation, 25*(22), 1243-1251.

Fusco, O., Ferrini, A., Santoro, M., Lo Monaco, M. R., Gambassi, G. & Cesari, M. (2012). Physical function and perceived quality of life in older persons. *Aging Clinical and Experimental Research, 24*(1), 68-73.

Geravand, M., Korondi, P. Z., Werner, C., Hauer, K. & Peer, A. (2017). Human sit-to-stand transfer modeling towards intuitive and biologically-inspired robot assistance. *Autonomous Robots, 41*(3), 575-592.

Ghisla, M. K., Cossi, S., Timpini, A., Baroni, F., Facchi, E. & Marengoni, A. (2007). Predictors of successful rehabilitation in geriatric patients: Subgroup analysis of patients with cognitive impairment. *Aging Clinical and Experimental Research, 19*(5), 417-423.

Gill, T. M., Guo, Z. & Allore, H. G. (2006). The epidemiology of bathing disability in older persons. *Journal of the American Geriatrics Society, 54*(10), 1524-1530.

Glock, G., Priesack, K., Apt, W., Strach, H., Krabel, S. & Bovenschulte, M. (2018). Branchenbericht: Pflege und Versorgung - Qualität der Arbeit, Beschäftigung und Beschäftigungsfähigkeit im Wechselspiel von Technologie, Organisation und Qualifikation. In Bundesministerium für Arbeit und Soziales (Hrsg.), *Forschungsbericht 522/2*. Berlin.

Glover, J., Holstius, D., Manojlovich, M., Montgomery, K., Powers, A., Wu, J. et al. (2003). *A robotically-augmented walker for older adults*. Pittsburgh: Computer Science Department, Carnegie Mellon University.

Goldin-Meadow, S. & Alibali, M. W. (2013). Gesture's role in speaking, learning, and creating language. *Annual Review of Psychology, 64*(1), 257-283.

Graafmans, W. C., Lips, P., Wijlhuizen, G. J., Pluijm, S. M. & Bouter, L. M. (2003). Daily physical activity and the use of a walking aid in relation to falls in elderly people in a residential care setting. *Zeitschrift für Gerontologie & Geriatrie, 36*(1), 23-28.

Graf, B. (2009). An adaptive guidance system for robotic walking aids. *Journal of Computer Engineering & Information Technology, 17*, 109-120.

Guler, A., Kardaris, N., Chandra, S., Pitsikalis, V., Werner, C., Hauer, K. et al. (2016). Human joint angle estimation and gesture recognition for assistive robotic vision. In: Hua G. & Jégou H. (Hrsg.), *Computer vision – ECCV 2016 Workshops. ECCV 2016. Lecture notes in computer science*, vol 9914. Springer, Cham.

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G. et al. (1994). A short physical performance battery assessing lower extremity function: Association with self-reported disability and prediction of mortality and nursing home admission. *Journal of Gerontology, 49*(2), M85-94.

Gure, T. R., Langa, K. M., Fisher, G. G., Piette, J. D. & Plassman, B. L. (2013). Functional limitations in older adults who have cognitive impairment without dementia. *Journal of Geriatric Psychiatry and Neurology, 26*(2), 78-85.

Haider, S., Luger, E., Kapan, A., Titze, S., Lackinger, C., Schindler, K. E. et al. (2016). Associations between daily physical activity, handgrip strength, muscle mass, physical performance and quality of life in prefrail and frail community-dwelling older adults. *Quality of Life Research, 25*(12), 3129-3138.

Häkkinen, A., Heinonen, M., Kautiainen, H., Huusko, T., Sulkava, R. & Karppi, P. (2007). Effect of cognitive impairment on basic activities of daily living in hip fracture patients: A 1-year follow-up. *Aging Clinical and Experimental Research, 19*(2), 139-144.

Hall, K. S., Cohen, H. J., Pieper, C. F., Fillenbaum, G. G., Kraus, W. E., Huffman, K. M. et al. (2017). Physical performance across the adult life span: Correlates with age and physical activity. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 72*(4), 572-578.

Harada, C. N., Natelson Love, M. C. & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine, 29*(4), 737-752.

Haskell, W. L. (1994). J.B. Wolffe Memorial Lecture. Health consequences of physical activity: Understanding and challenges regarding dose-response. *Medicine and Science in Sports and Exercise, 26*(6), 649-660.

Hauer, K. (2018). Bewertung von AAL-Ambient-Assisted-Living-Systemen bei Personen mit kognitiver Schädigung: Match vs. Mismatch. In O. Bendel (Hrsg.), *Pflegeroboter* (S. 89-111). Wiesbaden: Springer Fachmedien Wiesbaden.

Heiland, E. G., Welmer, A. K., Wang, R., Santoni, G., Angleman, S., Fratiglioni, L. et al. (2016). Association of mobility limitations with incident disability among older adults: a population-based study. *Age and Ageing, 45*(6), 812-819.

Hernandez-Belmonte, U. H. & Ayala-Ramirez, V. (2016). Real-time hand posture recognition for human-robot interaction tasks. *Sensors (Basel), 16*(1).

Higgins, J. P. T. & Green, S. (Hrsg.). (2011). *Cochrane handbook for systematic reviews of interventions 5.1.0*. Chichester: John Wiley & Sons.

Hirata, Y., Hara, A. & Kosuge, K. (2007). Motion control of passive intelligent walker using servo brakes. *IEEE Transactions on Robotics, 23*(5), 981-990.

Hirsch, J. A., Winters, M., Sims-Gould, J., Clarke, P. J., Ste-Marie, N., Ashe, M. et al. (2017). Developing a comprehensive measure of mobility: Mobility over varied environments scale (MOVES). *BMC Public Health, 17*(1), 513-513.

Hirvensalo, M., Rantanen, T. & Heikkinen, E. (2000). Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. *Journal of the American Geriatrics Society, 48*(5), 493-498.

Hort, J., Laczó, J., Vyhnálek, M., Bojar, M., Bures, J. & Vlcek, K. (2007). Spatial navigation deficit in amnestic mild cognitive impairment. *Proceedings of the National Academy of Sciences of the United States of America, 104*(10), 4042-4047.

Hülsken-Giesler, M. (2015). Neue Technologien in der Pflege. Wo stehen wir – was ist zu erwarten? In Bundesanstalt für Arbeitsschutz und Arbeitsmedizin & Initiative Neue Qualität der Arbeit (Hrsg.), *Intelligente Technik in der beruflichen Pflege Von den Chancen und Risiken einer Pflege 4.0* (S. 10-13). Dortmund, Berlin: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, Initiative Neue Qualität der Arbeit

Jagger, C., Arthur, A. J., Spiers, N. A. & Clarke, M. (2001). Patterns of onset of disability in activities of daily living with age. *Journal of the American Geriatrics Society, 49*(4), 404-409.

Jensen, J., Lundin-Olsson, L., Nyberg, L. & Gustafson, Y. (2002). Fall and injury prevention in older people living in residential care facilities. A cluster randomized trial. *Annals of Internal Medicine, 136*(10), 733-741.

Ka, H. W., Ding, D. & S., R. (2015). Computer access technologies for controlling assistive robotic manipulators: Potentials and challenges. *Austin Journal of Robotics & Automation, 2*(1), 1007.

Katz, S., Ford, A. B., Moskowitz, R. W., Jackson, B. A. & Jaffe, M. W. (1963). Studies of illness in the aged the index of ADL: A standardized measure of biological and psychosocial function. *Journal of the American Medical Association, 185*, 914-919.

Kensing, F. & Blomberg, J. (1998). Participatory design: Issues and concerns. *Computer Supported Cooperative Work (CSCW), 7*(3), 167-185.

Khosravi, P. & Ghapanchi, A. H. (2016). Investigating the effectiveness of technologies applied to assist seniors: A systematic literature review. *International Journal of Medical Informatics, 85*(1), 17-26.

Kim, D., Hazlett-Knudsen, R., Culver-Godfrey, H., Rucks, G., Cunningham, T., Portee, D. et al. (2012). How autonomy impacts performance and satisfaction: Results from a atudy with spinal cord injured subjects using an assistive robot. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, 42*(1), 2-14.

Kirasic, K. C. (1991). Spatial cognition and behavior in young and elderly adults: Implications for learning new environments. *Psychology and Aging, 6*(1), 10-18.

Knols, R. H., Stoller, O. & de Bruin, E. D. (2018). Handbuch Bewegungs- und Sportgerontologie. In U. Granacher, H. Mechling & C. Voelcker-Rehage (Hrsg.), *Handbuch Bewegungs- und Sportgerontologie* (S. 575-581). Schorndorf: Hofmann-Verlag.

Koceska, N., Koceski, S., Beomonte Zobel, P., Trajkovik, V. & Garcia, N. (2019). A Telemedicine robot system for assisted and independent living. *Sensors (Basel), 19*(4), 834.

Krings, B.-J., Böhle, K., Decker, M., Nierling, L. & Schneider, C. (Hrsg.). (2014). *Serviceroboter in Pflegearrangements*. Karlsruhe: KIT Scientific Report.

Ku, L. E., Chang, S. M., Pai, M. C. & Hsieh, H. M. (2019). Predictors of caregiver burden and care costs for older persons with dementia in Taiwan. *International Psychogeriatrics 31*(6), 885-894.

Kulyukin, V., Kutiyanawala, A., LoPresti, E., Matthews, J. & Simpson, R. (2008, April). *iWalker: Toward a rollator-mounted wayfinding system for the elderly.* Paper presented at the 2008 IEEE International Conference on RFID, Nevada, USA.

Kunze, C. & König, P. (2017). Systematisierung technischer Unterstützungssysteme in den Bereichen Pflege, Teilhabeunterstützung und aktives Leben im Alter. In I. Hämmerle & G. Kempter (Hrsg.), *Umgebungsunterstütztes Leben: Beiträge zum Usability Day XV* (S. 15-21). Lengerich: Pabst Science Publisher.

LaPlante, M. P., Harrington, C. & Kang, T. (2002). Estimating paid and unpaid hours of personal assistance services in activities of daily living provided to adults living at home. *Health Services Research, 37*(2), 397-415.

Lee, C. C., Czaja, S. J., Moxley, J. H., Sharit, J., Boot, W. R., Charness, N. et al. (2019). Attitudes toward computers across adulthood from 1994 to 2013. *The Gerontologist, 59*(1), 22-33.

Lewis, J. R. (1995). IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. *International Journal of Human-Computer Interaction, 7*(1), 57-78.

Lindemann, U., Schwenk, M., Klenk, J., Kessler, M., Weyrich, M., Kurz, F. et al. (2016). Problems of older persons using a wheeled walker. *Aging Clinical and Experimental Research, 28*(2), 215-220.

Lindwedel-Reime, U., Röll, N., Lautenschläger, S., Gradel, C., König, P. & Kunze, C. (2016). *Effekte und Nutzen altersgerechter Assistenzsysteme - Leitfaden für die Planung und Durchführung von Studien zur Evaluation neuer technischer Assistenzsysteme in Forschungs- und Entwicklungsprojekten*. Karlsruhe, Furtwangen: FZI Forschungszentrum Information am Karlsruher Institut für Technologie, Hochschule Furtwangen.

Liu, H. & Wang, L. (2018). Gesture recognition for human-robot collaboration: A review. *International Journal of Industrial Ergonomics, 68*, 355-367.

Louie, W. Y., McColl, D. & Nejat, G. (2014). Acceptance and attitudes toward a human-like socially assistive robot by older adults. *Assistive Technology, 26*(3), 140-150.

Mahoney, F. I. & Barthel, D. W. (1965). Functional evaluation: The Barthel index. *Maryland State Medical Journal, 14*, 61-65.

Mann, W. C., Hurren, D., Tomita, M. & Charvat, B. (1995). An analysis of problems with walkers encountered by elderly persons. *Physical & Occupational Therapy In Geriatrics, 13*(1-2), 1-23.

Manzeschke, A., Weber, K., Rother, E. & Fangerau, H. (2013). *Ethische Fragen im Bereich Altersgerechter Assistenzsysteme*. Berlin: VDI/VDE.

Martin, S., Kelly, G., Kernohan, W. G., McCreight, B. & Nugent, C. (2008). Smart home technologies for health and social care support. *Cochrane Database Syst Rev*(4), Cd006412.

Martins, M., Santos, C., Frizera, A. & Ceres, R. (2015). A review of the functionalities of smart walkers. *Medical Engineering & Physics, 37*(10), 917-928.

Martins, M., Santos, C. P., Frizera-Neto, A. & Ceres, R. (2012). Assistive mobility devices focusing on smart walkers: Classification and review. *Robotics and Autonomous Systems, 60*(4), 548-562.

Mavridis, N. (2015). A review of verbal and non-verbal human-robot interactive communication. *Robotics and Autonomous Systems, 63*, 22-35.

McFadyen, B. J. & Prince, F. (2002). Avoidance and accommodation of surface height changes by healthy, community-dwelling, young, and elderly men. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 57*(4), B166-174.

Memon, M., Wagner, S. R., Pedersen, C. F., Beevi, F. H. A. & Hansen, F. O. (2014). Ambient assisted living healthcare frameworks, platforms, standards, and quality attributes. *Sensors (Basel, Switzerland), 14*(3), 4312-4341.

Menning, S. & Hoffmann, E. (2009). Funktionale Gesundheit und Pflegebedürftigkeit. In K. Böhm, C. Tesch-Römer & T. Ziese (Hrsg.), *Gesundheit und Krankheit im Alter. Beiträge zur Gesundheitsberichterstattung des Bundes* (S. 62-78). Berlin: Robert Koch-Institut.

Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review, 19*(4), 478-489.

Morris, A., Donamukkala, R., Kapuria, A., Steinfeld, A., Matthews, J. T., Dunbar-Jacob, J. et al. (2003, September). *A robotic walker that provides guidance.* Paper presented at the 2003 IEEE International Conference on Robotics and Automation (ICRA), Tapei, Taiwan.

Moustris, G. P. & Tzafestas, C. S. (2016, Dezember). *Intention-based front-following control for an intelligent robotic rollator in indoor environments.* Paper presented at the 2016 IEEE Symposium Series on Computational Intelligence (SSCI), Athens, Greece.

Muro-de-la-Herran, A., Garcia-Zapirain, B. & Mendez-Zorrilla, A. (2014). Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications. *Sensors (Basel), 14*(2), 3362-3394.

Naik, A. D., Concato, J. & Gill, T. M. (2004). Bathing disability in community-living older persons: Common, consequential, and complex. *Journal of the American Geriatrics Society, 52*(11), 1805-1810.

Najafi, B., Khan, T. & Wrobel, J. (2011). Laboratory in a box: Wearable sensors and its advantages for gait analysis. *IEEE Engineering in Medicine and Biology Society Annual Conference, 2011*, 6507-6510.

Nowossadeck, S. (2013). Demografischer Wandel, Pflegebedürftige und der künftige Bedarf an Pflegekräften. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 56*(8), 1040-1047.

Oliva-Moreno, J., Peña-Longobardo, L. M., García-Mochón, L., Del Río Lozano, M., Mosquera Metcalfe, I. & García-Calvente, M. D. M. (2019). The economic value of time of informal care and its determinants (The CUIDARSE Study). *PLOS ONE, 14*(5), e0217016-e0217016.

Onder, G., Finne-Soveri, H., Soldato, M., Liperoti, R., Lattanzio, F., Bernabei, R. et al. (2009). Distress of caregivers of older adults receiving home care in European countries: Results from the AgeD in HOme Care Study. *The American Journal of Geriatric Psychiatry, 17*(10), 899-906.

Page, S., Saint-Bauzel, L., Rumeau, P. & Pasqui, V. (2017). Smart walkers: An application-oriented review. *Robotica, 35*(6), 1243-1262.

Pai, M. C. & Jacobs, W. J. (2004). Topographical disorientation in community-residing patients with Alzheimer's disease. *International Journal of Geriatric Psychiatry, 19*(3), 250-255.

Palopoli, L., Argyros, A., Birchbauer, J., Colombo, A., Fontanelli, D., Legay, A. et al. (2015). Navigation assistance and guidance of older adults across complex public spaces: The DALi approach. *Intelligent Service Robotics, 8*(2), 77-92.

Passini, R., Rainville, C., Marchand, N. & Joanette, Y. (1995). Wayfinding in dementia of the Alzheimer type: Planning abilities. *Journal of Clinical and Experimental Neuropsychology, 17*(6), 820-832.

Paulo, J., Peixoto, P. & Nunes, U. J. (2017). ISR-AIWALKER: Robotic walker for intuitive and safe mobility assistance and gait analysis. *IEEE Transactions on Human-Machine Systems, 47*(6), 1110-1122.

Payr, S., Werner, F. & Werner, K. (2015a). AAL robotics: State of the field and challenges. *Studies in Health Technology and Informatics, 212*, 117-124.

Payr, S., Werner, F. & Werner, K. (2015b). *Potential of robotics for Ambient Assisted Living*. Wien: Austrian Research Institute for Artificial Intelligence, Research Group for Assisted Living Technologies.

Pedersen, M. M., Holt, N. E., Grande, L., Kurlinski, L. A., Beauchamp, M. K., Kiely, D. K. et al. (2014). Mild cognitive impairment status and mobility performance: An analysis from the Boston RISE study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 69*(12), 1511-1518.

Peters, E., Pritzkuleit, R., Beske, F. & Katalinic, A. (2010). Demografischer Wandel und Krankheitshäufigkeiten. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 53*(5), 417-426.

Platt, J. (2000). Probabilistic outputs for support vector machines and comparisons to regularized likelihood methods. In A. J. Smola, P. Bartlett, B. Schölkopf & D. Schurrmans (Hrsg.), *Advances in large aargin classifiers*: MIT Press.

Podsiadlo, D. & Richardson, S. (1991). The timed "Up & Go": A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society, 39*(2), 142-148t

Pudane, M., Petrovica, S., Lavendelis, E. & Ekenel, H. K. (2019). Towards truly affective AAL systems. In I. Ganchev, N. M. Garcia, C. Dobre, C. X. Mavromoustakis & R. Goleva (Hrsg.), *Enhanced living environments: Algorithms, architectures, platforms, and systems* (S. 152-176). Cham: Springer International Publishing.

Reed, C., Belger, M., Vellas, B., Andrews, J. S., Argimon, J. M., Bruno, G. et al. (2016). Identifying factors of activities of daily living important for cost and caregiver outcomes in Alzheimer's disease. *International Psychogeriatrics, 28*(2), 247-259.

Ren, J., Wu, Y. D., Chan, J. S. & Yan, J. H. (2013). Cognitive aging affects motor performance and learning. *Geriatrics & Gerontology International, 13*(1), 19-27.

Rentschler, A. J., Simpson, R., Cooper, R. A. & Boninger, M. L. (2008). Clinical evaluation of Guido robotic walker. *Journal of Rehabilitation Research and Development, 45*(9), 1281-1293.

Rispens, S. M., Van Dieën, J. H., Van Schooten, K. S., Cofré Lizama, L. E., Daffertshofer, A., Beek, P. J. et al. (2016). Fall-related gait characteristics on the treadmill and in daily life. *Journal of neuroengineering and rehabilitation, 13*, 12-12.

Robert Koch-Institut (Hrsg.). (2015). *Welche Auswirkungen hat der demografische Wandel auf Gesundheit und Gesundheitsversorgung?* Berlin: RKI.

Robles-Garcia, V., Corral-Bergantinos, Y., Espinosa, N., Jacome, M. A., Garcia-Sancho, C., Cudeiro, J. et al. (2015). Spatiotemporal gait patterns during overt and covert evaluation in patients with Parkinson s disease and healthy subjects: Is there a Hawthorne effect? *Journal of Applied Biomechanics, 31*(3), 189-194.

Rodriguez-Losada, D., Matia, F., Jimenez, A., Galan, R. & Lacey, G. (2005, April). *Implementing map based navigation in Guido, the robotic smartwalker.* Paper presented at the Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA), Barcelona, Spain.

Rothgang, H., Fünfstück, M. & Kalwitzki, T. (2020). Personalbemessung in der Langzeitpflege. In K. Jacobs, A. Kuhlmey, S. Greß, J. Klauber & A. Schwinger (Hrsg.), *Pflege-Report 2019: Mehr Personal in der Langzeitpflege - aber woher?* (S. 147-157). Berlin, Heidelberg: Springer Berlin Heidelberg.

Rumeau, P., Pasqui, V. & Vigourou, N. (2012). A generic method for the assessment of smart walkers. *Gerontechnology, 11*(2), 345.

Salminen, A. L., Brandt, A., Samuelsson, K., Toytari, O. & Malmivaara, A. (2009). Mobility devices to promote activity and participation: A systematic review. *Journal of Rehabilitation Medicine, 41*(9), 697-706.

Scheffer, A. C., Schuurmans, M. J., van Dijk, N., van der Hooft, T. & de Rooij, S. E. (2008). Fear of falling: Measurement strategy, prevalence, risk factors and consequences among older persons. *Age and Ageing, 37*(1), 19-24.

Schmucker, R. (2020). Arbeitsbedingungen in Pflegeberufen. In K. Jacobs, A. Kuhlmey, S. Greß, J. Klauber & A. Schwinger (Hrsg.), *Pflege-Report 2019: Mehr Personal in der Langzeitpflege - aber woher?* (S. 49-60). Berlin, Heidelberg: Springer Berlin Heidelberg.

Schuldt, C., Laptev, I. & Caputo, B. (2004, August). *Recognizing human actions: A local SVM approach.* Paper presented at the Proceedings of the 17th International Conference on Pattern Recognition (ICPR), Cambrigde, UK.

Schulz, R., Wahl, H. W., Matthews, J. T., De Vito Dabbs, A., Beach, S. R. & Czaja, S. J. (2015). Advancing the aging and technology agenda in gerontology. *The Gerontologist, 55*(5), 724-734.

Schwinger, A. & Tsiasioti, C. (2018). Pflegebedürftigkeit in Deutschland. In K. Jacobs, A. Kuhlmey, S. Greß, J. Klauber & A. Schwinger (Hrsg.), *Pflege-Report 2018: Qualität in der Pflege* (S. 173-204). Berlin, Heidelberg: Springer Berlin Heidelberg.

Sermeus, W. & Bruyneel, L. (2019). *Investing in Europe's health workforce of tomorrow: Scope for innovation and collaboration - Summary report of the three Policy Dialogues*. Leuven, Belgium: Centre for Health Services & Nursing Research, Catholic University Leuven.

Sjölund, B.-M., Wimo, A., Engström, M. & von Strauss, E. (2015). Incidence of ADL disability in older persons, physical activities as a protective factor and the need for informal and formal care. Results from the SNAC-N Project. *PLOS ONE, 10*(9), e0138901-e0138901.

Snider, S. E., Quisenberry, A. J. & Bickel, W. K. (2016). Order in the absence of an effect: Identifying rate-dependent relationships. *Behavioural Processes, 127*, 18-24.

Soubra, R., Chkeir, A. & Novella, J.-L. (2019). A systematic review of thirty-one assessment tests to evaluate mobility in older adults. *BioMed Research International, 2019*, 1354362-1354362.

Spasova, S., Baeten, R., Coster, S., Ghailani, D., Peña-Casas, R. & Vanhercke, B. (2018). *Challenges in long-term care in Europe. A study of national policies 2018*. Brussels: European Commission. Verfügbar unter: https://ec.europa.eu/social/main.jsp?catId-=738&langId=en&pubId=8128&furtherPubs=yes [Zugriff: 11.12.2019].

Statistisches Bundesamt. (2016). *Ältere Menschen in Deutschland und der EU*. Verfügbar unter: https://www.bmfsfj.de/blob/93214/95d5fc19e3791f90f8d582d61b13a95e/aeltere-menschen-deutschland-eu-data.pdf [Zugriff: 11.12.2019].

Statistisches Bundesamt. (2019a). *Bevölkerung im Wandel – Annahmen und Ergebnisse der 14. koordinierten Bevölkerungsvorausberechnung*. Verfügbar unter: https://www.destatis.de/DE/Presse/Pressekonferenzen/2019/Bevoelkerung/pressebroschuere-bevoelkerung.pdf?__blob=publicationFile [Zugriff: 11.12.2019].

Statistisches Bundesamt. (2019b). *Pflegebedürftige: Deutschland, Stichtag, Art der Versorgung, Altersgruppen.* Verfügbar unter: https://www-genesis.destatis.de/genesis/online?sequenz=tabelleErgebnis&selectionname=22400-0001 [Zugriff: 10.12.2019].

Stordeur, S., D'hoore, W., van der Heijden, B., Di Bisceglie, M., Laine, M. & van der Schoot, E. (2005). Führungsqualität, Arbeitszufriedenheit und berufliche Bindung von Pflegekräften. In H. M. Hasselhorn, H. M. Müller, P. Tackenberg, A. Kümmerling & M. Simon (Hrsg.), *Berufsausstieg bie Pflegepersonal: Arbeitsbedingungen und beabsichtigter Berufsausstieg bei Pflegepersonal in Deutschland und Europa* (S. 30-48). Bremerhaven: NW Verlag.

Swenor, B. K., Simonsick, E. M., Ferrucci, L., Newman, A. B., Rubin, S. & Wilson, V. (2015). Visual impairment and incident mobility limitations: The health, aging and body composition study. *Journal of the American Geriatrics Society, 63*(1), 46-54.

Tacken, M., Marcellini, F., Mollenkopf, H., Ruoppila, I. & Széman, Z. (2005). Use and acceptance of new technology by older people. Findings of the international MOBILATE survey: 'Enhancing mobility in later life'. *Gerontechnology, 3*(3), 126-137.

Takayanagi, N., Sudo, M., Yamashiro, Y., Lee, S., Kobayashi, Y., Niki, Y. et al. (2019). Relationship between daily and in-laboratory gait speed among healthy community-dwelling older adults. *Scientific Reports, 9*(1), 3496.

Thrun, S., Fox, D., Burgard, W. & Dellaert, F. (2001). Robust Monte Carlo localization for mobile robots. *Artificial Intelligence, 128*(1), 99-141.

Tinetti, M. E., Speechley, M. & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *New England Journal of Medicine, 319*(26), 1701-1707.

Topo, P. (2009). Technology studies to meet the needs of people with dementia and their caregivers: A literature review. *Journal of Applied Gerontology, 28*(1), 5-37.

Tsui, K. M., Feil-Seifer, D. J., Matarić, M. J. & Yanco, H. A. (2009). Performance evaluation methods for assistive robotic technology. In R. Madhavan, E. Tunstel & E. Messina (Hrsg.), *Performance evaluation and benchmarking of intelligent systems* (S. 41-66). Boston, MA: Springer US.

UN DESA (2019). *World population prospects 2019*, Online Edition, 1. Rev. New York.

van Halteren-van Tilborg, I. A., Scherder, E. J. & Hulstijn, W. (2007). Motor-skill learning in Alzheimer's disease: A review with an eye to the clinical practice. *Neuropsychology Review, 17*(3), 203-212.

Vanbellingen, T., Kersten, B., Van Hemelrijk, B., Van de Winckel, A., Bertschi, M., Muri, R. et al. (2010). Comprehensive assessment of gesture production: A new test of upper limb apraxia (TULIA). *European Journal of Neurology, 17*(1), 59-66.

Varnai, P., Farla, K., Glasgow, D., Romeo, S. & Simmonds, P. (2018). *AAL market and investment report. A study prepared for the AAL Programme (Active and Assisted Living) by Technopolis Group*. Verfügbar unter: http://www.aal-europe.eu/wp-content/uploads/2018/11/AAL-Market-report-Technopolis-180604.pdf [Zugriff: 11.12.2019].

Verbakel, E. (2018). How to understand informal caregiving patterns in Europe? The role of formal long-term care provisions and family care norms. *Scandinavian journal of public health, 46*(4), 436-447.

Veronese, N., Bolzetta, F., Toffanello, E. D., Zambon, S., De Rui, M., Perissinotto, E. et al. (2014). Association between short physical performance battery and falls in older people: The Progetto Veneto Anziani study. *Rejuvenation Research, 17*(3), 276-284.

Wachaja, A., Agarwal, P., Zink, M., Adame, M. R., Möller, K. & Burgard, W. (2017). Navigating blind people with walking impairments using a smart walker. *Autonomous Robots, 41*(3), 555-573.

Wang, H., Kläser, A., Schmid, C. & Cheng-Lin, L. (2011, June). *Action recognition by dense trajectories.* Paper presented at the 2011 IEEE Conference on Computer Vision & Pattern Recognition (CVPR), Colorado, USA.

Wang, T., Merlet, J.-P., Sacco, G., Robert, P., Turpin, J.-M., Teboul, B. et al. (2016). Walking analysis of young and elderly people by using an intelligent walker ANG. *Robotics and Autonomous Systems, 75*, 96-106.

Webber, S. C., Porter, M. M. & Menec, V. H. (2010). Mobility in older adults: A comprehensive framework. *The Gerontologist, 50*(4), 443-450.

Webster, K. E., Wittwer, J. E. & Feller, J. A. (2005). Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. *Gait & Posture, 22*(4), 317-321.

Wee, S.-L., Liu, C., Goh, S.-N., Chong, W. F., Aravindhan, A. & Chan, A. (2014). Determinants of use of community-based long-term care services. *Journal of the American Geriatrics Society, 62*(9), 1801-1803.

Weerdesteyn, V., Nienhuis, B. & Duysens, J. (2005). Advancing age progressively affects obstacle avoidance skills in the elderly. *Human Movement Science, 24*(5-6), 865-880.

Werle, J. & Hauer K. (2016). *Design of a bath robot system - User definition and user requirements based on International Classification of Functioning, Disability and Health (ICF)*. Paper presented at the 2016 IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), New York, USA.

Werner, C., Ullrich, P., Geravand, M., Peer, A., Bauer, J. M. & Hauer, K. (2018). A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. *Disability & Rehabilitation: Assistive Technology, 13*(1), 31-39.

Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62*(6), 644-653.

Werner, C., Wiloth, S., Lemke, N. C., Kronbach, F., Jansen, C. P., Oster, P. et al. (2017). People with dementia can learn compensatory movement maneuvers for the sit-to-stand task: A randomized controlled trial. *Journal of Alzheimer's Disease, 60*(1), 107-120.

Whitson, H. E., Cronin-Golomb, A., Cruickshanks, K. J., Gilmore, G. C., Owsley, C., Peelle, J. E. et al. (2018). American Geriatrics Society and National Institute on Aging Bench-to-Bedside Conference: Sensory impairment and cognitive decline in older adults. *Journal of the American Geriatrics Society, 66*(11), 2052-2058.

WHO (2001). *International Classification of Functioning, Disability and Health (ICF)*. Geneva: World Health Organization.

WHO (2014). *Concept note: Opening the GATE for assistive health technology: Shifting the paradigm.* Verfügbar unter: https://www.who.int/phi/implementation/assistive_technology/concept_note.pdf [Zugriff: 21.11.2019].

WHO (2016). *Global strategy on human resources for health: Workforce 2030*. Verfügbar unter: https://www.who.int/hrh/resources/pub_globstrathrh-2030/en/ [Zugriff: 11.12.2019].

WHO (2019). *Assistive devices and technologies*. Verfügbar unter: https://www.who.int/disabilities/technology/en/ [Zugriff: 11.12.2019].

Wiener, J. M., Hanley, R. J., Clark, R. & Van Nostrand, J. F. (1990). Measuring the activities of daily living: Comparisons across national surveys. *Journal of Gerontology, 45*(6), S229-237.

Williamson, J. D. & Fried, L. P. (1996). Characterization of older adults who attribute functional decrements to "old age". *Journal of the American Geriatrics Society, 44*(12), 1429-1434.

Wu, C.-Y., Hu, H.-Y., Huang, N., Fang, Y.-T., Chou, Y.-J. & Li, C.-P. (2014). Determinants of long-term care services among the elderly: A population-based study in Taiwan. *PLOS ONE, 9*(2), e89213.

Wu, Q., Chan, J. S. & Yan, J. H. (2016). Mild cognitive impairment affects motor control and skill learning. *Reviews in the Neurosciences, 27*(2), 197-217.

Yu, H., Spenko, M. & Dubowsky, S. (2003). An adaptive shared control system for an intelligent mobility aid for the elderly. *Autonomous Robots, 15*(1), 53-66.

Ziegler, U. & Doblhammer, G. (2008). Cohort changes in the incidence of care need in West Germany between 1986 and 2005. *European Journal of Population / Revue européenne de Démographie, 24*(4), 347-362.

Abbildungsverzeichnis

Tabellenverzeichnis

Abkürzungsverzeichnis

AAL	Ambient Assisted Living
AAL-JP	Ambient Assisted Living – Joint Programme
ADL	Activity of Daily Living
ASQ	After-Scenario Questionnaire
BAuA	Bundesministerium für Arbeitsschutz und Arbeitsmedizin
BMBF	Bundesministerium für Bildung und Forschung
BMG	Bundesministerium für Gesundheit
CRR	Command Recognition Rate
EU	Europäische Union
FP7	7th Framework Programme
HRI	Human-Robot Interaction
ICC	Intraclass Correlation Coefficient
ICF	International Classification of Functioning, Disability and Health
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IQR	Interquartile Range
I-SUPPORT	ICT-Support bath robots
MMSE	Mini-Mental State Examination
MOBOT	Intelligent Active MObility Aid RoBOT Integrating Multimodal Communication
OGP	Observation-based Gestural Performance
REGE e. V.	Verein für Rehabilitationssport in der Geriatrie
SGP	Sensor-based Gestural Performance
STS	Sitzen-Stehen-Transfer
TSQ-WT	Telehealthcare Satisfaction Questionnaire – Wearable Technology
TULIA	Test of Upper Limb Apraxia
UN DESA	United Nations Department of Economic and Social Affairs
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e.V.
VDI	Verein Deutscher Ingenieure
WHO	World Health Organisation

Sonstige Publikationen, Kongressbeiträge und Lehrtätigkeiten

Sonstige Publikationen

Abel, B. Pomiersky, R., **Werner, C.,** Lacroix, A., Schäufele, M., Pfeiffer, K. & Hauer, K. (2019). Day-to-Day-Variability of Multiple Sensor-based Physical Activity Parameters in Older Persons with Dementia. *Archives of Gerontology and Geriatrics, 85*, 103911. DOI: 10.1016/j.archger.2019.103911

Dutzi, I., **Werner, C.** & Hauer, K. (2014). Trainierbarkeit und Rehabilitationsfähigkeit von Menschen mit Demenz. In Baden-Württemberg Stiftung gGmbH (Hrsg.). *Therapie bei Demenz – Körperliches Training bei Menschen mit Demenz* (S. 66-123). Schriftenreihe der Baden-Württemberg Stiftung; Nr. 74.

Geravand, M., Korondi, P. Z., **Werner, C.,** Hauer, K. & Peer, A. (2017). Human sit-to-stand transfer modeling towards intuitive and biologically-inspired robot assistance. *Autonomous Robots, 41*(3), 575-592. DOI: 10.1007/s10514-016-9553-5

Guler, A., Kardaris, N., Chandra, S., Pitsikalis, V., **Werner, C.**, Hauer, K., Tzafestas, C., Maragos, P. & Kokkinos, I. (2016). Human joint angle estimation and gesture recognition for assistive robotic vision workshop on assistive computer vision and robotics. In G. Hua & H. Jégou (Hrsg.). *Computer Vision – ECCV 2016 Workshops. Lecture Notes in Computer Science, vol. 9914* (S. 415-431). Cham, Schweiz: Springer International Publishing. DOI: 10.1007/978-3-319-48881-3_29

Hauer, K., Ullrich P. & **Werner, C.** (2020). Dual-task training in cognitively impaired and intact older populations to reduce fall risk: Evidence from previous Intervention trials by using a systematic review approach (S. 343-372). In M. Montero-Odasso & R. Camicioli (Hrsg.). Falls and cognition in older persons: Fundaments, assessment and therapeutic options. Cham, Schweiz: Springer International Publishing. DOI: 10.1007/978-3-030-24233-6_20

Heldmann, P., **Werner, C.,** Belala, N., Bauer, J. M. & Hauer, K. (2019). Early inpatient rehabilitation for acutely hospitalized older patients: a systematic review of outcome measures. *BMC Geriatrics, 19*(1), 189. DOI: 10.1186/s12877-019-1201-4

Jansen, C.-P., Diegelmann, M. Schilling, O. K., **Werner, C.**, Schnabel, E.-L., Wahl, H.-W. & Hauer, K. (2018). Pushing the boundaries: A physical activity intervention extends sensor-assessed life-space in nursing home residents. *The Gerontologist, 58*(5), 979-988. DOI: 10.1093/geront/gnx136

Korn O., Buchweitz L., Rees A., Bieber G., **Werner C.** & Hauer K. (2019). Using augmented reality and gamification to empower rehabilitation activities and elderly persons. A study applying design thinking. In T. Ahram (Hrsg.). *Advances in artificial intelligence, software and systems engineering. AHFE 2018. Advances in intelligent systems and computing*, vol. 787, (S. 219-229). Cham, Schweiz: Springer International Publishing. DOI: 10.1007/978-3-319-94229-2_21

Lemke, N.C., **Werner, C.**, Wiloth, S. & Hauer, K. (2019). Transferability and sustainability of motor-cognitive dual-task training in patients with dementia: A randomized controlled trial. *Gerontology, 65*(1), 68-83. DOI: 10.1159/000490852

Lemke N.C., Wiloth, S., **Werner, C.** & Hauer, K. (2017). Validity, test-retest reliability, sensitivity to change and feasibility of motor-cognitive dual task assessments in patients with dementia. *Archives of Gerontology and Geriatrics, 70*, 169-179. DOI: 10.1016/j.archger.2017.01.016

Litz, E., Ball, C., Jansen, C.-P., **Werner, C.**, de Bruin, E. & Hauer, K. (2020). Validation of a motor-cognitive assessment for a stepping exergame in older adults: Use of game-specific, internal data stream. *Games for Health Journal*, 9(1):1-13. DOI: 10.1089/g4h.2019.0081

Pomierky, R., Abel, B., **Werner, C.**, Pfeiffer, K., Schäufele, M. & Hauer, K. (2020). Increasing physical activity in people with dementia: A randomized controlled trial. Journal of Aging and Physical Activity. DOI: 10.1123/japa.2019-0183

Ullrich, P., Eckert, T., Bongartz, M., **Werner, C.**, Kiss, R., Bauer, J.M. & Hauer, K. (2019). Life-space mobility in older persons with cognitive impairment after discharge from geriatric rehabilitation. *Archives of Gerontology and Geriatrics, 81*, 192-200. DOI: 10.1016/j.archger.2018.12.007

Ullrich, P., **Werner, C.**, Bongartz, M., Kiss, R., Bauer, J. & Hauer, K. (2019). Validation of the modified Life-Space Assessment in multimorbid older persons with cognitive impairment. *The Gerontologist, 59*(2), e66-e75. DOI: 10.1093/geront/gnx214

Ullrich, P., **Werner, C.**, Eckert, T., Bongartz, M., Kiss, R., Feisst, M., Delbaere, K. Bauer, J. M. & Hauer, K. (2019). Cut-off for the Life-Space Assessment in persons with cognitive impairment. *Aging Clinical and Experimental Research, 31*(9), 1331-1335. DOI: 10.1007/s40520-018-1062-2

Werner, C., Dutzi, I. & Hauer, K. (2014). Theoretische Grundlagen demenzieller Erkrankungen. In Baden-Württemberg Stiftung gGmbH (Hrsg.). *Therapie bei Demenz – Körperliches Training bei Menschen mit Demenz* (S. 14-63). Schriftenreihe der Baden-Württemberg Stiftung; Nr. 74.

Werner, C. & Hauer, K. (2016). Mit Sportsgeist gegen Demenz. In Baden-Württemberg Stiftung gGmbH (Hrsg.). *100! Was die Wissenschaft vom Altern weiß* (S. 97-105). Stuttgart: S. Hirzel Verlag.

Werner, C., Rosner, R., Wiloth, S., Lemke, N. C., Bauer, J. M. & Hauer, K. (2018). Time course of changes in motor-cognitive exergame performances during task-specific training in patients with dementia: identification and predictors of early training response. *Journal of NeuroEngineering and Rehabilitation, 15*(1), 100. DOI: 10.1186/s12984-018-0433-4

Werner, C., Wiloth, S., Lemke, N.C., Kronbach, F. & Hauer, K. (2018). Development and validation of a novel motor-cognitive assessment strategy of compensatory sit-to-stand maneuvers in people with dementia. *Journal of Geriatric Physical Therapy, 41*(3), 143-154. DOI: 10.1519/JPT.0000000000000116

Werner, C., Wiloth, S., Lemke, N.C., Kronbach, F., Jansen, C.-P., Oster, P., Bauer, J. M. & Hauer, K. (2017). People with dementia can learn compensatory movement maneuvers for the sit-to-stand task: A randomized controlled trial. *Journal of Alzheimer's Disease, 60*(1),107-120. DOI: 10.3233/JAD-170258

Wiloth, S., Lemke, N., **Werner, C.** & Hauer, K. (2016). Validation of a computerized, game-based assessment strategy to measure training effects on motor-cognitive functions in people with dementia. *JMIR Serious Games, 4*(2), e12. DOI: 10.2196/games.5696

Wiloth, S., **Werner, C.**, Lemke, N. C. & Hauer, K. (2018). Motor-cognitive effects of a computerized, game-based training method in people with dementia: a randomized controlled trial. *Aging & Mental Health, 22*(9), 1124-1135. DOI: 10.1080/13607863.2017. 1348472

Zlatintsi, A., Dometios, A. C., Kardaris, N., Rodomagoulakis, I., Koutras, P., Pagaeorgiou, X. Maragos, P. Tzafestas, K, Vartholomeaos, P., Hauer, K., **Werner C.**, Annicchiarico, R., Lombardi, M. G., Adriano, F., Asfur, T., Sabatini, A. M., Güler, A., Kokkinos, I., Klein, B. & López, R., (2019). I-SUPPORT: a Robotic Platform of an Assistive Bathing Robot for the Elderly Population. Under Review in *Robotics and Autonomous Systems.*

Kongressbeiträge

Abel, B., **Werner, C.**, Pomiersky, R. & Hauer, K. (2017, September). *Die Tag-zu-Tag-Variabilität der körperlichen Aktivität bei hochbetagten Menschen mit Demenz*. 29. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 50*(Suppl. 3), S323-01. DOI: 10.1007/s00391-017-1301-8

Bongartz, M., Ullrich, P., Eckert, T., **Werner, C.**, Kiss, R., Abel, B., Bauer, J. M. & Hauer, K. (2018, September). *Zusammenhänge zwischen motorischer Leistungsfähigkeit und körperlicher Alltagsaktivität bei älteren Personen mit kognitiver Einschränkung nach geriatrischer Rehabilitation*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Köln (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 51*(Suppl. 1), S128. DOI: 10.1007/s00391-018-1435-3

Bongartz, M., Ullrich, P., Eckert, T., **Werner, C.**, Kiss, R., Abel, B., Bauer, J. M. & Hauer, K. (2018, Oktober). *Associations of motor performance and qualitative/quantitative physical activity behavior in older persons with cognitive impairment after discharge from geriatric rehabilitation*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S144. DOI: 10.1007/s41999-018-0097-4

Chalvatzaki, G., Papageorgiou, X. S., **Werner, C.**, Hauer, K., Tzafestas, C. S. & Maragos, P. (2016, Juni). *Experimental comparison of human gait tracking algorithms: Towards a context-aware mobility assistance robotic walker*. 24th Mediterranean Conference on Control and Automation (MED), Athen, Griechenland (Vortrag). Konferenzpublikation: *Proceedings 24th Mediterranean Conference on Control and Automation* (MED), ISBN: 978-1-4673-8347-9, S. 719-724. DOI: 10.1109/MED.2016.7535962

Gogulla, S., Lemke, N., **Werner, C. &** Hauer, K. (2014, September). *Motorisch-kognitive Effekte eines neuen computergestützten Trainings bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Halle (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 47*(Suppl. 1), S143. DOI: 10.1007/s00391-014-0807-6

Günther-Lange, M., **Werner, C.**, de Bruin, E. & Hauer, K. (2017, September). *Effekte eines computergestützten, spielebasierten Trainings auf motorisch-kognitive Fähigkeiten bei älteren Menschen*. 29. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 50*(Suppl. 3), S323-04. DOI: 10.1007/s00391-017-1301-8

Hauer K., Gogulla S., Lemke N. & **Werner, C.** (2015, April). *Motor-cognitive effects of a novel computer-based training in patients with dementia*. The International Association of Gerontology and Geriatrics - European Region (IAGG-ER) 8th Congress, Dublin, Irland (Vortrag).

Hauer, K. Günther-Lange, M. & **Werner. C.** (2017, Juli). *Effects of a new computerized motor-cognitive memory training in older persons*. 21st International Association of Gerontology and Geriatrics (IAGG) World Congress of Gerontology and Geriatrics. San Francisco, California, USA (Vortrag). Abstract: *Innovation in Aging, 1*(Suppl. 1), 1051-1052. DOI: 10.1093/geroni/igx004.3843

Hauer, K. Günther-Lange, M. & **Werner. C.** (2018, Oktober). *Effects of a new computerized motor-cognitive memory training in older persons*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S146. DOI: 10.1007/s41999-018-0097-4

Hauer, K., Heldmann, P. & **Werner, C.** (2019, November). *Early inpatient rehabilitation in geriatric patients: A systematic review of outcome measures*. Gerontological Society of America (GSA) 2019 Annual Scientific Meeting. Austin, Texas, USA (Poster). Abstract: *Innovation in Aging*, *3*(Suppl. 1), S169-170. DOI: 10.1093/geroni/igz038.604

Hauer, K., Lemke, N.C., **Werner C. &** Wiloth, S., (2018, Oktober). *Transferability and sustainability of effects of dual-task training in patients with dementia*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S248. DOI: 10.1007/s41999-018-0097-4

Hauer, K., Lemke, N., Wiloth, S. & **Werner, C.** (2017, Juli). *Biometrical quality of strategies to assess dual task performance in persons with dementia*. 21st International Association of Gerontology and Geriatrics (IAGG) World Congress of Gerontology and Geriatrics. San Francisco, California, USA (Vortrag). Abstract: *Innovation in Aging, 1*(Suppl. 1), S.1097-1098. DOI: 10.1093/geroni/igx004.4023

Hauer, K, Litz, E., Ball, C., Jansen C.-P., **Werner, C.,** Bauer, J. M. & de Bruin, E. (2018, September). *Validation of a motor-cognitive assessment for a stepping exergame in older adults: use of game-specific, internal data stream*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Köln (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 51*(Suppl. 1), S73. DOI: 10.1007/s00391-018-1435-3

Hauer K., **Werner C.,** Ullrich P., Geravand M. & Peer, A. (2015, September). *Evaluation studies of robotic rollators by the user perspective: A systematic review*. IEEE/RSJ International Conference on Intelligence Robots and Systems (IROS). 28. September - 2. Oktober 2015, Hamburg (Vortrag).

Hauer K., **Werner C.,** Ullrich P., Wiloth, S., Lemke, N. & Rosner, R. (2018, November). *Changes in motor-cognitive performances during an exergame intervention in persons with dementia*. Gerontological Society of America (GSA) 2018 Annual Scientific Meeting. Boston, Massachusetts, USA (Vortrag). Abstract: *Innovation in Aging, 2*(Suppl. 1), 440. DOI: 10.1093/geroni/igy023.1648

Hauer, K., Wiloth, S., Lemke, N. & **Werner, C.** (2017, Juli). *Validation of a computerized, game-based assessment strategy in persons with dementia*. 21st International Association of Gerontology and Geriatrics (IAGG) World Congress. San Francisco, California, USA (Vortrag). Abstract: *Innovation in Aging, 1*(Suppl.1), S.1286-1286. DOI: 10.1093/geroni/igx004.4695

Heldmann, P., **Werner, C.,** Hauer, K. & Bauer, J. M. (2019, Januar). Assessment strategies in early, ward-based rehabilitation in vulnerable, multimorbid geriatric patients admitted to acute medical care. 22th Mobility Exercise Meeting (MobEx), Trondheim, Norwegen (Vortrag).

Heldmann, P., **Werner, C.,** Hauer, K. & Bauer, J. M. (2019, September). *Validation of the patient-specific functional scale (PSFS) in geriatric patients with cognitive impairment*. 15th International Congress of the European Geriatric Medicine Society (EuGMS), Krakau, Polen (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S62. DOI: 10.1007/s41999-019-00221-0

Heldmann, P., **Werner, C.,** Hauer, K. & Bauer, J. M. (2019, September). Validi*erung der patientenspezifischen Funktionsskala (PSFS) bei geriatrischen Patienten mit kognitiven Einschränkungen im Akutkrankenhaus*. 31. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 52*(Suppl. 2), S147. DOI: 10.1007/s00391-019-01592-6

Lemke, N., Gogulla, S., **Werner, C.** & Hauer, K. (2014, September). *Spezifisches Training verbessert trainierte und nicht-trainierte Dual-Task Leistungen bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Halle (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 47*(Suppl. 1), S67. DOI: 10.1007/s00391-014-0807-6

Lemke, N.C., Wiloth, S., **Werner, C.** & Hauer, K. (2016, September). *Konstruktvalidität, Test-Retest-Reliabilität, Veränderungssensitivität und Durchführbarkeit von Dual-Task Assessmentverfahren bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Stuttgart (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 49*(Suppl. 1), S59. DOI: 10.1007/s00391-016-1123-0

Papageorgiou, X. S., Chalvatzaki, G., Lianos, K.-N., **Werner, C**., Hauer, K., Tzafestas, C. S. & Maragos, P. (2016, Juni). *Experimental validation of human pathological gait analysis for an assisted living intelligent robotic walker*. 6th IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), UTown, Singapur (Vortrag). Konferenzpublikation: *Proceedings of the 6th IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, ISBN: 978-1-5090-3288-4, S. 1086-1091. DOI: 10.1109/BIOROB.2016.7523776

Pomiersky, R., **Werner, C.**, Abel, B. & Hauer, K. (2017, September). *Steigerung körperlicher Aktivität bei geriatrischen Patienten mit Demenz: Eine randomisiert-kontrollierte Studie*. 29. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 50*(Suppl. 3), S313-02. DOI: 10.1007/s00391-017-1301-8

Ullrich, P., Eckert, T., Bongartz, M., **Werner, C.**, Kiss, R., Bauer, J. M. & Hauer, K. (2018, Oktober). *„Life-Space"-Mobilität geriatrischen Patienten mit motorischen und kognitiven Einschränkungen nach der Rehabilitation*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Köln (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 51*(Suppl. 1), S126. DOI: 10.1007/s00391-018-1435-3

Ullrich, P., Eckert, T., Bongartz, M., **Werner, C.**, Kiss, R., Bauer, J .M. & Hauer, K. (2018, Oktober). *Life-space mobility among multimorbid older persons with multiple impairments following rehabilitation*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S151. DOI: 10.1007/s41999-018-0097-4

Ullrich, P., **Werner, C.**, Eckert, T., Bongartz, M. Kiss, R., Bauer, J. M. & Hauer, K. (2018, Oktober). *Increasing life-space mobility in multimorbid older persons with motor and cognitive impairment*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Vortrag). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S7. DOI: 10.1007/s41999-018-0097-4

Ullrich, P., **Werner, C.**, Eckert, T., Bongartz, M. Kiss, R., Bauer, J. M. & Hauer, K. (2018, September). *Steigerung der „Life-Space"-Mobilität von älteren Personen mit kognitiven Einschränkungen nach der Rehabilitation*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Köln (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 51*(Suppl. 1), S17. DOI: 10.1007/s00391-018-1435-3

Werner, C., Chalvatzaki, G., Papageorgiou, X. S., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (2018, Oktober). *Concurrent validity of a mobile sensor-based gait analysis system on a smart walker in older adults with gait impairments*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Vortrag). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S25. DOI: 10.1007/s41999-018-0097-4

Werner, C., Chalvatzaki, G., Papageorgiou, X. S., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (2019, September). *Ganganalyse mittels smartem Rollator: Eine Validierungsstudie bei älteren Personen mit Mobilitätseinschränkungen*. 31. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 52*(Suppl. 2), S155. DOI: 10.1007/s00391-019-01592-6

Werner, C., Heldmann, P., Bauer, J. M. & Hauer, K. (2019, September). *Concurrent validity, test-retest reliability, and minimal detectable change of a single body-fixed-sensor to assess gait characteristics during rollator-assisted walking in geriatric patients*. 15th International Congress of the European Geriatric Medicine Society (EuGMS), Krakau, Polen (Poster). Abstract: *European Geriatric Medicine, 9*(Supp. 1), S96. DOI: 10.1007/s41999-019-00221-0

Werner, C., Lemke, N., Wiloth, S. Kronbach, F. & Hauer, K. (2016, September). *Effekte eines standardisierten motorischen Lernprogramms auf den Sitzen-Stehen-Transfer bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Stuttgart (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 49*(Suppl. 1), S39. DOI: 10.1007/s00391-016-1123-0

Werner, C., Lemke, N., Wiloth, S. Kronbach, F. & Hauer, K. (2016, September). *Validierung eines motorisch-kognitiven Assessmentverfahrens zur Beurteilung kompensatorischer Bewegungen beim Sitzen-Stehen-Transfer von Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Stuttgart (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 49*(Suppl. 1), S58. DOI: 10.1007/s00391-016-1123-0

Werner, C., Moustris, G. P., Tzafestas, C. S. & Hauer, K. (2017, September*). Nutzerorientiere Evaluation der Effektivität eines robotergestützten Rollators mit Navigationssystem*. 29. Jahreskongress der Deutschen Gesellschaft für Geriatrie (DGG). Frankfurt am Main (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 50*(Suppl. 3), S323-02. DOI: 10.1007/s00391-017-1301-8

Werner, C., Rosner, R., Wiloth, S., Lemke, N. C., Bauer, J. M. & Hauer, K. (2018, September). *Veränderungen von motorisch-kognitiven Exergame-Leistungen im Verlauf eines aufgabenspezifischen Trainingsprogramms bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Köln (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 51*(Suppl. 1), S9-S10. DOI: 10.1007/s00391-018-1435-3

Werner, C., Rosner, R., Wiloth, S., Lemke, N. C., Bauer, J. M. & Hauer, K. (2018, Oktober). *Time course of changes in motor-cognitive exergame performance during task-specific training in patients with dementia: Identification and predictors of early training response*. 14th International Congress of the European Geriatric Medicine Society (EuGMS), Berlin (Poster). Abstract: *European Geriatric Medicine, 9*(Suppl. 1), S251. DOI: 10.1007/s41999-018-0097-4

Werner, C., Ullrich, P., Eckert, T., Bongartz, M. Kiss, R., Bauer, J. M. & Hauer, K. (2019, Januar). *Increasing life-space mobility in older persons with cognitive impairment following geriatric rehabilitation*. 22th Mobility Exercise Meeting (MobEx), Trondheim, Norwegen (Poster).

Werner, C., Ullrich, P., Eckert, T., Bongartz, M. Kiss, R., Bauer, J. M. & Hauer, K. (2019, April). Steigerung der „Life-Space-Mobilität" durch ein poststationäres Heimtrainingsprogramm bei älteren Personen mit kognitiver Einschränkung. Jahrestagung der Deutschen Vereinigung für Sportwissenschaft, Kommission Gesundheit, Hamburg (Vortrag).

Werner, C., Ullrich, P., Geravand, M. Peer, A. & Hauer, K. (2015, Januar). *Evaluation studies of robotic rollators by the user perspective: A systematic review*. 18th Mobility Exercise Meeting (MobEx), Bologna, Italien (Vortrag).

Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016, September). *Evaluation von robotergestützten Rollatoren aus der Perspektive der Nutzer*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Stuttgart (Poster). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 49*(Suppl. 1), S123-124. v: 10.1007/s00391-016-1123-0

Wiloth, S., Lemke, N.C., **Werner, C.** & Hauer, K. (2016, September). *Validierung eines computergestützten, spiele-basierten Assessmentverfahrens zur Erfassung motorisch-kognitiver Leistungen bei Menschen mit Demenz*. Gemeinsamer Jahreskongress der Deutschen Gesellschaft für Gerontologie und Geriatrie (DGGG) und Deutschen Gesellschaft für Geriatrie (DGG), Stuttgart (Vortrag). Abstract: *Zeitschrift für Gerontologie und Geriatrie, 49*(Suppl. 1), S59. DOI: 10.1007/s00391-016-1123-0

Öffentlichkeitsvorträge

Werner, C. (2016, Oktober). *Spielebasiertes Training zur Förderung der Gleichgewichtsfähigkeit*. Informations- und Mitmachtag Stadt Heidelberg, Sportkreises Heidelberg und Netzwerk „Mehr Bewegung lebenslang", Heidelberg.

Werner, C. (2014, Oktober). *Intelligente Assistenzsysteme zur Bewältigung von Alltagsaufgaben*. Tag der offenen Tür am AGAPLESION BETHANIEN KRANKENHAUS HEIDELBERG, Heidelberg.

Akademische Lehrtätigkeiten und Fortbildungsseminare

Eidam, A., Trumpfheller, A. & **Werner, C.** (2019, Oktober). *Einführung in das Geriatrische Assessment.* HeiCuMed (Ausbildungscurriculum für Medizinstudierende), Block I, Innere Medizin, Modul „Medizin des Alterns und des alten Menschen" (praktische Übungen).

Hauer, K. & **Werner, C.** (2012, Oktober, November; 2017, März; 2018, März, Oktober; 2019, Oktober). *Bedeutung von Kraft und koordinativer Leistung für die Lebensqualität im Alter, Bestimmung von Koordinations- und Kraftleistung*. HeiCuMed (Ausbildungscurriculum für Medizinstudierende), Querschnittsfach „Prävention und Gesundheitsförderung" (Vortrag & praktische Übungen).

Hauer, K. & Werner, C. (2019, Februar). Assistenzsysteme und digitale Trainingssysteme im klinischen Setting. Interdisziplinäres Kolloquium für Studierende des Marsilius-Kollegs der Ruprecht-Karls-Universität Heidelberg, Assistenzsysteme und digitale Technologien im Alter, Heidelberg (Vortrag & praktische Übungen).

Hauer, K. & **Werner, C.** (2018, September). *Movement and ageing*. Summer School 2018 des Marsilius-Kollegs der Ruprecht-Karls-Universität Heidelberg, Humans in Motion – Der Mensch in Bewegung. Perspectives from Sciences, Technology and Humanities, Heidelberg (Vortrag).

Specht-Leible, N., Jansen, C.-P., Trumpfheller, A. & **Werner, C.** (2015, Juni, Juli; 2017, Juli; 2018, Oktober; 2019, Juni, Oktober). *Mobilität und Sturz im Alter*. Weiterbildungsseminar an der AGAPLESION AKADEMIE HEIDELBERG für Pflegefachkräfte, Zusatzqualifikation „Führerschein Geriatrie", Heidelberg (Vortrag & praktische Übungen).

Werner, C. (2017, Juni). *Physical activity and basic motor skills in people with dementia – Instant aging and basic motor skills*. Summer School 2017 des Netzwerks für AlternsfoRschung (NAR) der Ruprecht-Karls-Universität Heidelberg (Vortrag).

Wiloth, S. & **Werner, C.** (2016, Juni). *Sturzprävention bei Menschen mit Demenz*. Fortbildungsseminar des Caritasverbands München und Freising für Pflegekräfte und Physiotherapeuten, Caritas Institut für Bildung und Entwicklung, München (Vortrag & praktische Übungen).

Gutachtertätigkeiten und Betreuung studentischer Abschlussarbeiten

Peer-Review-Tätigkeiten:

- Aging and Mental Health
- Alzheimer's Research & Therapy
- BMJ Open
- Disability and Rehabilitation
- European Journal of Physical and Rehabilitation Medicine
- Gerontology
- International Journal of Geriatric Psychiatry
- Sensors
- Zeitschrift für Gerontologie und Geriatrie

Betreuung von studentischen Abschlussarbeiten:

- Herbers, Malte (2016). Welche Faktoren beeinflussen die Testdauer eines standardisierten motorisch-kognitiven Tests bei Personen mit beginnender bis mittelgradigen demenzieller Erkrankung? Untersuchung eines spielebasierten Assessments in Anlehnung an den Zahlenverbindungstest (Bachelorthesis, Sportwissenschaft)
- Kronbach, Florian (2015). Effekte eines standardisierten körperlichen Lernprogramms auf eine motorische Schlüsselqualifikation (Sitzen-Stehen-Transfer) bei Patienten mit beginnender bis mittelgradiger Demenz (Dissertation, Medizin)
- Rosner, Rosner (2017). Analyse der Effekte eines demenzspezifischen, computergestützten kognitive-motorischen Trainings: Dosis-Wirkungs-Beziehung und Prädiktorenanalyse (Dissertation, Medizin)
- Tetz, Jessica (2015). Effekte eines standardisierten motorischen Lernprogrammes auf den Sitzen-Stehen-Transfer bei älteren Personen mit beginnender bis moderater demenzieller Erkrankung im Alltag (Bachelorthesis, Sportwissenschaft)

Anhang A: Erklärung gemäß § 8 Abs. (1) c) und d) der Promotionsordnung der Fakultät

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

FAKULTÄT FÜR VERHALTENS- UND EMPIRISCHE KULTURWISSENSCHAFTEN

Promotionsausschuss der Fakultät für Verhaltens- und Empirische Kulturwissenschaften der Ruprecht-Karls-Universität Heidelberg
Doctoral Committee of the Faculty of Behavioural and Cultural Studies of Heidelberg University

Erklärung gemäß § 8 (1) c) der Promotionsordnung der Universität Heidelberg für die Fakultät für Verhaltens- und Empirische Kulturwissenschaften
Declaration in accordance to § 8 (1) c) of the doctoral degree regulation of Heidelberg University, Faculty of Behavioural and Cultural Studies

Ich erkläre, dass ich die vorgelegte Dissertation selbstständig angefertigt, nur die angegebenen Hilfsmittel benutzt und die Zitate gekennzeichnet habe.
I declare that I have made the submitted dissertation independently, using only the specified tools and have correctly marked all quotations.

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Declaration in accordance to § 8 (1) d) of the doctoral degree regulation of Heidelberg University, Faculty of Behavioural and Cultural Studies

Ich erkläre, dass ich die vorgelegte Dissertation in dieser oder einer anderen Form nicht anderweitig als Prüfungsarbeit verwendet oder einer anderen Fakultät als Dissertation vorgelegt habe.
I declare that I did not use the submitted dissertation in this or any other form as an examination paper until now and that I did not submit it in another faculty.

Vorname Nachname
First name Family name Christian Werner

Datum, Unterschrift
Date, Signature 22.01.2020

Anhang B: Manuskripte zur publikationsbasierten Dissertation

Manuskript I
Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62* (6), 644-653. DOI: 10.1159/000444878

Manuskript II
Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2018). A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. *Disability and Rehabilitation: Assistive Technology*, *13*(1), 31-39. DOI: 10.1080/17483107.2016.1278470

Manuskript III
Werner, C., Moustris, G. P., Tzafestas, C. S. & Hauer, K. (2018). User-oriented evaluation of a robotic rollator that provides navigation assistance in frail older adults with and without cognitive impairment. *Gerontology, 64*(3), 278-290. DOI: 10.1159/000484663

Manuskript IV
Werner, C., Chalvatzaki, G., Papageorgiou, X. S., Tzafestas, C. S., Bauer, J. M. & Hauer, K. (2019). Assessing the concurrent validity of a gait analysis system integrated into a smart walker in older adults with gait impairments. *Clinical Rehabilitation, 33*(10), 1682-1687. DOI: 10.1177/0269215519852143

Manuskript V
Geravand, M., **Werner, C.,** Hauer, K. & Peer, A. (2016). An integrated decision making approach for adaptive shared control of mobility assistive robots. *International Journal of Social Robotics, 8*(5), 631-648. DOI: 10.1007/s12369-016-0353-z

Manuskript VI
Werner, C. Geravand, M., Korondi, P. Z., Peer, A., Bauer, J. M. & Hauer, K. Evaluating the sit-to-stand transfer assistance from a smart walker in older adults with motor impairments. *Geriatrics & Gerontology International.* DOI: 10.1111/GGI.13874

Manuskript VIII
Werner, C., Dometios, A. C., Maragos, P., Tzafestas, C. S., Bauer, J. M. & Hauer, K. Evaluating the task effectiveness and user satisfaction with different operation modes for an assistive bathing robot in older adults with bathing disability. Under review in *Assistive Technology*.

Manuskript VII
Werner, C., Kardaris, N., Koutras, P., Zlatintsi, A., Maragos, P., Bauer, J. M. & Hauer, K. Improving gesture-based interaction between an assistive bathing robot and older adults via user training on the gestural commands. *Archives of Gerontology and Geriatrics, 87, 103996.* DOI: 10.1016/j.archger.2019.103996.

Manuskript I

Werner, C., Ullrich, P., Geravand, M., Peer, A. & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62*(6), 644-653.

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Evaluation Studies of Robotic Rollators by the User Perspective: A Systematic Review

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Key Words
Systematic review · Evaluation studies · Ambient assisted living · Robotics · Rollator · Walker · Self-help devices · Human-robot interaction · Mobility · User experience

Abstract
Background: Robotic rollators enhance the basic functions of established devices by technically advanced physical, cognitive, or sensory support to increase autonomy in persons with severe impairment. In the evaluation of such ambient assisted living solutions, both the technical and user perspectives are important to prove usability, effectiveness and safety, and to ensure adequate device application. ***Objective:*** The aim of this systematic review is to summarize the methodology of studies evaluating robotic rollators with focus on the user perspective and to give recommendations for future evaluation studies. ***Methods:*** A systematic literature search up to December 31, 2014, was conducted based on the Cochrane Review methodology using the electronic databases PubMed and IEEE Xplore. Articles were selected according to the following inclusion criteria: evaluation studies of robotic rollators documenting human-robot interaction, no case reports, published in English language. ***Results:*** Twenty-eight studies were identified that met the predefined inclusion criteria. Large heterogeneity in the definitions of the target user group, study populations, study designs and assessment methods was found across the included studies. No generic methodology to evaluate robotic rollators could be identified. We found major methodological shortcomings related to insufficient sample descriptions and sample sizes, and lack of appropriate, standardized and validated assessment methods. Long-term use in habitual environment was also not evaluated. ***Conclusions:*** Apart from the heterogeneity, methodological deficits in most of the identified studies became apparent. Recommendations for future evaluation studies include: clear definition of target user group, adequate selection of subjects, inclusion of other assistive mobility devices for comparison, evaluation of the habitual use of advanced prototypes, adequate assessment strategy with established, standardized and validated methods, and statistical analysis of study results. Assessment strategies may additionally focus on specific functionalities of the robotic rollators allowing an individually tailored assessment of innovative features to document their added value.

C.W. and P.U. contributed equally to this work.

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Introduction

In older persons, the ability to move independently represents a hallmark of autonomous living [1] and quality of life [2], while being physically active is associated with numerous positive health outcomes [3, 4]. However, sensory, motor or cognitive impairments restrict mobility in frail, older persons [5]. Motor key functions such as standing, walking, or transfers are substantial challenges for their daily activities leading to high risk exposure of falls as documented in residents of senior homes [6]. Effects of motor impairment are augmented by sensory deficits such as visual impairment, leading to restricted functional independence [7], or by cognitive impairment, leading to spatiotemporal disorientation or executive dysfunction [8]. To overcome or compensate for such impairments and to improve the quality of life of affected persons, assistive devices as in walking aids (e.g. canes, walkers, rollators) have been developed with an early focus on mobility support. They provide support of postural stability and mobility [9], reduce risk of falling [10] and improve activity and participation [11]. However, such conventional mobility devices may not cover the needs of persons suffering from major functional or cognitive impairments.

In the context of ambient assisted living (AAL), robotically augmented rollators with various high-tech functionalities have been developed to provide physical, sensory and cognitive assistance, and/or health monitoring for further support [12]. The development and evaluation of such a robotic rollator (RR) is still a new, emerging research field mainly driven by technical engineering goals. However, as technical functionalities translate into assistive devices for the target population, the human-robot interaction and user perspective shift in the development focus. Apart from the sheer technical evaluation of concepts and functionalities, needs, requirements and preferences of potential users will have to guide the development and evaluation of assistive technology devices [13, 14]. In addition to technical testing, which verifies the functional capability of devices, an evaluation with focus on user performance, physical demands and subjective experiences of the RR is essential to prove the usability, ensure safety and demonstrate the added value for the intended user group. The change from technical to user perspective may, however, lead to specific methodological challenges including the study design and assessment strategy. To our knowledge, no systematic review on the evaluation of RRs with focus on the user perspective has been published. Therefore, the aim of this systematic review was to summarize the methodology of studies evaluating the human-robot interaction from a user perspective and to give recommendations for future evaluation studies.

Methods

Initial search terms were compiled and iteratively refined by team members with expertise in the clinical and in the technical research field. The literature search was conducted using the electronic databases PubMed and IEEE Xplore. Search terms included both controlled vocabulary (i.e. MeSH Terms, IEEE Terms) and keywords of relevance identified during searches. The detailed search strategy used in PubMed, which was modified for IEEE Xplore, is presented in the online supplementary table 1 (see www.karger.com/doi/10.1159/000444878 for all online suppl. material).

Manual searches were performed to identify additional studies by scanning reference lists of relevant articles and by reviewing key authors' own databases. Studies were searched with focus on the evaluation of an RR (or robotic wheeled walker) by experiments, trials, or interventions in human beings independent of the type of outcome measurement. No restrictions regarding age or health status of the subjects were made. Single case reports were excluded. For the purpose of this review, the term 'robotic' includes the normal function of a rollator enhanced by additional physical, sensory, or cognitive robotic support while walking, also including sit-to-stand transfers. Studies evaluating solely monitoring functionalities without taking into account any user supporting functionalities or the subjective user experience were excluded. The search was limited to articles in the English language published up to December 31, 2014.

The selection process was conducted following the methodology as described in the method guidelines of the Cochrane Collaboration [15]. Titles and abstracts were identified by the standardized search strategy. For abstracts which met the inclusion criteria or for those with unclear status, full-text articles were analyzed for inclusion. Each step of study selection, based on predefined eligibility criteria, was performed independently by 2 reviewers (P.U. and C.W.). Any disagreements were resolved by consensus or third-party adjudication (K.H.). After inclusion, data on the user group, sample characteristics and the methodological approach were extracted by 1 researcher (C.W.) and confirmed by 2 other researchers (P.U. and D.S.). If an article described more than one study, the results for each study were extracted separately.

Results

A total of 8,989 articles were identified through database searching, and another 79 were added through manual searches. After removing duplicates, the initial search resulted in 8,876 articles. Of these, 235 were found to be related to the search topic based on title and abstract. After reviewing full texts, 148 articles were excluded as they did not meet the predefined inclusion criteria (fig. 1). An-

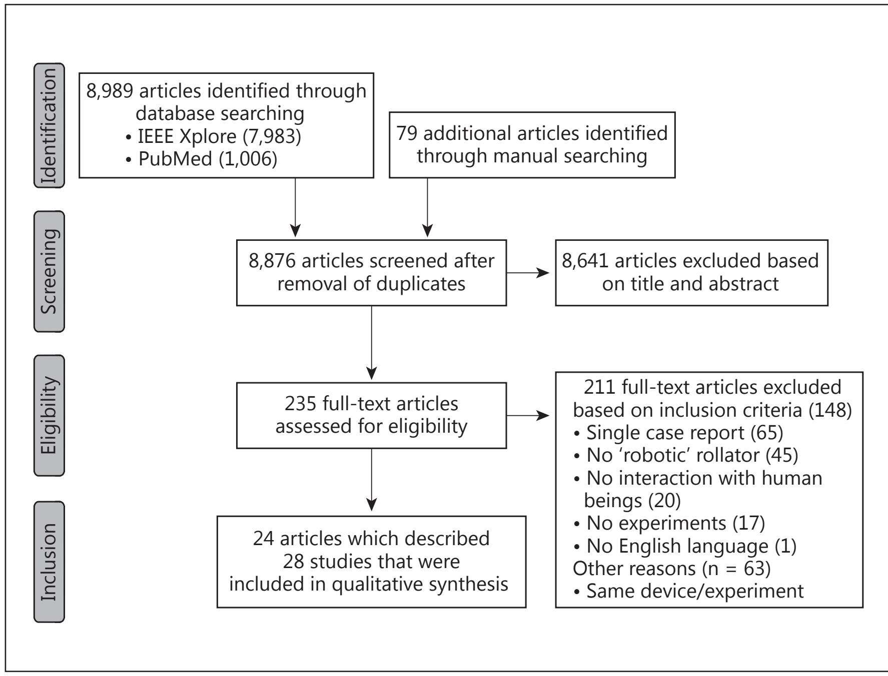

Fig. 1. Flowchart of the study selection process and extraction methodology.

other 63 were discarded, as these articles described either identical experiments with the same RR, or various stages of development of a certain RR. In both cases, the article providing the most comprehensive information with focus on the user perspective was included. If different articles contained similar information, the one with the most recent development stage was included. Twenty-four articles published between 2001 and 2015 were identified for inclusion in the review. As 2 articles reported on 2 [16, 17] and 1 article on 3 independent studies [18], the final data extraction was based on 28 studies[1]. The detailed review results extracted for each study are presented in the online supplementary table 2 , containing information on the names of devices, the definition of user groups, study sample, study object, study design and selected assessment methods.

User Group Definitions

Apart from 2 articles [19, 20], all mentioned a target user group for the RR; however, their definition differed substantially in accuracy and explicitness. Five articles provided a generic description in broad terms such as 'elderly (disabled) people' [21–25], 2 defined users by setting-specific characteristics such as 'persons in nursing and assisted living homes', partly amended by disease-related criteria (e.g. Alzheimer's disease, stroke) [26, 27], and 10 provided brief information on users' motor-functional (e.g. 'with mobility problems'), cognitive (e.g. 'with cognitive impairment') and/or visual status (e.g. 'visually impaired') [17, 18, 28–35], but without staging impairment levels based on any screening or assessment instrument. Three articles described users by disease categories (e.g. Parkinson's disease, hemiplegia) [16, 36, 37] without detailed information on the patients' functional impairment level. Specific impairment-related definitions based on established, validated assessment methods (i.e. Walking Index for Spinal Cord Injury [WISCI II], Functional Ambulation Classification) were documented in only 2 articles [12, 38].

Study Samples

The mean sample size of the studies was 7.2 [standard deviation (SD) ± 4.3]. The exact number of subjects was not reported in 5 studies [18[1–3], 35, 37]. No study presented a sample size calculation.

Samples differed considerably regarding age, impairments, or diseases. The age of subjects ranged from 14 [22] to 97 years [31] with age information lacking in half of the studies (14 of 28) [16[1], 17[1], 18[1–3], 20, 23, 25, 27–29, 35, 37].

[1] When necessary, the individual studies of these articles are distinguished with numeric coding (i.e. [16[1, 2], 17[1, 2], 18[1–3]]).

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Thirteen studies included subjects with motor, functional, cognitive, visual and/or neurological impairments [12, 16[1, 2], 17[1, 2], 26, 27, 30–32, 34, 36, 38], whereas a convenient (e.g. 'ordinary adult males') [19, 20, 23, 24, 33], mixed (e.g. 'healthy subjects and subjects with motor and cognitive impairment') [18[1–3], 21, 22, 29, 35, 37] or setting-specific sample (e.g. 'residents of retirement facility') [28] was used in 14 studies. In studies including impaired subjects, definitions and staging of the severity level of impairment were mostly absent (15 of 20) [17[1, 2], 18[2, 3], 22, 26, 29–32, 34, 35, 37, 38]. In only 6 studies were motor-functional or cognitive impairment levels defined by established and validated screening or assessment instruments [e.g. Timed Up and Go (TUG), Mini-Mental State Examination] [12, 16[1, 2], 21, 27, 36].

In 10 studies, subjects did not match with the predefined user group [18[1–3], 22–24, 27, 28, 33, 37]. However, due to the unspecific and wide-ranging user group definitions given in a number of articles, most studies (15 of 28) were carried out with subjects who were covered by these broad definitions [12, 16[1, 2], 17[1, 2], 21, 26, 29–32, 34–36, 38]. In three studies, a user group definition and/or a description of the study sample was completely missing [19, 20, 25].

Design of Studies

Depending on study objectives, three different types of studies were performed: (1) observational; (2) comparative, or (3) interventional.

Observational Studies

Fourteen articles reported on observational studies [12, 18, 20, 22, 24, 29, 35, 37] or single observational experiments as part of their studies [16, 17, 23, 26, 28, 33], focusing predominantly on the verification of technical capability and/or the subjective user evaluation of the RRs. User performance was used as the study object in only one of these studies [26]. In observational studies/experiments, outcomes were only descriptively presented, without providing any reference values.

Comparative Studies

Fourteen articles included comparative studies [19, 21, 25, 27, 28, 30–32, 34, 38] or single comparative experiments in addition to observations [16, 17, 26, 33]. Comparisons were further distinguished into four categories: (1) 'inter-device comparisons' in which RRs and conventional devices (e.g. cane, folding/wheeled walker) or fully unassisted walking/sit-to-stand transfers were compared [19, 21, 26, 27, 30, 32, 34, 38]; (2) 'intra-device comparisons' in which different assistance levels (e.g. activated vs. nonactivated obstacle avoidance), interface designs, or development stages of the same RR were compared [17[2], 19, 25–28, 30, 31, 33, 34]; (3) comparisons in a pre/post-test study design with focus on the user experience [34] or the technical functionality [23], assessed before and after/over a series of trials, and (4) comparisons between outcomes of a newly developed robotic monitoring functionality and those of an external criterion measure as a reference measurement [16[2]].

Interventional Studies

Two articles described studies that used an interventional approach, providing training opportunities with the RR [16, 36]. In one study, the subjects' gait performance with the robotic gait assistance system was assessed on 6 consecutive days [16[1]]. However, subjects seemed to use the RR only during test procedures and not in their daily routine. Although the ultimate research hypothesis for this 'interventional' approach was lacking, we assumed that the repeated use represented a type of training intervention in order for the subjects to get used to using the RR. In the other study, a 4-week randomized controlled trial was conducted to evaluate the effects of ambulation training with an RR compared to a traditional rehabilitation therapy method using parallel bars [36]. In this study, assessment methods were used to evaluate the subjects' motor-functional performance after the robot-assisted training intervention.

Statistical Analysis

An inferential statistical analysis of outcomes was included in only 3 studies [19, 34, 36]. In 25 studies, outcomes were presented using solely descriptive or qualitative data (e.g. frequencies, means, SDs and user comments) [12, 16[1, 2], 17[1, 2], 18[1–3], 20–33, 35, 37, 38].

Assessment Methods

Assessment measures used in identified studies can be classified into five categories: (1) established clinical performance-based measures assessing subjects' functional ability to perform a requested task by simple quantitative time-, range-, or rating-based outcomes (e.g. gait speed, walking distance, rating score) or by more detailed, qualitative outcomes captured by external technical measures (e.g. step time, double support time); (2) tailored assessment methods in terms of self-designed performance-based measures specifically tailored to specific functionalities of the RR (e.g. guidance system, obstacle avoidance). In addition to simple quantifiable time- or count-based outcomes (e.g. walking time, number of collisions), these assessment methods predominantly used more technique-based and qualitative outcomes (e.g. path deviation, distance to obstacle); (3) assessment methods used to evaluate the subject's physical and physiological demands during the use of the RR; (4) subjective evaluation measures to assess a user's experience with the RR, and (5) technical evaluation measures to assess the technical capability of the RR.

As technical evaluation measures used in 9 studies [12, 16[2], 18[1, 2], 20, 22–24, 33] exclusively focused on the technical verification of the RR with limited relevance for the user perspective, we do not further address and discuss these measures in this review.

Clinical Performance-Based Measures

Established clinical performance-based measures were used in 3 studies [21, 32, 36]. In one of these, the subjects' gait and functional performance with the RR were assessed by the 4-meter walk test (4MWT), a modified version of the TUG, and spatiotemporal gait parameters (i.e. step time, double support time) captured by video camera during both tests [21]. Other studies documented the subjects' motor performance by the 6-min walk test (6MWT), 10-meter walk test (10MWT) and Performance Oriented Mobility Assessment (POMA) [36], or only by the 10MWT [32]. The most frequently used outcomes were gait speed [21, 32, 36], completion time [21], or walking distance and rating scores for functional performance (POMA) [36].

In one study, an established screening test for assessing the functional ability of subjects to perform activities of daily living (ADL) was used (Barthel ADL Index) [36].

Tailored Assessment Measures

In 10 studies, assessment strategies included self-designed performance-based measures specifically tailored to specific robotic functionalities [16[1, 2], 17[2], 19, 25–28, 31, 34]. Obstacle avoidance and guidance systems were evaluated while subjects completed walking paths [25, 28] or obstacle courses [17[2], 31, 34], navigation and localization systems while performing navigational tasks [26, 27], and gait assistance systems by analyzing the subject's gait during robot-assisted walking [16[1, 2], 19]. Simple quantifiable outcomes of these tests included number of collisions [26, 31, 34], reorientations [34], navigational mistakes [27] or abnormal gait patterns [16[1, 2]], walking time [34], or achievement of task [26]. More specifically tailored, technique-based outcomes, as used in 8 studies, comprised of deviations from an optimal path [17[2], 25, 28, 31], distance to obstacles [17, 26], maximum speed and walking distance [26], mean and SD of robot's velocity [19] and gait variability (i.e. SD of gait speed/step length) [16[1, 2]]. To obtain such technically advanced outcomes, 5 studies used the data flow created by the technical systems installed on the RR, including laser rangefinders (LRF) [16[1, 2], 28], a video camera and sonar sensors [17[2]], or a web camera [31]. In the other 3 studies, information on the technical measure to capture these outcomes was nonexistent [19, 25, 26]. Out of the studies that determined outcomes with the robot-integrated technical systems, only one seemed to process raw data (LRF data) into outcome variables (i.e. path deviation) by using an already established method for robust position estimation of mobile robots in indoor environments ('Monte Carlo localization') [28]. In the other 4 studies, it remained unclear whether raw data were analyzed by self-designed or potentially established methods [16[1, 2], 17[2], 31].

In 2 inter-device comparative studies, a bicycle speedometer attached to the conventional device [16] or an LRF placed in the test environment [26] was used to assess technically advanced outcomes such as walking distance or gait variability also when not using the RR. However, a reference, or any information on the psychometric quality of these methods, was missing in both studies.

In 4 studies including tailored assessment measures, test procedures appear to be nonstandardized [16[2], 26, 34] or have been insufficiently described [28].

Evaluation of Physical and Physiological Demands

Four studies assessed subjects' physical and physiological demands with motorized RRs during time-based performance-based measures (i.e. navigational trail, 10MWT) [26, 32] or during walking with standardized gait speed [19, 33]. In 2 studies, the exertion of force applied to steer the RR was measured using the force/torque sensors integrated on the robot's handles [19, 26]. One also reported on forces required to operate a conventional walker, but did not mention the method to capture these forces [26]. The other study additionally evaluated the oxygen consumption (VO_2) and metabolic cost of transport (metabolic cost per unit of mass and distance travelled) during robot-assisted gait using open-circuit respirometry [19]. In the remaining 2 studies, the muscle activity in the lower extremities was recorded by electromyography (EMG) [32, 33], and one also measured torso kinematics by a tri-axial accelerometer attached to the subject's back [32].

Subjective Evaluation Measures

Nineteen studies included measures to evaluate the subjects' experience with the RR [12, 16[1], 17[1, 2], 18[1, 3], 19, 22–24, 26–30, 34, 35, 37, 38]. However, assessment instruments to perform such subjective evaluations varied widely in methodological quality. Nine studies documented solely nonspecific comments of nonstandardized surveys [16[1], 17[2], 18[1], 22, 24, 28, 29, 35, 37], 3 used standardized (dichotomous) questions [27, 30, 38], 4 used self-designed structured questionnaires, each with different multistage rating scales (e.g. 1–5, 0–100) [12, 17[1], 19, 34], 2 mentioned the use of questionnaires but did not provide detailed information on contents or a reference [18[3], 26], and 1 presented results of the subjective evaluation by response categories referring to different items but without mentioning the assessment instrument used for this purpose [23]. Most frequently used outcomes of standardized surveys included maneuverability [12, 17[1], 38], safety [12, 30, 38] and comfort [12, 19, 34].

Discussion

The aim of this systematic review was to summarize the methodology of evaluation studies of RRs with focus on the user perspective. Identified studies showed large heterogeneity in definitions of potential users, study population, study design and assessment methods. We found major methodological shortcomings related to insufficient sample descriptions and sample sizes, lack of appropriate, standardized and validated assessment instruments, and lack of statistical analysis of study results. No generic methodology to evaluate RRs could be identified.

User Group Definitions

The majority of user group definitions seemed inadequate to guide a technical development of an AAL system. Generic, setting-specific, nonspecific impairment-based or disease-oriented definitions do not relate to specific functional impairments of potential users, but cover users with a wide range of different functional abilities and requirements. The effective design of AAL systems in such heterogeneous user groups may not be feasible. The main goal of an AAL system should rather be to overcome or compensate for specific impaired functions. Clear impairment-related definitions are therefore mandatory to specifically tailor AAL developments for specific impairments of users and to ensure that innovative functionalities effectively address a user's needs. When such specific impairment-related definitions are additionally based on standardized and validated assessment methods with established cutoff values, a general comparability of developments and evaluations will be feasible.

Definitions according to impairment levels will in turn allow specifications such as risk stratification of potential users. With this, the user group will be further classified, opening up the option to exclude persons with no or minor impairment, with no need for assistive devices, or with advanced impairment or unacceptable risk exposure when using the device (triage). Another specification may focus on the main function of the specific device. For example, when an AAL system such as a RR basically supports gait performance, a specific definition based on standardized and validated gait assessment (e.g. 10MWT) will be superior compared to less specific definitions such as general functional scores (e.g. Barthel ADL Index).

As the user group of RRs may be old and multimorbid persons, also highly prevalent age-associated impairments might be included in the definitions, depending on the specific functionalities or complexity of devices (e.g. inclusion of cognitive impairment with respect to navigation functions in disoriented persons).

Study Samples

Overall, sample sizes seemed rather limited to give a consistent picture of the user perspective. Surprisingly, the statistical analysis of documented data was not in the focus of studies as only a very limited number included such analyses (3 of 28) and none of these presented a sample size calculation as a prerequisite of statistical analysis.

A remarkable number of studies (10 of 28) evaluated RRs in persons who were not covered by the predefined user group, considerably limiting the user perspective of these studies. Study results with inadequate, convenient or insufficiently described samples may not suffice to allow conclusions for persons with specific impairments which may represent the potential users of the RR. To ensure that RRs meet a user's needs and requirements and become successful on the market, it seems mandatory to involve the intended users at all stages of the design and evaluation process of such assistive robotic technologies [39–41].

Design of Studies

Observational Studies

The most heterogeneous group of studies covered observational studies that used solely descriptive data presentations without providing any reference or comparative values. Findings and conclusions of these studies were thus mainly based on the authors' subjective percep-

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tion and appraisal. However, when using standardized and validated outcome measures with well-established cutoff values or other assistive mobility devices for comparison, such observations lose their merely subjective and study-specific nature and enable the objective appraisal of outcomes related to other studies or the documentation of an added value of the RR compared to other devices. From a user as well as a technical perspective, observational studies that descriptively presented nonclassifiable or noncomparable outcomes therefore seem to have limited value.

Comparative Studies

The documentation and perception of an added value of the RR is of utmost importance for potential users. Innovative high-tech developments may be fascinating and mandatory for engineering research; however, they may also lead to rather complicated devices for everyday use, not easy to maneuver, too complex to operate, or too expensive to afford. A comparison of RRs with established, low-tech devices ('inter-device comparative study design') may therefore be useful to demonstrate to users the benefit of RR usage.

Comparisons may also be used for the evaluation of single functionalities to document the effect of a specified functionality (e.g. activated guidance system) or the progress of a new development stage. Such an 'intra-device comparative' study design allows a tailored assessment of the subjects' functional performances, physical and physiological demands, and user experience in specific assistance levels or development stages of the RR.

Frail, older persons may initially be intimidated by the robot's appearance in early stages of development (e.g. without casing, exposed hardware) which may in turn result in a more negative user perception before actually having used the RR. Subjective user evaluations, in a pre-/posttest study design, provide the opportunity to assess the subjects' initial impressions of the RR and whether there are potentially negative prejudices, which may, however, be overcome after actual use of the RR.

Independent of different types of comparative studies, such a study design should definitely include a statistical analysis to compare results, which was however seldom used in the identified studies.

Interventional Studies

An interventional study design represents a new aspect in evaluation studies with strong focus on the user perspective. Newly developed RRs may not necessarily meet a user's acceptance or provide usability and efficiency when using them for the first time. Insufficient training opportunities or instruction prior to assessment measures may jeopardize study outcomes [42]. An adequate practice time therefore seems mandatory to prevent initial problems in operating the RR and may further increase the impact on outcomes. Particularly when comparing RRs with a subject's own conventional assistive devices, brief instructions may not be sufficient, as subjects are already much more familiar and better trained with their own devices.

Overall, we identified a lack of studies investigating usability of RRs in natural environments with adequate long-term evaluation of habitual use. The development and evaluation of RRs seemed to occur rather in engineering laboratories than in clinical settings, as already reported for other robotic assistance systems (e.g. service robots, robotic exoskeleton) [43]. This may be explained by the fact that most of the identified studies evaluated research prototypes in rather early development stages, not yet ready for market launch. In such stages, it is important to manipulate specific variables of a prototype in order to investigate their effects precisely and to optimize technical functionalities accordingly [41]. Since laboratory evaluations also require less time and provide highly standardized conditions, a restricted experimental study design may have been favored. However, for the ultimate goal of RRs to assist mobility of impaired persons in daily life, tests for habitual use seem to be mandatory documenting risk, experience-based perception of use, and quality of life with high relevance for users as well as caregivers.

Assessment Methods

Clinical Performance-Based Measures

Internationally well-established, clinical performance-based measures allow a worldwide comparability of results, but may be insufficient to cover the particular added value of specific robotic functionalities (e.g. obstacle avoidance, navigation assistance) as the outcome variables do not necessarily refer to the subjects' abilities potentially affected by the RR [42]. In addition, clinical assessment methods may be limited by subjective rating (POMA) or limited with respect to less detailed, unidimensional outcomes such as gait speed (4MWT, 10MWT) or TUG. Augmenting such measures with technical assessment systems (e.g. video analysis system) allows a multidimensional analysis of the subjects' gait, including outcomes related to insecure gait or postural (in-)stability (e.g. width of base of support, double vs. single limb support) and reduction of the risk of falls as a main target of RRs.

Even established and validated assessment methods may have their limitations when inadequately used. Outcomes such as gait speed (4MWT) and task completion time (TUG) may be inappropriate when comparing a nonmotorized, conventional device with a motorized RR with limited maximum speed. In such comparisons, a superior outcome for the low-tech device seems almost mandatory and may indicate an insufficient selection of a study outcome. The use of ADL scales (e.g. Barthel ADL Index) to evaluate the effects of a robot-assisted ambulation training appears also inappropriate, since they include, if any, only very few sub-items targeting the subject's walking ability.

Another potential methodological pitfall may be related to performance-based outcome variables with ambiguous consequences: a motorized RR will improve gait speed in less impaired persons without substantial risk. However, improved performance may be traded off by a substantially higher risk of falling in more impaired persons.

Tailored Assessment Methods

The quality of an assessment strategy substantially depends on the appropriateness of methods with focus on the newly developed functionalities to document the added value of RRs. Clinical performance-based measures may be attractive because of their well-established psychometric properties; however, they have been developed for clinical purpose and may not cover new functionalities in innovative assistive technologies [42]. An assessment strategy specifically tailored to the specific functionality to be evaluated may help to achieve this goal. In RRs, depending on the functionalities installed, a huge data flow created by the robot-integrated sensing technique already exists to control motor or cognitive assistance systems. Using this data flow for assessment purposes may allow highly qualitative and quantitative tailored assessments exactly tuned to the newly developed functionality in order to document the added value of the RR. For example, when focusing on functionalities providing navigational assistance, the data flow from laser sensors, which is used to feed back the position of the RR, could be processed into a superior assessment of walking trajectories during a navigational task. When using such data for the purpose of assessment, it seems mandatory to examine or to provide sufficient information on the psychometric qualities of the robot-integrated sensor technique and the analysis method used to process raw data into the outcome variables. However, it appeared that only 1 study used an already established method for this approach [28]. Furthermore, to ensure reliable, reproducible and comparable outcomes, the test procedure of tailored assessment measures has to be also clearly standardized.

Evaluation of Physical and Physiological Demands

Measures such as EMG, respirometry, accelerometry, or measurements of applied steering forces to the RR allow a detailed insight into relevant physical and physiological effects on objective parameters, which may be indicators for the subject's individual physical exertion (e.g. VO_2, muscle activity). However, some of these rather laborious measures (e.g. EMG, respirometry) seem less amenable for old and multimorbid persons and may have therefore been used predominantly in studies including only young, healthy adults [19, 33]. To prevent overtaxing by test conditions, alternative methods to evaluate physical exertion are available which may increase amenability by standardized and validated subjective rating [e.g. 44].

Subjective Evaluation Measures

In studies including subjective evaluation measures, a wide range of methods (e.g. nonspecific comments, self-designed questionnaires) related to a variety of different aspects of the subject's experience with the RR was used which may considerably limit the comparability of outcomes. The overall lack of already established, validated questionnaires for the subjective evaluation of assistive technology [e.g. 45–47] might be due to two reasons: (1) established questionnaires have been developed for a generic evaluation of a wide range of assistive technology devices but may be limited for evaluating specific functionalities of individual devices [45]; (2) some questionnaire items may also be inappropriate to evaluate prototypes after a short-term experiment in a restricted test scenario, covering aspects such as quality of life, usability in daily routine, durability, or services [45–47] whose assessment may only be feasible after habitual use of the devices over an extended period of time. However, the subjective evaluation measures used in the identified studies rather targeted the subject's actual experience directly after using the RR. This may explain the use of self-developed questionnaires including items already assessable after short-term use in an artificial setting (e.g. maneuverability, safety, ease of use). However, only once these questionnaires have been validated before application and internationally established cutoff values are available, will such assessment instruments guarantee high psychometric quality and allow comparability of study results [48].

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Limitations

Only information available in the articles was evaluated in this review, although the authors may have used additional or more detailed methodology, not stated in the articles. The evaluation of AAL prototypes may require elaborate and costly ethical application, and study procedures ('Medical Product Act') may have prevented RRs to be tested in comprehensive studies with adequate sample sizes and the target user group as well as in natural environments with adequate long-term evaluation of habitual use. The role of clinical partners in AAL research projects may offer opportunities to solve such problems. Clinical partners may be able to provide specific impairment-based user group definitions, to recruit a satisfactory number of potentially adequate subjects and to investigate the habitual use of AAL systems in natural environments.

Conclusions

Apart from the heterogeneity, methodological deficits in most of the identified studies became apparent. Recommendations for future evaluation studies include: (1) clear definition of the target user group by valid, specific impairment-based criteria; (2) adequate selection of subjects with predefined inclusion criteria representative of potential users; (3) inclusion of other assistive mobility devices for comparison; (4) inclusion of the habitual use of advanced prototypes in evaluation rather than mere short-term, restricted, experimental test scenarios for single functionalities of prototypes not finalized for use in the target user group; (5) selection of established, standardized and validated assessment methods; (6) implementation of a specifically tailored assessment strategy, focusing on specific functionalities of the RR, and (7) statistical analysis of study results. These recommendations, given for RRs, may also apply in general to the development and evaluation of AAL systems with focus on the user perspective.

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References

1 Hirvensalo M, Rantanen T, Heikkinen E: Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. J Am Geriatr Soc 2000;48:493–498.

2 Groessl EJ, Kaplan RM, Rejeski WJ, Katula JA, King AC, Frierson G, Glynn NW, Hsu FC, Walkup M, Pahor M: Health-related quality of life in older adults at risk for disability. Am J Prev Med 2007;33:214–218.

3 Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, Salem GJ, Skinner JS: American college of sports medicine position stand. Exercise and physical activity for older adults. Med Sci Sports Exerc 2009;41:1510–1530.

4 McAuley E, Konopack JF, Motl RW, Morris KS, Doerksen SE, Rosengren KR: Physical activity and quality of life in older adults: influence of health status and self-efficacy. Ann Behav Med 2006;31:99–103.

5 Chaudhry SI, McAvay G, Ning Y, Allore HG, Newman AB, Gill TM: Geriatric impairments and disability: the cardiovascular health study. J Am Geriatr Soc 2010;58:1686–1692.

6 Rapp K, Becker C, Cameron ID, Konig HH, Buchele G: Epidemiology of falls in residential aged care: analysis of more than 70,000 falls from residents of Bavarian nursing homes. J Am Med Dir Assoc 2012;13:187.e1–6.

7 Raina P, Wong M, Massfeller H: The relationship between sensory impairment and functional independence among elderly. BMC Geriatr 2004;4:3.

8 Pai MC, Jacobs WJ: Topographical disorientation in community-residing patients with Alzheimer's disease. Int J Geriatr Psychiatry 2004;19:250–255.

9 Bateni H, Maki BE: Assistive devices for balance and mobility: benefits, demands, and adverse consequences. Arch Phys Med Rehabil 2005;86:134–145.

10 Graafmans WC, Lips P, Wijlhuizen GJ, Pluijm SM, Bouter LM: Daily physical activity and the use of a walking aid in relation to falls in elderly people in a residential care setting. Z Gerontol Geriatr 2003;36:23–28.

11 Salminen AL, Brandt A, Samuelsson K, Toytari O, Malmivaara A: Mobility devices to promote activity and participation: a systematic review. J Rehabil Med 2009;41:697–706.

12 Frizera-Neto A, Ceres R, Rocon E, Pons J: Empowering and assisting natural human mobility: the simbiosis walker. Int J Adv Robot Syst 2011;8:34–50.

13 European Commission: Guidelines on medical devices. Clinical evaluation: a guide for manufacturers and notified bodies. 2009. http://ec.europa.eu/health/medical-devices/files/meddev/2_7_1rev_3_en.pdf.

14 Schulz R, Wahl HW, Matthews JT, De Vito Dabbs A, Beach SR, Czaja SJ: Advancing the aging and technology agenda in gerontology. Gerontologist 2015;55:724–734.

15 Higgins J, Green S (eds): Cochrane Handbook for Systematic Reviews of Interventions 5.1.0. Chichester, John Wiley & Sons, 2011.

16 Mou W-H, Ming-Fang C, Chien-Ke L, Yuan-Han H, Shih-Huan T, Li-Chen F: Context-aware assisted interactive robotic walker for Parkinson's disease patients. IEEE/RSJ Int Conf Intell Robot Syst, Vilamoura, 2012, pp 329–334.

17 Yu H, Spenko M, Dubowsky S: An adaptive shared control system for an intelligent mobility aid for the elderly. Autonomous Robots 2003;15:53–66.

18 Bühler C, Heck H, Nedza J, Wallbruch R: Evaluation of the MOBIL walking and lifting aid; in Marincek C, Bühler C, Knops H, Andrich R (eds): Assistive Technology Added Value to the Quality of Life. Amsterdam, ISO Press, 2001, vol 10, pp 210–215.

19 Grondin SL, Li Q: Intelligent control of a smart walker and its performance evaluation. IEEE Int Conf Rehabil Robot, Seattle, 2013, pp 6650346.

20 Taghvaei S, Hirata Y, Kosuge K: Vision-based human state estimation to control an intelligent passive walker. IEEE/SICE Int Symp Syst Integr, Sendai, 2010, pp 146–151.

21 Rumeau P, Pasqui V, Vigourou N: A generic method for the assessment of smart walkers. Gerontechnology 2012;11:345.

22 Wasson G, Sheth P, Huang C, Alwan M: Intelligent mobility aids for the elderly; in Alwan M, Felder R (eds): Eldercare Technology for Clinical Practitioners. Totowa, Humana Press, 2008, pp 53–76.

23 Xu W, Huang J, Wang Y, Cai H: Study of reinforcement learning based shared control of walking-aid robot. IEEE/SICE Int Symp Syst Integr, Kobe, 2013, pp 282–287.

24 Ko C-H, Yi-Hung H, Yao-Tse C, Agrawal SK, Kuu-Young Y: Guidance and obstacle avoidance of passive robot walking helper based on receding horizon control. IEEE Int Conf Autom Sci Eng, Taipei, 2014, pp 1032–1037.

25 Hirata Y, Oscar C Jr, Asami H, Kosuge K: Human-adaptive motion control of active and passive type walking support system. IEEE Int Work Adv Robot Soc Imp, Nagoya, 2005, pp 139–144.

26 Graf B: An adaptive guidance system for robotic walking aids. J Comput Inf Technol 2009;17:109–120.

27 Kulyukin V, Kutiyanawala A, LoPresti E, Matthews J, Simpson R: iWalker: toward a rollator-mounted wayfinding system for the elderly. IEEE Int Conf Radio Freq Identif, Las Vegas, 2008, pp 303–311.

28 Morris A, Donamukkala R, Kapuria A, Steinfeld A, Matthews JT, Dunbar-Jacob J, Thrun S: A robotic walker that provides guidance. IEEE Int Conf Robot Autom, Pittsburgh, 2003, pp 25–30.

29 Glover J, Holstius D, Manojlovich M, Montgomery K, Powers A, Wu J, Kiesler S, Matthews J, Thrun S: A robotically-augmented walker for older adults. Technical report cmu-cs03-170. Pittsburgh, Computer Science Department, Carnegie Mellon University, 2003.

30 Chugo D, Asawa T, Kitamura T, Jia S, Takase K: A motion control of a robotic walker for continuous assistance during standing, walking and seating operation. IEEE/RSJ Int Conf Intell Robot Syst, St. Louis, 2009, pp 4487–4492.

31 Kikuchi T, Tanaka T, Tanida S, Kobayashi K, Mitobe K: Basic study on gait rehabilitation system with intelligently controllable walker (i-Walker). IEEE Int Conf Robot Biomim. Tianjin, 2010, pp 277–282.

32 Tamura T, Sekine M, Kuno H, Fujie M, Mori A, Andoh K: Evaluation of walkers for elderly people. IEEE Int Conf Eng Med Biol Soc, Istanbul, 2001, pp 1391–1392.

33 Jang J, Yu S, Han J, Han C: Development of a walking assistive service robot for rehabilitation of elderly people; in Takahashi Y (ed): Service Robot Applications. Rijeka, InTech, 2008, pp 139–158.

34 Rentschler AJ, Simpson R, Cooper RA, Boninger ML: Clinical evaluation of Guido robotic walker. J Rehabil Res Dev 2008;45:1281–1293.

35 Mori H, Kotani S, Saneyoshi K, Sanada H, Kobayashi Y, Mototsune A: Research and development project for practical use of robotic travel aid for the visually impaired. Int Conf Disab Virt Real Ass Tech, Veszprém, 2002, pp 123–130.

36 Annicchiarico R: Enhancing service delivering, improving quality of life, preserving independence through assistive technology. Stud Health Technol Inform 2012;180:14–18.

37 Lee J, Kyung K, Jongbae K, Won-Kyung S: Essential feedback on first prototypes of smart mobile walker and upper extremity assistive robot. Int Conf Ubiq Robot Amb Intell, Daejeon, 2012, pp 65–66.

38 Lee G, Ohnuma T, Nak Young C, Soon-Geul L: Walking intent-based movement control for JAIST active robotic walker. IEEE Trans Syst Man Cyber 2014;44:665–672.

39 Tsui K, Feil-Seifer D, Matarić M, Yanco H: Performance evaluation methods for assistive robotic technology; in Madhavan R, Tunstel E, Messina E (eds): Performance Evaluation and Benchmarking of Intelligent Systems. New York, Springer, 2009, pp 41–66.

40 Scherer M: The change in emphasis from people to person: introduction to the special issue on assistive technology. Disabil Rehabil 2002;24:1–4.

41 Salminen A, Petrie H: Evaluating assistive technology prototypes: laboratory or real life contexts? in Placencia Porrero I, Ballabio E (eds): Improving the Quality of Life for the European Citizen: Technology for Inclusive Design and Equality. Amsterdam, IOS Press, 1998, pp 414–419.

42 Fuhrer M: Assistive technology outcomes challenges met and yet unmet. Am J Phys Med Rehabil 2001;80:529–535.

43 Pearce A, Adair B, Miller K, Ozanne E, Said C, Santamaria N, Morris M: Robotics to enable older adults to remain living at home. J Aging Res 2012;2012:538169.

44 Borg G: Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982;14:377–381.

45 Demers L, Weiss-Lambrou R, Ska B: Development of the Quebec User Evaluation of Satisfaction with assistive Technology (QUEST). Assist Technol 1996;8:3–13.

46 Day H, Jutai J: Measuring the Psychosocial Impact of Assistive Devices: the PIADS. Can J Psychol 1996;9:159–168.

47 Scherer MJ, Cushman L: Measuring subjective quality of life following spinal cord injury: a validation study of the assistive technology device predisposition assessment. Disabil Rehabil 2001;23:387–393.

48 Bartneck C, Kulić D, Croft E, Zoghbi S: Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. Int J Soc Robotics 2009;1:71–81.

Table 1. Overview of the search term used in PubMed

Assistive mobility device	Robotic functionality	Gait/mobility support	Evaluation measure
#1 ‘robotics’[Mesh]	#14 ‘electric power supplies’[Mesh]	#23 ‘gait’[Mesh]	#32 ‘evaluation studies as topic’[Mesh]
#2 ‘walkers’[Mesh]	#15 robot*[tiab]	#24 ‘Walking’[Mesh]	#33 ‘Technology Assessment, Biomedical’[Mesh]
#3 ‘self-help devices’[Mesh]	#16 smart[tiab]	#25 ‘Dependent Ambulation’[Mesh]	#34 evaluat*[tiab]
#4 ‘biomedical technology’[Mesh]	#17 intelligent[tiab]	#26 gait[tiab]	#35 assess*[tiab]
#5 robot*[tiab]	#18 power*[tiab]	#27 walk*[tiab]	#36 measur*[tiab]
#6 rollator*[tiab]	#19 electric[tiab]	#28 ambulant*[tiab]	#37 trial*[tiab]
#7 mobile platform*[tiab]	#20 motorized[tiab]	#29 mobility[tiab]	#38 experiment*[tiab]
#8 mobility aid*[tiab]	#21 motorised[tiab]	#30 OR (#23-#29)	#39 test*[tiab]
#9 mobility device*[tiab]	#22 OR (#14-#22)	#31 (#13 AND #22 AND #30)	#40 clinical[tiab]
#10 assistive device*[tiab]	#23 (#13 AND #22)		#41 OR (#32-#40)
#11 assistive system*[tiab]			#42 (#13 AND #22 AND #30 AND 41)
#12 walking aid*[tiab]			
#13 OR (#1-#12)			

Table 2. Study characteristics and assessment methods of the 28 studies included in this systematic review

Name of device Authors [Ref. No.]	User group definition	Study sample	Study object	Study design	Assessment methods Type: outcome measurement: outcome variable
Context-aware Assisted Interactive RObotic Walker (CAIROW) Mou et al. 2012 [16[1,2]]	PD patients	Study 1 n = 6 (F = n/a) Age: n/a PD patients of senior care unit; mHY, stage range 1.5-3	UP	IV: repeated assessment on six consecutive days	TAM: gait analysis on straight walking path[b]; CAIROW gait analysis system (based on LRF)[b]: SD of gait speed/step length; expert rating of gait[d]: number of abnormal gait patterns (festinating gait, freezing of gait)
			UE	OB	SEM: user comments[c] after gait analysis
		Study 2 n = 7 (F = n/a) Mean age: 86 yrs PD patients of senior care unit; mHY, stage range 1-3	UP	Inter-DC: walking with CAIROW vs. normal walking (with own/ without assistive device)	TAM: gait analysis on walking path with obstacles, people randomly passing by, up- and down-going slopes, short section for backward walking[d]; CAIROW gait analysis system[b] or LRF[c] placed in test environment when normal walking: SD of gait speed/step length; expert rating of gait[d]: number of abnormal gait patterns
			TC (gait analysis system)	EC: gait analysis system vs. expert rating	TEM (see original article for details)
Care-O-bot II Graf 2009 [26]	Elderly people in home environment	n = 6 (F = 5) Age range: 86-92 yrs Inhabitants of an old people's residence using mobility aids in daily life	UP, PD	Inter-/intra-DC: target mode (robot-determined motion control) vs. direct control mode (user-determined motion control) vs. conventional walker	TAM: navigation trail in old people's residence with a ramp, tables, and people randomly passing by[d]; robot's guidance system[c], bicycle speedometer[c] mounted on conventional walker: walking time, number of collisions, maximum speed, walking distance, distance to obstacle PHY: force/torque sensors[c] in robot's handles, force measurement when using conventional walker not reported[d]: pushing force
			UP	OB	TAM: navigation trail in old people's residence with transition between ground floor and 1[st] floor, a ramp, tables, people randomly passing by[d]: achievement of target
			UE	OB	SEM: questionnaire[b] after navigation trail: n/a
Chugo group walker Chugo et al. 2009 [30]	Elderly people in need for nursing in daily routine	n = 7 (F = n/a) Age: ≥ 67 yrs People in need of long-term care at level I or II in Japanese Long-term Insurance System	UE	Inter-/intra-DC: STS transfer without assistance vs. with previous/novel STS assistance system	SEM: questionnaire[b] after STS transfer : ease of standing up, fear of falling (1= inferior, 3 = same, 5 = better feeling compared to STS transfer without assistance)
CO-Operative Locomotion Aide (COOL-Aide) Wasson et al. 2008 [22]	Elderly people	n = 12 (F = 2) Mean age (SD): 36.8 (18.1) yrs Healthy subjects (n = 8), subjects with disorders affecting mobility (cerebral palsy, familial torsion dystonia) (n = 8) note: (1) total sample, (2) - (5) subsample: only healthy subjects	TC (guidance, user intent detection and obstacle avoidance system)	OB	TEM (see original article for details)
			TC (obstacle avoidance system with vs. without stability preservation)	Intra-DC: standard vs. stability-preserved obstacle avoidance	TEM (see original article for details)
			UE	OB	SEM: user comments[d] after performing a set of short obstacle courses
Gait Rehabilitation Service Robot (GRSR) Jang et al. 2008 [33]	Disabled or elderly with mobility problems or paralysis; weighing up to 75 kg	n = 2 (F = 0) Mean age (SD): 28.5 (2.1) yrs Ordinary adult males	TC (guidance system)	OB	TEM (see original article for details)
			PD	Intra-DC: 40/20 % body weight support vs. full body weight	PHY: EMG[a] during straight walking with standardized gait speed of 0.2 m/s: muscle activity of lower extremities (EMG signal) (quadriceps, hamstrings, gastrocnemius, tibialis anterior)

Table 2. (continued)

Name of device Authors [Ref. No.]	User group definition	Study sample	Study object	Study design	Assessment methods Type: outcome measurement: outcome variable
Guido Rentschler et al. 2008 [34]	Frail elderly people with visual impairment	n = 17 (F = n/a) Mean age (SD): 85.3 (7.0) yrs Residents of a supportive living facility/nursing home with visual impairment due to macular degeneration, cataract, glaucoma or other reasons; mean time (SD) since onset of visual impairment: 20.4 (13.0) yrs; ambulatory (≥ 20 min within 90 min period) with limited assistance	UP UE	Inter-/intra-DC: Guido vs. conventional assistive mobility device or normal walking (with own/ no assistive device); automatic (user-determined motion control) vs. manual mode (shared user-robot motion control) PPC: before and after 3 trials	TAM: obstacle course with randomly placed obstacles before each trial[d]: walking time, number of obstacle/wall collisions, number of reorientations SEM: Subjective Mobility Questionnaire[b] after obstacle course: appearance, ease of use, usefulness in living enviroment, embarrassment (1 = best score; 5 = worst score)
Hitachi walker Tamura et al. 2001 [32]	Elderly people who have difficulty walking	n = 6 (F = n/a) Mean age (SD): 82 (7.9) yrs Subjects ambulatory with supervision (n = 4), subjects in need for walking assistance (n = 2)	UP PD	Inter-DC: Hitachi vs. caster vs. conventional walker; robot vs. parallel bars	CPM:10MWT[a]: gait speed PHY: EMG[c], tri-axial accelerometer[c] during non-standardized gait speed (10MWT): muscle activity (EMG signal), trunk acceleration
HUST walking-aid robot Xu et al. 2013 [23]	Elderly or disabled people	n = 3 (F = n/a) Age: n/a Volunteering subjects with/ without experience using robot; one subject with restricted knee joint to imitate lower limb disorders	TC (motion control system) UE	PPC: autonomous learning process of HUST in motion behavior over a series of trials OB	TEM (see original article for details) SEM: subjective evaluation after completing a series of obstacle courses, assessment measure not reported[d]: flexibility, comfort, maneuverability, obstacle avoidance
i-Go Ko et al. 2014 [24]	Elderly people	n = 3 (F = n/a) Age: “in their twenties”	TC (guidance system) UE	OB	TEM (see original article for details) SEM: user comments[d] after completing an S-shaped walking path
Intelligent Mobility Platform (IMP) Glover 2003 [29]	Older adults (primarily without major visual or cognitive impairment)	n = 6 (F = n/a) Age: n/a Residents of a care facility with/ without need for walker	UE	OB	SEM: user comments[d] after presentation and informal testing of the robot
iWalker Kulyukin et al. 2008 [27]	Persons with stroke, early- to mid-stage AD, traumatic brain injury, macular degeneration, cataracts, visual impairment; primarily in nursing and assisted living homes	n = 4 (F = n/a) age: n/a Clients of in-home supportive service currently using cane, walker or bot, with history of way finding problems; MMSE, mean score (SD): 26 (3.6)	UP UE	Inter-DC: iWalker vs. conventional device (cane/walker) accompanied by researcher Intra-DC: map-based (+ auditory cues) vs. text-and-arrow-based (+ auditory cues) user interface design	TAM: several navigation trails[b] : walking time, number of navigational mistakes SEM: dichotomous question[b]: choice of user interface; user comments[d]

Table 2. (continued)

Name of device Authors [Ref. No.]	User group definition	Study sample	Study object	Study design	Assessment methods Type: outcome measurement: outcome variable
i-Walker (EU) Annicchiarico 2012 [36]	Post-stroke patients with hemiparesis	n = 20 (F = 11) Mean age: 59.9 yrs Acute hemiparetic stroke patients (event < 1 yrs) receiving rehabilitation treatment; MMSE score ≥ 20; CNS upper & lower limb > 0	UP	IV (RCT): robot-assisted ambulatory training (EG) vs. in parallel bars (CG) (4 weeks, 5x a week)	CPM: POMA[a]: total score; 6mWT[a]: walking distance; 10MWT[a]: gait speed ADL screening: Barthel ADL Index[a]: score
i-Walker (Japan) Kikuchi et al. 2010 [31]	Patients with imbalanced motor/sensory functions (e.g. hemiplegic patients), difficulties in smooth walking	n = 6 (F = 2) Mean age (SD): 88.7 (6.1) yrs Residents of elder care facility with wheelchair due to loss of vision/muscle strength which occasionally train walking with forearm caster walker; chronic disease: stroke, dementia, muscle atrophy, high blood pressure, heart failure, AD, cataract, PD	UP	Intra-DC: passive vs. active robot motion control system	TAM: walking path with obstacles[b], robot-integrated web camera[c]: deviations from a path marked on the floor, number of collisions
JAIST Active Robotic Walker (JARoW) Lee et al. 2014 [38]	Elderly people with certain level of ambulatory capability (FAC score 4-5)	n = 5 (F = 4) Age range: 75-84 yrs Subjects using traditional walkers in daily routine	UE	Inter-DC: JARoW vs. conventional walker	SEM: questionnaire[b] after walking around for 10 min: ease of walking, safety, maneuverability, suggestions for improvements
MOBIL walking & lifting aid Bühler et al. 2001 [18[1]]	Frail, elderly and walking disabled people	<u>Study 1</u> n ≥ 2 (F = n/a) Age: n/a Selected users, technical and rehabilitation experts	TC (overall system functionality) UE	OB	TEM (see original article for details) SEM: user/expert ratings, comments and interviews[d]
MOBIL test bed [18[2]]	Frail, elderly and walking disabled people	<u>Study 2</u> n ≥ 2 (F = n/a) Age: n/a Rehabilitation engineers, walking impaired persons	TC (overall system functionality)	OB	TEM (see original article for details)
MOBIL walking & lifting aid, MOBIL test bed [18[3]]	Frail, elderly and walking disabled people	<u>Study 3</u> n ≥ 2 (F = n/a) Age: n/a Community-dwelling people, institutionalized elderly disabled people, care staff	UE	OB	SEM: questionnaire[b] after demonstration, video presentations, practical trials: n/a

Table 2. (continued)

Name of device Authors [Ref. No.]	User group definition	Study sample	Study object	Study design	Assessment methods Type: outcome measurement: outcome variable
Nomad XR 4000 Morris et al. 2003 [28]	Frail older people with cognitive impairment	n = 4 (F = n/a) Age: n/a Residents of a retirement facility	UP	Intra-DC: passive (no navigational assistance) vs. active (with navigational assistance) vs. forced mode (full robot motion control)	TAM: navigational trail[d]; robot's navigation system (based on LRF, 'Monte Carlo localization')[a]: deviation from optimal path
			UE	OB	SEM: user comments after navigational trails[d]
Personal Aid for Mobility and Monitoring (PAMM SmartWalker) Yu et al. 2003 [17[1,2]]	Independently living or institutionalized elderly people with mobility difficulties due to physical frailty and/or disorientation due to age and sickness	Study 1 n = 8 (F = n/a) Age: n/a Elderly residents of assisted living facility with mobility aid	UE	OB	SEM: questionnaire[b] after free driving at facility: ease of control, going straight, turning, heaviness, support, satisfaction (1 = worst score, 5 = best score)
		Study 2 n = 8 (F = 5) Age range: 84-95 yrs Elderly residents of assisted living facility with need for walkers	UP	Intra-DC: full robot motion control vs. adaptive shared user-robot motion control vs. without any motion control	TAM: wall-limited walking path through assisted living facility[d]; robot's vision-based localization system (based on charged-coupled device camera)[b]: deviations from robot-generated, pre-planned path, distance to wall
			UE	OB	SEM: user comments[d]
Robotic Mobility Platform (RMP) Grondin & Qinggou 2013 [19]	n/a	n = 10 (F = 5) Mean age (SD): 24.6 (3.0) Subjects without previous/current gait-related injuries and without experience in using rollators or robotic walkers	UP, PD	Intra-DC: novel vs. previous motion control system	TAM: walking with targeted velocity of 1 m/s through a circular path in low-traffic hallways[b]; technical outcome measurement not reported[d]: mean and SD of robot velocity; PHY: force/torque sensor[a] under robot's left handle: pushing force
			PD	Inter-/intra-DC: novel vs. previous motion control system vs. conventional rollator vs. no assistive device	PHY: walking with targeted velocity of 1 m/s through the circular path[c] (use of a Hall effect sensor mounted on the conventional rollator to display target velocity); respirometry[a]: metabolic cost of transport, oxygen consumption
			UE	Intra-DC: novel vs. previous motion control system	SEM: questionnaire[b]: comfort, intuition, speed control, exertion, overall experience (0 = worst score, 5 = best score)
robuWALKER Rumeau et al. 2012 [21]	elderly people	n = 8 (F = 5) Mean age (SD): 82.6 (8.7) yrs Healthy elderly (n = 4): 4MWT < 4s, TUG < 13s, MMSE score ≥ 26; elderly patients with motor & cognitive impairment (n = 4): 4MWT > 4s, TUG > 13s, MMSE mean score (SD): 20 (3.5); all subjects without experience in using walking frames	UP	Inter-DC: robuWalker vs. conventional walker	CPM: 4MWT[a]: gait speed, modified TUG[a]: completion time; gait analysis by video recordings[c] during 4MWT and TUG: step time, double support time

Table 2. (continued)

Name of device Authors [Ref. No.]	User group definition	Study sample	Study object	Study design	Assessment methods Type: outcome measurement: outcome variable
Robotic Travel Aid (RoTA) Mori et al. [35]	visually impaired community-dwelling people, hospital patients, or residents of senior homes loss of ability to walk with mobility aids for the blinds	n > 60 (F = n/a) Age: n/a Blind and weak-sighted elderly people	UE	OB	SEM: user comments[d] after walking course
RT Walker Taghvaei et al. 2010 [20]	n/a	n = 2 (F = n/a) Age: n/a	TC (motion control system)	OB	TEM (see original article for details)
SIMBIOSIS Walker Frizera-Neto et al. 2011 [12]	SCI patients mainly using wheelchair, but usually able to walk for short periods of time with assistance of device, WISCI II = 16	n = 8 (F = n/a) Age: n/a Subjects with preserved cognitive functions; ability to (1) maintain standing position, (2) walk 10 m without assistance of another person and with or without support of a mobility aid, and (3) to grasp; WISCI II, mean score (SD): 15.9 (2.9)	TC (user intent detection system) UE	OB OB	TEM (see original article for details) SEM: questionnaire[b] after completing U-shaped walking path: maneuverability, safety, posture & comfort (0 = worst score, 100 = best score)
Smart Mobile Walker (SMW) Lee et al. 2012 [37]	elderly people, people with hemiplegia, people with incomplete SCI	n ≥ 2 (F = n/a) Age: n/a Stroke patients, SCI patients, clinical experts	UE	OB	SEM: user comments/interviews[d] after demonstrations
Walking Helper Hirata et al. 2005 [25]	elderly people, disabled people	n = 8 (F = n/a) Age: n/a	UP	Intra-DC: novel vs. traditional motion control system	TAM: following S-shaped walking path[b] (marked on the floor); technical outcome measurement not reported[d]: deviation from path marked on the floor

Abbreviations: PD = Parkinson's disease; F = females; n/a = not available; mHY = modified Hoehn and Yahr Scale; UP = User performance; UE = User experience; IV = interventional; OB = observational; TAM = tailored assessment measure; LRF = laser rangefinder; SD = standard deviation; SEM = subjective evaluation measure; TC = technical capability; inter-DC = inter-device comparative; EC = comparison with external criterion measure; TEM = technical evaluation measure; PD = physical/physiological demands; intra-DC = intra-device comparative; PHY = evaluation of physical or physiological demands; STS = sit-to-stand; EMG = electromyography; PPC = pretest-posttest comparative; CPM = clinical performance-based measure; 10MWT = 10-meter walk test; MMSE = Mini-Mental State Examination; CNS = Canadian Neurological Scale; RCT = randomized controlled intervention trial; EG = experimental group; CG = control group; POMA = Performance Oriented Mobility Assessment; 6mWT = 6-minute walk test; ADL = activities of daily living; AD = Alzheimer's disease; FAC = Functional Ambulation Classification; TUG = Timed Up and Go; 4MWT = 4-meter walk test; WISCI = Walking Index for Spinal Cord Injury; SCI = Spinal Cord Injury.

[a] established, standardized and validated assessment test or outcome measurement.
[b] standardized, but not validated test procedure or outcome measurement.
[c] potentially an established outcome measurement, but no reference given.
[d] non-standardized or unclear test procedure or outcome measurement.

Manuskript II

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A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users

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ABSTRACT

Purpose: To evaluate the effectiveness and perception of robotic rollators (RRs) from the perspective of users.

Methods: Studies identified in a previous systematic review published 2016 on the methodology of studies evaluating RRs by the user perspective were re-screened for eligibility based on the following inclusion criteria: evaluation of the human-robot interaction from the user perspective, use of standardized outcome measurements, and quantitative presentation of study results.

Results: Seventeen studies were eligible for inclusion. Due to the clinical and methodological heterogeneity across studies, a narrative synthesis of study results was conducted. We found conflicting results concerning the effectiveness of the robotic functionalities of the RRs. Only a few studies reported superior user performance or reduced physical demands with the RRs compared to unassisted conditions or conventional assistive mobility devices; however, without providing statistical evidence. The user perception of the RRs was found to be generally positive.

Conclusions: There is still no sufficient evidence on the effectiveness of RRs from the user perspective. More well-designed, high-quality studies with adequate study populations, larger sample sizes, appropriate assessment strategies with outcomes specifically tailored to the robotic functionalities, and statistical analyses of results are required to evaluate RRs at a higher level of evidence.

IMPLICATIONS FOR REHABILITATION

- RRs cover intelligent functionalities that focus on gait assistance, obstacle avoidance, navigation assistance, sit-to-stand transfer, body weight support, or fall prevention.
- The evaluation from the user perspective is essential to ensure that RRs effectively address users' needs, requirements and preferences.
- The evidence on the effectiveness of RRs is severely hampered by the low methodological quality of most of the available studies.
- RRs seem generally to be perceived as positive by the users.
- There is very limited evidence on the effectiveness and benefits of RRs compared to conventional assistive mobility devices.
- Further research with high methodological quality needs to be conducted to reach more robust conclusions about the effectiveness of RRs.

KEYWORDS: Assistive technology, mobility, robotics, walkers, systematic review, evaluation studies, human-robot interaction

INTRODUCTION

The maintenance of mobility is fundamental for the quality of life, wellbeing, and autonomous life of older people [1,2], and being physically active is associated with numerous positive health outcomes in this population [3-5]. Impaired mobility is, however, common among the elderly [6,7] and has been shown to be a risk factor for subsequent disability, loss of independence, and mortality [2,8,9].

To enhance mobility, extend independent living and, ultimately, to improve the quality of life of affected people, assistive mobility devices (AMDs) such as walkers, which are used more than any other AMD except the cane [10], have been developed with early focus on physical support [11]. However, as mobility in the elderly may not only be restricted by motor but also by sensorial and/or cognitive impairments [12], conventional AMDs (i.e. canes, crutches, walkers, rollators) may not be sufficient to cover the needs of persons suffering from such additional geriatric deficits.

Recent advances in robotics have made it possible to develop a new class of more intelligent walkers by integrating robotic technology, electronics and mechanics [13]. According to the user's needs, these so-called 'smart walkers', 'robotic walkers', or 'robotic rollators' (RRs) are not restricted to their primary focus, i.e. physical support, but are capable of providing mobility assistance in different functional domains [14,15]. Overall, RRs have evolved to provide physical support, sensorial and cognitive assistance, and/or health monitoring [16]. More specifically, they may cover robotic functionalities that focus on gait assistance [17], sit-to-stand (STS) transfer [18-20], partial body weight support (BWS) [21,22], obstacle avoidance [23-25], navigation assistance [26-28], and/or fall prevention [29,30]. A more detailed survey of the various high-tech functionalities of RRs can be found in Martins et al. [31,32].

An important part in the development process of RRs represents the verification of the technical capability of the devices and their functionalities. However, in addition to such technical testing, an evaluation that considers the user perspective in terms of the user's performance, physical demands and satisfaction with the RRs is also essential to enable and optimize a user-focused development, to prove the usability and effectiveness, and to document the potential added value of the innovative, robotic functionalities for the intended user group [33]. In general, to ensure that assistive technology devices meet the needs, requirements and preferences of users and to become successful on the market, the product development and such evaluation processes have to be closely aligned and guided by continuous end-user input at all stages [31,34,35].

The evaluation of RRs from the user perspective seemed to be associated with significant methodological challenges [31,36]. In our recent systematic review on the methodology of studies evaluating RRs by the user perspective, the identified studies showed large heterogeneity in study population, design of studies/test scenarios, and assessment methods. No generic methodology to evaluate RRs from the user perspective could be identified [19]. We also found major methodological shortcomings related to insufficient sample sizes, lack of appropriate standardized and validated assessment methods, and lack of statistical analyses of study results.

The evidence of the effectiveness and positive user perception of the RRs might have been substantially influenced by these study limitations and different methodological approaches. However, as we did not report the results of the studies identified in our previous review, we were so far not able to address this topic. To our knowledge, also no other systematic review has been published on the results of studies evaluating RRs by the user perspective. Therefore, the purpose of this article is to summarize and review study results reported for the evaluation of RRs from the user perspective.

METHODS

This review involved studies identified in our previous systematic review on the methodology of studies evaluating RRs by the user perspective [33]. The literature search, inclusion criteria, and study selection process of the previous systematic review have been described there in detail, so only relevant information for the analysis of study results are reported here. The systematic literature search in the electronic databases PubMed and IEEE Xplore, reference lists of relevant publications, and key author's own databases was performed there until December 31, 2014. The studies identified by this search were re-screened and assessed for eligibility in the current review based on the following inclusion criteria: (1) evaluation of the human-robot interaction (HRI) from the user perspective; (2) use of a standardized outcome measurement, and (3) quantitative presentation of study results. The selection process was performed by two independent reviewers (C.W. and P.U.). Disagreement was resolved by consensus or third-party adjudication (K.H.). After inclusion, relevant data were extracted by 1 researcher (C.W.) and confirmed by another researcher (P.U.).

RESULTS

After removing duplicates, screening titles and abstracts, and assessing the full-text articles, our previous systematic review covered 28 studies [33]. Of these, 11 studies were excluded after re-screening for eligibility in the current review as four did not present quantitative data on study results, four did not use standardized outcome measurements, two did not provide sufficient information on the outcome measurement used, and one did not evaluate the HRI by the user perspective (see Figure 1).

[Figure 1 near here]

The remaining 17 studies were reviewed and review results were extracted in table format, containing information on the names of RRs, study sample, robotic functionality to be tested, design of studies/test scenarios, assessment methods, and study results (see Table 1).

The methodology of identified studies was described and discussed in detail in our previous systematic review [33]. In this article, we extracted only information on the study methodology relevant for an adequate presentation, understanding, and discussion of the study results.

[Table 1 near here]

Study sample

The sample size of included studies averaged 7.7 ± 4.5 subjects (range, 2-20). The mean age of subjects ranged from 25 [37] to 89 years [38], with age information lacking in four studies [17,25-27]. Study samples differed considerably across studies, covering impaired subjects (e.g. motor, functional, cognitive, visual, and/or neurological) [16-18,23,25,26,28,38-41], healthy young adults [22,37], healthy and impaired elderly [42], or setting-specific subjects (i.e. residents of retirement facility) [27].

Design of studies and test scenarios

Seventeen articles described comparative studies or test scenarios in which RRs were compared with conventional AMDs or unassisted walking/STS transfers ('inter-device comparison') [17,18,23,28,37,40-42], or in which different assistance levels (e.g. activated vs. non-activated navigation assistance) [22,23,25,27,28,38], development stages [18,37] or user-interface designs [26] of the same RR were compared to each other ('intra-device comparison'). Three articles reported on observations and provided only descriptive data without any reference or comparative values for classification of study results [16,25,28]. Two articles described interventional studies that evaluated the effects of an RR-assisted ambulation training compared to traditional ambulation training on parallel bars [39] or of the repeated use of a RR over six consecutive days [17]. One article described a test scenario in pre-post-test design in which the subjective user perception of the overall RR functionality was assessed before and after a series of trials [23].

Assessment methods

Depending on the specific RR to be evaluated, assessment methods addressed different robot-integrated functionalities. Eight studies evaluated the physical support [17,18,22,37,39,41,42], four the navigation assistance [25-28] and four the sensorial assistance functionality of the RR [23,25,28,38]. Six studies included (also) assessment methods that addressed no specific assistance functionality but rather the overall functionality of the RR [16,23,25,28,37,40].

Physical support

The ability of the RR in supporting users' gait and motor-functional performance was assessed by clinically well-established walking and functional mobility tests (4-Meter Walk Test [4MWT], 10-Meter Walk Test, [10MWT], Timed Up and Go [TUG]) [41,42], gait analysis methods [17,42], self-designed walking paths [37], a subjective expert rating of abnormal gait patterns (festinating gait, freezing of gait) [17], or a single dichotomous question on the ease of walking with a RR [40]. The most frequently used outcome of these assessment methods was gait speed or RR velocity [37,41,42].

The STS functionality of the RR was evaluated by a self-designed user questionnaire on the ease and confidence of standing up with the RR [18].

The physical demands when using the RRs was evaluated by measuring the exertion of force applied to steer the RR [28,37], the oxygen consumption and metabolic cost of transport (COT, metabolic cost per unit of mass and distance travelled) [37], the torso kinematics and/or the muscle activity in lower limbs [22,41] during time-based performance tasks (navigation trail, 10MWT) or during walking with standardized gait speed.

To investigate the potential of the RR as rehabilitation training device, the subjects' gait and motor-functional performance and ability in activities of daily living (ADLs) were assessed by the 6-Min Walk Test (6MWT), 10MWT, Performance Oriented Mobility Assessment (POMA), and the Barthel ADL Index [39].

Cognitive assistance

Robotic functionalities that aimed to assist navigation and localization were evaluated on self-designed navigation trails [25-28]. Outcomes related to subjects' navigation performance covered simple quantifiable outcomes (e.g. task completion time, target achievement [28]) and more detailed, technique-based outcomes (e.g. deviation from optimal path [25,27], walking distance [28]) which were specifically tailored to the functionality to be tested and most frequently derived from the data flow created by the robot-integrated sensing technologies (e.g. laser range finder). One study used a dichotomous subjective question to assess subjects' preference of two user different user-interface designs of the RR's navigation assistance system [26].

Sensorial assistance

Obstacle avoidance and guidance functionalities of the RRs were evaluated on self-designed obstacle courses/walking paths [23,38] or during navigation trials [25,28]. The subjects' sensorial performance with the RRs was assessed by simple quantifiable outcomes such as task completion time or number of collisions [23,28,38], or by more technique-based, tailored outcomes such as the distance to obstacles [25,28] or the deviation from a path marked on the floor [38].

Overall functionality

Assessment methods that addressed the overall functionality of the RRs covered self-designed structured questionnaires with different items and different multistage rating scales to evaluate the subjective user experience with the RR [16,23,25,28,37,40]. The most frequently used questionnaire item addressed the manoeuvrability of the RRs [16,25,37,40].

Study results

Study results were predominantly (82.4%) presented by descriptive statistics (e.g. frequencies, means, SDs) [16-18,22,25-28,38,40-42]. Only three out of 17 studies (17.6%) performed an inferential statistical analysis of outcomes [23,37,39].

In the following, we present the study results related to the different assistance functionalities to be evaluated in the identified studies.

Physical support

Out of the studies that compared robot-assisted walking and walking with conventional AMDs or without support of an AMD [17,40-42], two reported superior gait performance with the RR, as indicated by a smaller number of abnormal gaits and lower gait variability (i.e. SD of gait speed) [17] or more positive responses on the ease of walking in robot-assisted walking [40]. The other two studies reported an inferior gait and motor-functional performance with the RR in clinically established walking or functional mobility tests, documented by an increased TUG completion time, increased step time and double limb support time during the TUG, and/or a slower gait speed (4MWT, 10MWT) [41,42]. In one of these studies, subjects achieved a higher gait speed (10MWT) with the RR when compared to walking in parallel bars [41].

One study reported the highest questionnaire scores for the use of the most recent development stage of the robotic STS assistance system, indicating that subjects perceived the STS transfer with this new development stage as being easier and associated with less fear of falling than with the previous development stage or without any assistance [18].

The study comparing subjects' gait performance with two different HRI systems reported no significant differences in the mean and SD of the RR speed between the newly developed and the traditional, state-of-the-art HRI system and that subjects were able to achieve a similar good speed control to the targeted speed with both HRI systems [37].

In two studies, walking with motorized RRs was reported to be more physically demanding than with conventional walkers, documented by an increased VO2 and significant greater COT [37], or substantially higher forces applied to control the RR [28]. In contrast, another study presented a lower muscle activity in lower limbs and trunk acceleration during robot-assisted gait when compared to walking with conventional AMDs [41]. One of these studies also compared the forces required to steer the RR when using two different HRI systems (traditional vs. newly developed system) and showed that these forces were significantly higher with the most recent version [37]. In another study assessing physiological demands in ambulation with different levels of RR's BWS system, muscle activity in lower limbs seemed to decrease with increasing BWS [22].

In the RCT study, robot-assisted ambulation training resulted in significant improved gait speed (10MWT) and motor-functional (POMA) and ADL performance (Barthel ADL Index), compared to the conventional ambulation training on parallel bars [39].

The interventional study performing gait analyses on six consecutive days reported the same positive level of subjects' gait performance over the entire 'intervention' period in terms of low gait variability and a small number of abnormal gait patterns in robot-assisted gait [17].

Cognitive assistance

In specifically tailored outcomes of the navigation trails, three studies reported superior user performance with the activated navigation assistance of the RRs in terms of smaller deviations from an optimal path [25,27] or a reduced walking distance [28] when compared to that with a conventional AMD or the same RR with non-activated navigation assistance. In less specific outcomes, however, one of these studies reported an inferior user performance in robot-assisted navigation, documented by a longer walking time and a slower maximum speed [28].

In all studies comparing different assistance level of the navigation assistance (e.g. shared user-robot vs. robot motion control), subjects achieved the highest user performance (smallest path deviations [25,27], shortest walking distance [28]) when the RRs provided maximum navigation assistance by the full robot motion control modes in which the subjects had no control over the motion direction of the RR but followed the RR rigidly along the robot-planned path.

When having the choice (dichotomous question) between two different user-interface designs for the navigation assistance system of a RR, most subjects (75%) seemed to prefer a map-based design when compared to a text-and-arrow based design (25%), as reported in one study [26].

Sensorial assistance

On obstacles courses, walking paths or during navigation trails, subjects tended to show a superior sensorial performance with the RRs with activated obstacle avoidance and guidance assistance when compared to that with a RR with non-activated sensorial assistance or a conventional walker, or without any AMD. Three out of four studies reported larger distances to the obstacles [25,28], a reduced number of collisions [28,38], or smaller deviations from a path marked on the floor [38] when using the RR with activated sensorial assistance. In one study, which performed a statistical data analysis, descriptive data indicated also fewer collisions but a longer walking time with the sensorial assistance of the RR; however, these trends could not be confirmed as statistically significant [23].

Out of the studies that compared different assistance levels of the RRs, one out of three reported a superior sensorial performance documented by larger distances to obstacles when maximum assistance was provided by the full robot motion control mode [28]. In the other studies, no apparent [25] or significant [23] differences in outcomes such as the distance to obstacles, number of collisions, or task completion time were observed.

Overall functionality

Independent of the different items included in the self-designed questionnaires (e.g. manoeuvrability, safety, comfort), a high number of positive responses [40] and positive average or median scores in the upper half [16,23,25] or even in the upper quartile [37] of the scales were achieved, suggesting, for instance, that the RRs were easy to manoeuvre or subjects felt safe and comfortable using the RR [16,23,25,37,40].

The study comparing subjects' user experience with two different development stages of the RR's HRI system reported positive average scores in the upper quartile of the rating scales for both the traditional and the newly developed HRI system, with no significant differences in any questionnaire item (e.g. comfort, overall experience, speed control) [37].

In the only study that assessed subjects' perception of the RR before and after the use of the RR, favourable average scores in the upper half of the rating scale were observed at pre- and post-test assessment with the tendency of more positive scores after participating in the study; however, the statistical analysis showed no significant differences between pre- and post-testing [23].

DISCUSSION

The purpose of this systematic review was to summarize the results of studies evaluating RRs from the perspective of users. Included studies showed large clinical and methodological heterogeneity (sample characteristics, study design, assessment methods, outcomes), and findings of studies were mainly based on the authors' subjective appraisal without statistical data analysis or reference values for comparison. Such evaluations are of very limited value at a low level of evidence and rather comparable to mere use case descriptions. The overall evaluation of the effectiveness and user perception of the RRs is therefore severely hampered. Although hard to compare, a limited number of studies reported a superior user performance in specific outcomes when using the robotic functionalities compared to unassisted conditions or the use of conventional AMDs; however, these studies were performed with small sample sizes and without providing statistical evidence. The users' physical demands seemed not to be reduced with the RRs when compared to that with a conventional AMD. The overall functionality of the RRs evaluated by subjective user questionnaires was generally rated as positive by the users.

Physical support

Clinically established functional or walking tests such as the 4MWT, 10MWT, or TUG show various methodological qualities; however, they do not prevent a misuse of an inappropriate study outcome. When using a motorized RR with limited maximum speed and comparing it to a conventional walker or walking without any AMD, it is almost mandatory that the subjects achieved an inferior gait speed or task completion time with the RR, as reported in two studies [41,42]. Choosing such inappropriate and unidimensional outcomes underestimate or even completely miss the potential benefits of a RR to support users' gait and motor-functional performance. Augmenting established clinical performance-based measures (e.g. 4MWT, TUG) with technical assessment measures, such as done in one study by a video-based gait analysis [42], allows for a multidimensional analysis of subjects' gait by further temporal-spatial gait parameters such as stride length, step time, or double limb support time. However, as such parameters are highly associated with gait speed and subjects' gait speed was limited in this study by RR's maximum speed, it is not very surprising that the subjects achieved superior performance also in these outcomes with the conventional walkers by which they were able to walk much faster. In contrast, studies evaluating subjects' RR-assisted gait and motor-functional performance by less time-/speed-dependent outcomes but more qualitative performance outcomes (e.g. number of abnormal gaits, gait variability) or by more user-based outcomes (e.g. subjective perception on ease of walking/standing up) reported superior user performance and satisfaction with the RR when compared to with a conventional walker or without support of an AMD. These findings suggest that RRs may well have the potential to provide an added value for subjects' gait and motor-functional performance; however, the documentation of this seems to depend substantially on the choice of an appropriate outcome.

The development of AAL systems should involve a multi-stage iterative process, including iterative refinement of robotic prototypes/functionalities and their regularly evaluation during development process ('iterative design-development-testing procedure' [43]). As reported in one study, the most recent development stage of the STS assistance system was more positively perceived and rated by the subject than the previous one [18]. In the sense of an iterative development process, such findings indicate that the re-design and optimization of this robotic functionality seems to have been successful in this study. In contrast, in another study that developed and evaluated a new, alternative technical approach for the HRI system , such re-design seems to have been less effective, as indicated by the significant higher physical demands and similar gait performance reported for the subjects when using the more recent approach compared to the traditional, state-of-the-art HRI system [37].

RRs are augmented with a lot of technical hardware components substantially increasing their weight and inertia. The motion control of such heavy-weight, high-tech devices using HRI forces is still a challenging problem in the development of RR [25]. Since the forces required to control them and users' physical demands were reported to be higher compared to low-weight, conventional AMDs [28,37] and further improvements of traditional HRI systems appear to be difficult to achieve [37], there seems to be still no generic and optimal solution for the HRI making the handling of RRs comparable to that of a conventional AMD. In one study, the substantially higher user-applied forces may, however, also be caused by subjects' attempt to exceed robot's limited maximum speed [28]. When choosing a maximum RR speed without having in mind subjects' maximum gait speed, it is not surprising that subjects intuitively push hard to further accelerate the RR. These findings may indicate not only methodological flaws in the design of this study but also less optimized technical solutions in the design of the RR.

The reduced trunk accelerations and EMG signals in lower extremities in robot-assisted gait compared to walking with conventional walkers might be a direct consequence of subjects' lower gait speed with the RR [41]. Since gait speed may be closely related to torso kinematics and muscle activity in lower extremities, these findings seem to be almost inevitable and may indicate shortcomings in the design of a study. To ensure comparability of outcomes such as muscle activity, it is mandatory to standardize subjects' gait speed when using different types of AMDs, such as done in [37].

When using a RR for gait rehabilitation purpose, it is crucial to have the possibility to specifically tailor the amount of robotic assistance according to the user's individual gait performance. Since the muscle activity of lower extremities decreased with increasing assistance level of the BWS system evaluated in one study [22], this robotic functionality seems to be high adaptable allowing a user-specific adjustment of RR's assistance levels in rehabilitation process.

Based on clinically established assessment methods (i.e. 6MWT, 10MWT, POMA, Barthel ADL Index) and adequate statistical analyses, results of the RCT study [39] indicate that RRs may not only be used as an intelligent AMD to support users directly in functional tasks of daily living (e.g. walking, STS transfer, navigation), but also for training purposes in rehabilitation practice.

In the other interventional study [17], the similar positive gait parameters without obvious changes over the 'intervention' period may suggest that either subjects did not require much time to get used to the RR and the RR allowed already initially a very satisfactory gait performance or that the repeated use for only a six times in the restricted intervention period may not be sufficient to achieve further improvements in outcomes.

Cognitive and sensorial assistance

Studies evaluating RRs that provided navigation assistance or obstacle avoidance showed promising but not conclusive results. In outcomes less specifically tailored to the robotic functionalities (e.g. walking time, walking speed), conventional, low-tech AMDs seem to allow a superior user performance when compared to RRs [23,28]. In more specifically tailored outcomes (e.g. walking distance, path deviation, distance to obstacles), however, users seem to achieve a superior performance rather by using a RR that actively provide robotic assistance [25,27,28,38]. These findings suggest that such specific outcomes, which can often be captured by the sensing technologies already integrated on the RRs to realize the high-tech assistance, may be much more appropriate to demonstrate the added value of robotic functionalities than rather unspecific outcomes.

Full robot motion control modes of the RRs provide maximum assistance in navigation, guidance, or obstacle avoidance and may allow highest user performances [25,27,28]; however, as the RR just tracks its self-generated path (around obstacles) without considering users' input in such modes, subjects may complain about having too little control about the motion of the RR [25]. From a clinical and user perspective, the motion control of a RR should rather be based on a sophisticated HRI which sufficiently bears in mind the user's input, provides adequate assistance only when needed, and gives the user a feeling of being in control of the RR at all time.

Overall functionality

In general, results of questionnaire-based surveys on the user-perceived overall functionality of the RRs suggest that subjects had positive experiences with the RR. The comparability and a more precise classification of study results is, however, severely limited due to the large variety of questionnaires, items and rating scales used to evaluate the subjective user experience. One of the most remarkable finding here may be that the manoeuvrability of the RRs was rated by the subjects as quite high [16,25,37]. As a lot of hardware components are required to realize intelligent robotic functionalities, it seems almost inevitable that RRs are heavier and probably also bulkier than conventional walkers. The high manoeuvrability reported for the RRs, however, highlights that there are already engineering approaches available that successfully address this issue in a user-satisfying manner.

In the study evaluating the user perception before and after the use of the RR [23], the positive results already obtained at pre-test without significant changes after the actual use of the RR indicated that subjects seemed to have initially no negative prejudices against the RR. Referring to descriptive data, the authors of this study also stated that the RR was slightly more positively rated after having used it for a few times (post-test); however, they could not confirm this trend as statistically significant. Since the user satisfaction of an AMD was reported to be related to the number of times it was used [44], giving the subjects the opportunity to use the RR more frequently or over a longer period of time may have further increased the positive impact on the user perception.

CONCLUSIONS

Overall, this systematic review has revealed that the evaluation of RRs from the user perspective is still understudied. So far, very limited data on the evidence for the effectiveness of RRs in improving users' mobility and functional performance or in reducing their physical demands as well as for the positive user perception of RRs are available. Only tentative conclusions can be drawn from the identified studies, which show large heterogeneity and mostly lack sufficient methodological quality. Intelligent functionalities of the RRs may have the potential to be beneficial for users, and RRs seemed to be generally perceived as positive; however, more well-designed, high-quality studies with adequate study populations, larger sample sizes, appropriate assessment strategies with outcomes specifically tailored to the robotic functionalities, and a statistical analysis of results are required to evaluate RRs from the user perspective at a higher level of evidence.

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Disclosure of interest

The authors report no conflicts of interest.

References

[1] Davis JC, Bryan S, Li LC, Best JR, Hsu CL, Gomez C, Vertes KA, Liu-Ambrose T. Mobility and cognition are associated with wellbeing and health related quality of life among older adults: a cross-sectional analysis of the Vancouver Falls Prevention Cohort. BMC Geriatr 2015;15:75.

[2] Hirvensalo M, Rantanen T, Heikkinen E. Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. J Am Geriatr Soc 2000;48:493-8.

[3] Pescatello LS, DiPietro L. Physical activity in older adults. An overview of health benefits. Sports Med 1993;15:353-64.

[4] Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, Salem GJ, Skinner JS. American College of Sports Medicine position stand. Exercise and physical activity for older adults. Med Sci Sports Exerc 2009;41:1510-30.

[5] McAuley E, Konopack JF, Motl RW, Morris KS, Doerksen SE, Rosengren KR. Physical activity and quality of life in older adults: influence of health status and self-efficacy. Ann Behav Med 2006;31:99-103.

[6] Verghese J, LeValley A, Hall CB, Katz MJ, Ambrose AF, Lipton RB. Epidemiology of gait disorders in community-residing older adults. J Am Geriatr Soc 2006;54:255-61.

[7] Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA, Wallace RB. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol 1994;49:M85-94.

[8] Rantanen T, Guralnik JM, Sakari-Rantala R, Leveille S, Simonsick EM, Ling S, Fried LP. Disability, physical activity, and muscle strength in older women: the Women's Health and Aging Study. Arch Phys Med Rehabil 1999;80:130-5.

[9] Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, Brach J, Chandler J, Cawthon P, Connor EB and others. Gait speed and survival in older adults. JAMA 2011;305:50-8.

[10] Russell JN, Hendershot GE, LeClere F, Howie LJ, Adler M. Trends and differential use of assistive technology devices: United States, 1994. Adv Data 1997:1-9.

[11] Patel M, Miro JV, Dissanayake G. Activity recognition from the interactions between an assistive robotic walker and human users. ACM/IEEE Int Conf Hum Robot Interact (HRI). Lausanne, 2011. p 221-2.

[12] Chaudhry SI, McAvay G, Ning Y, Allore HG, Newman AB, Gill TM. Geriatric impairments and disability: the cardiovascular health study. J Am Geriatr Soc 2010;58:1686-92.

[13] Frizera A, Ceres R, Pons JL, Abellanas A, Raya R. The smart walkers as geriatric assistive device. The simbiosis purpose. Gerontechnology 2008;7:108.

[14] Elias A, Frizera A, Bastos TF, Valad C, x00E. Robotic walkers from a clinical point of view: Feature-based classification and proposal of the UFES Walker. ISSNIP Biosig Biorobot Conf Biosig and Robot Better Safer Living. Manaus, Brazil, 2012. p 1-5.

[15] Wang T, Merlet J-P, Sacco G, Robert P, Turpin J-M, Teboul B, Marteu A, Guerin O. Walking analysis of young and elderly people by using an intelligent walker ANG. Rob Auton Syst 2016;75, Part A:96-106.

[16] Frizera-Neto A, Ceres R, Rocon E, Pons J. Empowering and assisting natural human mobility: the simbiosis walker. Int J Adv Robot Syst 2011;8:34-50.

[17] Mou W-H, Ming-Fang C, Chien-Ke L, Yuan-Han H, Shih-Huan T, Li-Chen F. Context-aware assisted interactive robotic walker for Parkinson's disease patients. IEEE/RSJ Int Conf Intell Robots Syst. Vilamoura, 2012. p 329-34.
[18] Chugo D, Asawa T, Kitamura T, Jia S, Takase K. A motion control of a robotic walker for continuous assistance during standing, walking and seating operation. IEEE/RSJ Int Conf Intell Robots Syst. St. Louis, MO, USA, 2009. p 4487-92.
[19] Geravand M, Korondi PZ, Werner C, Hauer K, Peer A. Human sit-to-stand transfer modeling towards intuitive and biologically-inspired robot assistance. Auton Robots 2016:1-18.
[20] Médèric P, Pasqui V, Plumet F, Bidaud P. Sit to stand transfer assisting by an intelligent walking-aid. Climbing and walking robots: proceedings of the 7th International Conference CLAWAR 2004. Berlin, Heidelberg: Springer Berlin Heidelberg; 2005. p 1127-35.
[21] Tan R, Wang S, Jiang Y, Ishida K, Nagano M. Adaptive controller for motion control of an omni-directional walker. IEEE Int Conf Mechatr Autom. Xi'an, China, 2010. p 156-61.
[22] Jang J, Yu S, Han J, Han C. Development of a Walking Assistive Service Robot for Rehabilitation of Elderly People. In: Takahashi Y, editor. Service Robot Applications: InTech; 2008. p 139-58. Available from: http://www.intechopen.com/books/service_robot_applications/development_of_a_walking_assistive_service_robot_for_rehabilitation_of_elderly_people.
[23] Rentschler AJ, Simpson R, Cooper RA, Boninger ML. Clinical evaluation of Guido robotic walker. J Rehabil Res Dev 2008;45:1281-93.
[24] Geravand M, Werner C, Hauer K, Peer A. An integrated decision making approach for adaptive shared control of mobility assistance robots. Int J Soc Robot 2016:1-18.
[25] Yu H, Spenko M, Dubowsky S. An adaptive shared control system for an intelligent mobility aid for the elderly. Auton Robots 2003;15:53-66.
[26] Kulyukin V, Kutiyanawala A, LoPresti E, Matthews J, Simpson R. iWalker: toward a rollator-mounted wayfinding system for the elderly. IEEE Int Conf Radio Freq Identif. Las Vegas, NV, USA, 2008. p 303-11.
[27] Morris A, Donamukkala R, Kapuria A, Steinfeld A, Matthews JT, Dunbar-Jacob J, Thrun S. A robotic walker that provides guidance. IEEE Int Conf Robot Autom. Taipei, Taiwan, 2003. p 25-30.
[28] Graf B. An adaptive guidance system for robotic walking aids. J Comput Inf Technol 2009;17:109-20.
[29] Hirata Y, Komatsuda S, Kosuge K. Fall prevention control of passive intelligent walker based on human model. IEEE/RSJ Int Conf Intell Robots Syst. Nice, France, 2008. p 1222-8.
[30] Merlet J-P. Preliminary design of ANG, a low-cost automated walker for elderly. In: Pisla D, Ceccarelli M, Husty M, Corves B, editors. New trends in mechanism science: analysis and design. Dordrecht: Springer Netherlands; 2010. p 529-36.
[31] Martins M, Santos C, Frizera A, Ceres R. A review of the functionalities of smart walkers. Med Eng Phys 2015;37:917-28.
[32] Martins MM, Santos CP, Frizera-Neto A, Ceres R. Assistive mobility devices focusing on Smart Walkers: Classification and review. Rob Auton Syst 2012;60:548-62.
[33] Werner C, Ullrich P, Geravand M, Peer A, Hauer K. Evaluation studies of robotic rollators by the user perspective: a systematic review. Gerontology 2016;62:644-53.
[34] Schulz R, Wahl H-W, Matthews JT, De Vito Dabbs A, Beach SR, Czaja SJ. Advancing the aging and technology agenda in gerontology. Gerontologist 2014;55:724-34.
[35] Choi YM, Sprigle SH. Approaches for evaluating the usability of assistive technology product prototypes. Assist Technol 2011;23:36-41.
[36] Tsui KM, Feil-Seifer DJ, Matarić MJ, Yanco HA. Performance evaluation methods for assistive robotic technology. In: Madhavan R, Tunstel E, Messina E, editors. Performance evaluation and benchmarking of intelligent systems. Boston, MA, USA: Springer US; 2009. p 41-66.
[37] Grondin SL, Li Q. Intelligent control of a smart walker and its performance evaluation. IEEE Int Conf Rehabil Robot. Seattle, WA, USA, 2013. p 6650346.
[38] Kikuchi T, Tanaka T, Tanida S, Kobayashi K, Mitobe K. Basic study on gait rehabilitation system with intelligently controllable walker (i-Walker). IEEE Int Conf Robot Biomim. Tianjin, China, 2010. p 277-82.

[39] AnnicchiaricoR. Enhancing service delivering, improving quality of life, preserving independence through assistive technology. Stud Health Technol Inform 2012;180:14-8.
[40] Lee G, Ohnuma T, Nak Young C, Soon-Geul L. Walking intent-based movement control for JAIST active robotic walker. IEEE Trans Syst Man Cyber 2014;44:665-72.
[41] Tamura T, Sekine M, Kuno H, Fujie M, Mori A, Andoh K. Evaluation of walkers for elderly people. IEEE Int Conf Eng Med Biol Soc. Istanbul, Turkey, 2001. p 1391-2.
[42] Rumeau. A generic method for the assessment of smart walkers. Gerontechnology 2012;11:345.
[43] Kamieth F, Arca A, Villalar J, Arredondo M, Dähne P, Wichert R, Jimenez-Mixco V. Exploring the Potential of Virtual Reality for the Elderly and People with Disabilities. In: Kim J, editor. Virtual Reality: InTech; 2010. p 395-418. Available from: http://www.intechopen.com/books/virtual-reality/exploring-the-potential-of-virtual-reality-for-the-elderly-and-people-with-disabilities.
[44] Brandt Å. Outcomes of rollator and powered wheelchair interventions: user satisfaction and participation [dissertation]. Lund University, Faculty of Medicine; 2003, 127 p.

Table 1. Study characteristics, assessment methods, and study results of the 17 studies identified in this systematic review

Name of RR Author, year [Ref. No]	Sample	Design	Assistance functionality	Assessment methods	Study results
CAIROW Mou et al., 2012 [17]	Study A n = 6 (F = n/a) Age: n/a PD patients, mHY stage 1.5-3	IV: repeated assessment on 6 consecutive days	PHY	Gait analysis: gait speed, step length Expert rating of gait: abnormal gait patterns (festinating gait, freezing of gait)	Gait speed, step length, abnormal gait patterns: in the same positive level without obvious changes over the entire 'intervention' period #
	Study B n = 7 (F = n/a) Mean age: 86 yrs PD patients, mHY stage 1-3	INTER: RR vs. normal walking (with own/ without AMD)	PHY	Gait analysis: gait speed, step length Expert rating of gait: abnormal gait patterns	SD of gait speed, abnormal gait patterns: RR < normal walking # Step length: n/a
Care-O-bot II Graf, 2009 [28]	n = 6 (F = 5) Age range: 86-92 yrs Inhabitants of an old people's residence using mobility aids in daily life	INTER, INTRA: robot motion control vs. user motion control vs. conventional AMD+ OBS	COG SENS PHY OA	Navigation trail with obstacles: walking time, number of collisions, maximum speed, walking distance, distance to obstacles Force/torque sensors: pushing force Navigation trail with obstacles: target achievement Self-designed questionnaire	Walking time: RR > conventional walker #, robot vs. user motion control: n/a Number of collisions, maximum speed: RR < conventional AMD #, robot vs. user motion control: n/a Walking distance: robot < user motion control or conventional AMD # Distance to obstacles: maximum distance with robot motion control Pushing force: RR > conventional AMD #, robot vs. user motion control: n/a Target achievement: all subjects could be passed by safely '80% of subjects felt safe and in control with the RR'
GRSR Jang et al., 2008 [22]	n = 2 (F = 0) Mean age (SD): 28.5 (2.1) yrs Ordinary adult males	INTRA: 20/40% BWS vs. FBW	PHY	EMG[a] during walking with standardized gait speed of 0.2 m/s: muscle activity of lower extremity muscles	EMG signal: 20% BWS < FBW (range -0.9 to -10.0%) #; 40% BWS << FWB (range -1.8 to -17.2%) #
Guido Rentschler et al., 2008 [23]	n = 17 (F = n/a) Mean age (SD): 85.3 (7.0) yrs Residents of a supportive living facility/nursing home with visual impairment (e.g. macular degeneration, cataract, glaucoma) Mean time (SD) since onset of visual impairment: 20.4 (13.0) yrs Ambulatory (≥ 20 min within 90 min period) with limited assistance	INTER, INTRA: RR vs. conventional AMD or normal walking (with own/without AMD); user motion control vs. shared user-robot motion control PPT: before and after RR usage	SENS OA	Obstacle course: walking time, number of collisions/reorientations Self-designed questionnaire: appearance, ease of use, usefulness, embarrassment (1 = best score; 5 = worst score)	Walking time: AMD < own/without AMD < Guido: n.s. differences Number of collisions: Guido < own/without AMD < conventional AMD: n.s. differences Number of reorientations: AMD < own/without AMD < Guido: n.s. differences Appearance: n/a Ease of use, usefulness, embarrassment: post-test < pre-test score: n.s. differences
Hitachi walker Tamura et al., 2001 [41]	n = 6 (F = n/a) Mean age (SD): 82 (7.9) yrs Subjects ambulatory with supervision (n = 4), subjects in need for walking assistance (n = 2)	INTER: RR vs. caster vs. conventional walker; RR vs. parallel bars	PHY	10MWT: gait speed EMG: muscle activity of gastrocnemius Tri-axial accelerometer: trunk acceleration	Gait speed, trunk acceleration: RR < caster < conventional walker #; RR > parallel bars # EMG signal: RR < caster < conventional walker #; RR vs. parallel bars not reported
iWalker Kulyukin et al., 2008 [26]	n = 4 (F = n/a) age: n/a Clients of in-home supportive service currently using cane and/or walker with history of way finding problems MMSE mean score (SD): 26 (3.6)	INTRA: map-based vs. text-and-arrow-based user-interface design of navigation system	COG	Dichotomous question: choice of user-interface design	Choice of user interface: 3 out of 4 subjects preferred map-based user interface design

i-Walker (EU) Annicchiarico, 2012 [39]	n = 20 (F = 11) Mean age: 59.9 yrs Acute hemiparetic stroke patients (event < 1 yrs) receiving rehabilitation treatment MMSE ≥20; CNS upper/lower limb > 0	IV (RCT): ambulatory training with RR(EG) vs. in parallel bars (CG); 4 weeks, 5x a week	PHY	POMA: total score 6MWT: walking distance 10MWT: gait speed Barthel ADL Index	Within both groups, T_1 vs. T_2: POMA total score, walking distance, gait speed, Barthel ADL Index: ↑ EG compared to CG, T_1 vs. T_2: POMA total score, gait speed, Barthel ADL Index: ↑ Walking distance: n.s differences
i-Walker (JP) Kikuchi et al., 2010 [38]	n = 6 (F = 2) Mean age (SD): 88.7 (6.1) yrs Residents of elder care facility with wheelchair due to loss of vision/muscle strength who occasionally train walking with forearm caster walker Chronic disease: stroke, dementia, muscle atrophy, high blood pressure, heart failure, AD, cataract, PD	INTRA: active vs. passive robot motion control system	SENS	Obstacle course: deviations from a path marked on the floor, number of collisions	Path deviations, number of collisions: active < passive motion control system #
JARoW Lee et al., 2014 [40]	n = 5 (F = 4) Age range: 75-84 yrs Subjects using traditional walkers in daily routine	INTER: RR vs. conventional AMD	OA	Self-designed questionnaire: ease of walking, safety, manoeuvrability (dichotomous items)	Ease of walking: 3 out of 5 subjects felt it was easier to walk with RR, 2 subjects had no opinion Safety: all subjects felt safe during RR use Manoeuvrability: 4 subjects felt able to use the RR in more locations than their current AMD
Nomad XR 4000 Morris et al., 2003 [27]	n = 4 (F = n/a) Age: n/a Residents of a retirement facility	INTRA: active vs. passive navigation assistance system vs. full robot motion control	COGN	Navigation trail: deviation from optimal path	Path deviation: full robot motion control < active < passive navigation assistance #
PAMM SmartWalker Yu et al., 2003 [25]	<u>Study A</u> n = 8 (F = n/a) Age: n/a Elderly residents of assisted living facility with mobility aid	OBS	OA	Self-designed questionnaire: ease of control, going straight, turning, heaviness, support, satisfaction (1 = worst score, 5 = best score)	Questionnaire items, mean (range): Ease of control: >3.5 (3-5), going straight: 3.5 (3-5), turning: >4 (2-5), heaviness: 3.5 (1-5), upport: 4 (2-5), satisfaction: >3 (1-5)
	<u>Study B</u> n = 8 (F = 5) Age range: 84-95 yrs Elderly residents of assisted living facility with need for walkers	INTRA: full robot motion control vs. shared user-robot motion control vs. without any motion control	COG SENS	Walking path: deviation from optimal path, distance to wall	Path deviation: full robot < shared user-robot < without motion control # Distance to wall: full robot ≈ shared user-robot > without motion control #
RMP Grondin & Qinggou 2013 [37]	n = 10 (F = 5) Mean age (SD): 24.6 (3.0) Subjects without previous/ current gait-related injuries and without experience in using rollators or robotic walkers	INTER, INTRA: previous vs. recent motion control system vs. conventional rollator vs. without AMD	PHY OA	Walking with targeted velocity of 1 m/s on a circular path: mean/SD of RR velocity Force/torque sensor pushing force Respirometry: COT, VO_2 Self-designed questionnaire: comfort, intuition, speed control, exertion, overall experience (0 = worst score, 5 = best score)	Mean/SD of RR velocity: n.s. differences between motion controllers; all subjects achieved a very good speed control to the targeted speed of 1 m/s with both motion controllers Pushing force: recent > previous motion control * COT: conventional rollator > without AMD *, previous/recent motion control > without AMD or conventional rollator *, n.s. differences between both motion controllers VO_2: RR > conventional rollator > no assistive device #

					Comfort, intuition, speed control, exertion, overall experience: n.s. differences between both motion controllers; similar positive user experience for both motion controllers (for all items: score ≥4)
robuWALKER Rumeau et al., 2012 [42]	n = 8 (F = 5) Mean age (SD): 82.6 (8.7) yrs Healthy elderly (n = 4): 4MWT < 4s, TUG < 13s, MMSE score ≥ 26 Elderly patients with motor & cognitive impairment (n = 4): 4MWT > 4s, TUG > 13s, MMSE mean score (SD): 20 (3.5) All subjects without experience in using walking frames	INTER: RR vs. conventional walker	PHY	4MWT: gait speed Modified TUG: completion time Gait analysis by video recordings: step time, double support time	4MWT, TUG: RR > conventional walker # Step time, double support time: RR > conventional walker #
SIMBIOSIS Walker Frizera-Neto et al., 2011 [16]	n = 8 (F = n/a) Age: n/a Subjects with preserved cognitive functions Ability to (1) maintain standing position, (2) walk 10 m without assistance of another person and with or without support of a mobility aid, and (3) to grasp WISCI II mean score (SD): 15.9 (2.9)	OBS	OA	Self-designed questionnaire: manoeuvrability, safety, posture & comfort (0 = worst score, 100 = best score)	Questionnaire items, mean (SD): Manoeuvrability: 74 (18.8) Safety: 90 (7.9) Posture & comfort: 89 (7.9)
- Chugo et al., 2009 [18]	n = 7 (F = n/a) Age: ≥ 67 yrs People in need of long-term care at level I or II in Japanese Long-term Insurance System	INTER, INTRA: STS transfer without assistance vs. with previous/recent STS assistance system	PHY	Self-designed questionnaire: ease of standing up, fear of falling (1= inferior, 3 = same, 5 = better feeling compared to STS transfer without any assistance)	No assistance vs. previous STS assistance system: ease of standing up, mean: 4; fear of falling, mean: 3 No assistance vs. recent STS assistance system: ease of standing up, mean: 4.5; fear of falling, mean: 4.5 → subjects felt easier to stand up using recent STS assistance system compared to the previous version or no assistance #

Abbreviations: RR= robotic rollator; F = females; n/a = not available; PD = Parkinson's disease; IV = interventional; PHY = physical; # = no statistical analysis given; INTER = inter-device comparative; AMD = assistive mobility device; SD = standard deviation; INTRA = intra-device comparative; OBS = observational; COG = cognitive; SENS = sensorial; OA = overall; BWS = body weight support; FBW = full body weight; EMG = electromyography; PPT = pre-post-test; n.s. = not significant; 10MWT = 10-Meter Walk Test; MMSE = Mini-Mental Status Examination; CNS = Canadian Neurological Scale; RCT = randomized controlled trial; EG = experimental group; CG = control group; POMA = Performance Oriented Mobility Assessment; 6MWT = 6-Min Walk Test; ADL = Activity of daily living; ↑ = significant higher; AD = Alzheimer's disease; COT = metabolic cost of transport, VO2 = oxygen consumption; * = significant ($p < .05$); 4MWT = 4-Meter Walk Test; TUG = Timed Up and Go; WISCI II = Walking Index for Spinal Cord Injury II; STS = sit-to-stand.

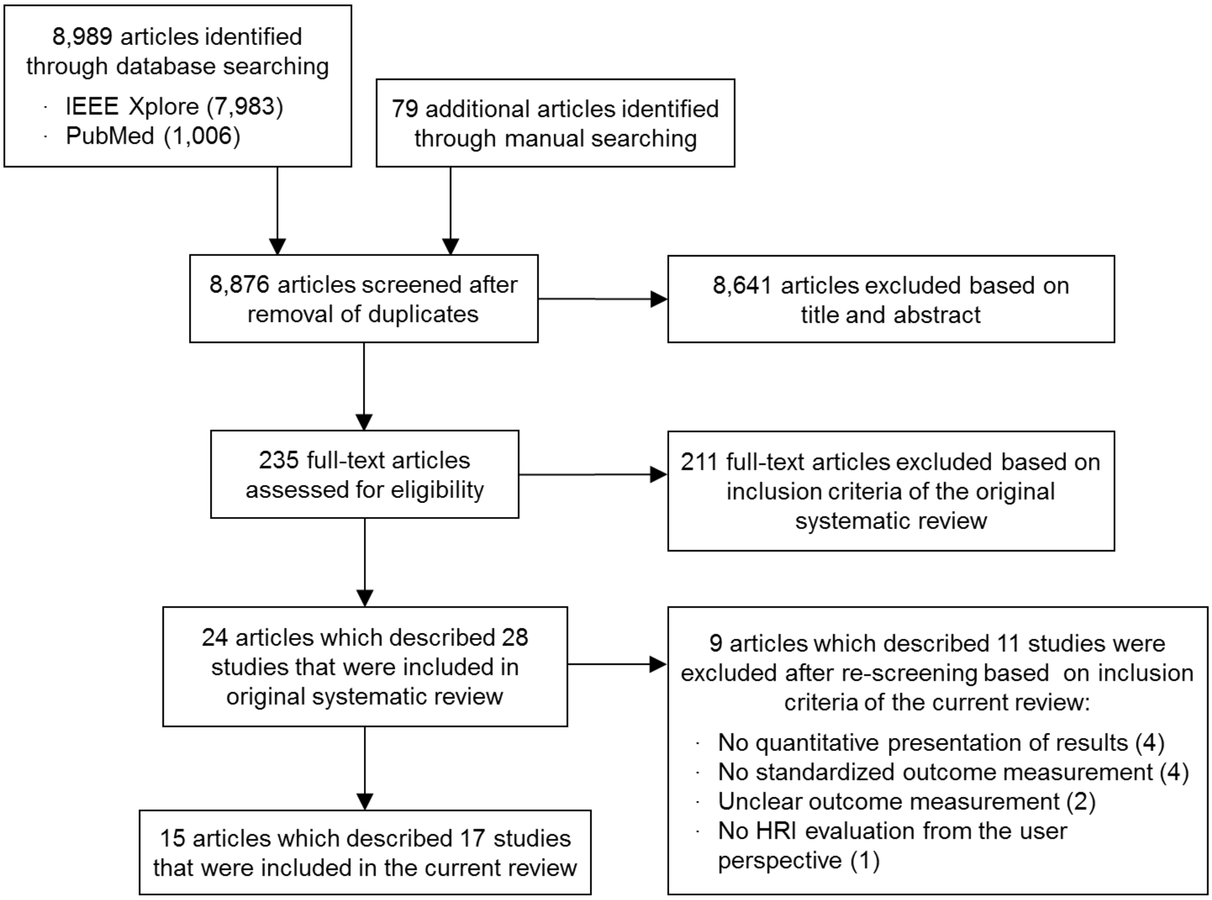

Figure 1. Flowchart of the study selection process and extraction of studies meeting the inclusion criteria.

Manuskript III

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User-Oriented Evaluation of a Robotic Rollator that Provides Navigation Assistance in Frail Older Adults with and without Cognitive Impairment

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Running Head: Navigation Assistance from a Robotic Rollator

ABSTRACT

Background: Navigational skills decline with age and this decline is even more pronounced in cognitively impaired older adults. Navigation assistance is an emerging functionality of robotic rollators (RRs). The evidence on the effectiveness of RR-integrated navigation systems in potential end-users is, however, scarce.

Objective: To determine whether RR-provided navigation assistance improves navigation within a real-life environment in the intended user group of frail older adults with and without cognitive impairment currently using a rollator in daily life.

Methods: A randomized, between-subject, 2x2 factorial design was conducted to test the effects of navigation assistance and cognitive status on participants' navigation performance. Twenty cognitively impaired (CI: Mini-Mental State Examination [MMSE] 17-26) and 22 not cognitively impaired (NCI: MMSE >26) older rollator users (age: 82.5 ± 8.7 years) were included. Participants were matched for cognitive status (CI vs. NCI) and randomized to one of two conditions: RR (1) with or (2) without activated navigation system. All participants had to complete a two-section navigation path with the RR in an unfamiliar, real-life environment. Participants with RR-assisted navigation were supported in wayfinding by directional audio cues of the RR-integrated navigation system. Participants without RR-assisted navigation had to complete the sections by orienting themselves along conventional signposts. Outcomes were success rate, completion and stopping time, number of stops, walking distance, and gait speed.

Results: The navigation assistance condition had no significant effect on the success rate in the CI, NCI or total group. We found significant interactions between navigation assistance and cognitive status for both sections (p = 0.002-0.040), such that RR-assisted navigation reduced the completion time (both sections), stopping time (section 1), and number of stops (section 2) in the CI ($p \leq$ 0.001-0.014) but not in the NCI group. On the more complex section 2, RR-assisted navigation led to a reduced stopping time and walking distance in the total group (p = 0.014-0.016).

Conclusion: The RR-integrated navigation system was effective for improving navigation within a real-life environment in potential end-users, especially in those with cognitive impairment. This is the first study to provide statistical evidence on the effectiveness of a RR-integrated navigation system in the intended user group.

Keywords: Assistive technology, mobility aid, smart walker, navigation assistance, evaluation, cognitive impairment, rehabilitation, human-robot interaction.

INTRODUCTION

Recent advances in technology have enabled the development of a new class of intelligent assistive mobility devices by integrating robotic technology, electronics, and mechanics [1]. These so-called “smart walkers”, “robotic walkers”, or “robotic rollators” (RRs) are no longer limited to the primary task of conventional assistive mobility devices in terms of physical assistance [2], but can provide assistance in additional functional domains (e.g., sensory and cognitive functions) that may restrict mobility in the elderly [3]. Apart from intelligent functionali-ties that focus on gait or sit-to-stand (STS) assistance, partial body weight support, fall pre-vention, and/or obstacle avoidance, also navigation systems for cognitive assistance in spa-tial orientation and wayfinding in indoor environments are frequently implemented on RRs [4]. Navigation involves maintaining a sense of spatial orientation and localization that enables successful movement from one location in the environment to another, and can be supported by external representations such as maps, signposts, or linguistic descriptions [5]. Naviga-tional skills decline with age [6,7], and cognitive impairment, which has been shown to be common in geriatric patients of rehabilitation centers and acute care hospitals as well as in nursing homes residents (40-80%) [8-10], is associated with an even more pronounced de-cline in these skills [11,12]. In addition, deficits in spatial orientation and wayfinding within un-familiar and familiar environments are among the first symptoms of dementia [13,14]. As the loss of navigational skills can lead to reduced mobility, autonomy, and independence [15,16], promoting spatial orientation and wayfinding by smart functionalities of a RR may therefore be highly beneficial to frail elderly with difficulty in navigation.

Navigation assistance has been implemented on the RRs in different ways [4]. There are RRs that guide the user along a preplanned path towards a previously specified destination rather passively, providing solely route directions in the form of audio cues (e.g., “Please turn right”), visual instructions (e.g., direction arrow on a screen), and/or haptic signals (e.g., vi-brating handles/bracelets) while the user has full motion control over the direction of travel [17-19]. Other RRs provide navigation assistance (also) more actively, controlling to some extent the motion direction of the RR to assist the user in staying on the preplanned path; for example, by a RR-generated virtual force that guides the user back to the path when he/she deviates from it [20], by adjusting the steering angle of the front wheels towards the path to be followed [21,22], or by slowing down the velocity of the RR when the user deviates to much from the preplanned path [23]. Independent of their technical implementation, the evidence gathered in evaluation studies on the effectiveness of such RR-integrated navigation assistance systems in the potential end-users is scarce. A systematic review on the evaluation of RRs from the user perspective reported that RR-provided navigation assistance may have a positive impact on users’ navigational performance. There is, however, limited evidence on the added value of such high-tech functionality due to methodological shortcomings related to non-specific user group definitions, inappropriate selection of study populations, insufficient sample descriptions and sample sizes, inadequate assessment methods and study out-comes, and lack of statistical analysis [24,25]. Based on these findings, it was concluded that further studies with high methodological quality are needed to address these limitations and to obtain further evidence on the effectiveness of RR-integrated, innovative functionalities in the potential user group [24].

METHODS

Research Question

The aim of the present study was to determine whether a navigation assistance system implemented on a RR can improve navigation within a real-life environment in the intended user group of frail older adults with and without cognitive impairment currently using a rollator in daily life. We hypothesized that cognitively impaired (CI) users would benefit more from the RR-integrated navigation assistance system than not cognitively impaired (NCI) users.

Intelligent Active Mobility Assistance Robot

The RR used in this study was developed in the MOBOT project (Intelligent Active MObility Aid RoBOT integrating Multimodal Sensory Processing, Proactive Autonomy and Adaptive Interaction), which focused on developing robotic mobility aids for indoor environments that provides intelligent and active mobility assistance to elderly people, by supporting safe autonomous proactive control of the physical user-robot interaction, and enabling multimodal sensory processing and natural human-robot communication. The MOBOT rollator-type mobility assistant (figure 1) integrates innovative functionalities such as STS assistance, obstacle detection and avoidance, indoor localization and navigation assistance, user following, gait tracking, and audio-gestural human-robot interaction into an overall context-aware mobility assistance robot. A more detailed and comprehensive overview of the MOBOT rollator's functionalities have been summarized previously [26]. As this study aimed to conduct an evaluation specifically tailored to the navigation assistance functionality of the MOBOT rollator, only this innovative assistance functionality was activated during test procedure and all others, which would have provided additional direct assistance to the participants (e.g., obstacle avoidance, STS assistance), were deactivated.

User Group Definition

The intended users of the MOBOT rollator were elderly persons in institutionalized settings (e.g., in-patients of the geriatric rehabilitation wards or acute care hospitals, nursing home residents) (1) with moderate motor impairment and (2) with mild-to-moderate or without cognitive impairment. The criteria for moderate motor impairment was defined as: (a) current use of a rollator and/or very slow usual gait speed (without walking aid) of < 0.6 m/s in the 4-meter walk test (4MWT, [27]) and (b) unable to stand up unassisted from a chair with seat placed at individuals knee height and/or time required to complete a 5-chair stand test of ≥ 16.7 s [27]. Mild-to-moderate cognitive impairment was defined as a score of 17-26 on the Mini-Mental State Examination (MMSE, [28]), and no cognitive impairment was defined as a MMSE score of > 26.

Navigation Assistance System

The development and implementation of the intelligent functionalities of the MOBOT rollator were based on the Robot Operating System (ROS) [29], which can currently be regarded as the most popular software framework for robotic research and development. The ROS contains a large collection of open-source drivers, algorithms, tools, and libraries for the development of various robot tasks. For the navigation assistance module of the MOBOT rollator, the ROS navigation stack was adopted, which is extensively used by research teams around the globe for autonomous robot navigation in mobile robots (e.g., Care-O-bot, TurtleBot, evarobot) [30]. ROS stacks are collections of algorithms and tools with a defined objective, in this case navigation. The ROS navigation stack has been successfully tested in real-life scenarios, navigating a mobile robot autonomously for 26.2 miles in a real office environment [31]. The task of navigation assistance of the MOBOT rollator comprises the following robot sub-tasks: map building, odometry, and localization. To enable these sub-tasks, the MOBOT rolla-tor was equipped with two high-precision quadrature optical encoders on the two rear driving wheels, a laser range finder (Hokuyo UTM-30LX) at the front of the MOBOT rollator facing towards the motion direction, and an inertial measurement unit (IMU, XSensMTi-G-700 GPS/INS) mounted on the chassis of the MOBOT rollator. Using the openSLAM Gmapping library, which creates maps from unknown environments based on captured laser scan data, a static map of the indoor environment was built in ROS. Odometry was used to estimate the pose (i.e., position and orientation) of the MOBOT rollator over time, relative to a starting position, by integrating the wheel rotation measurements of the encoders attached to the rear wheels. The odometry package used the dead reckoning approach, where the current pose is estimated from the known previous pose and relative measured displacements from the previous pose [32]. The position and orientation changes given in a known time period be-tween successive measurements can be also expressed as the velocity of the MOBOT rollator. Odometric pose estimation is a well-established technique in mobile robots, providing good short-term accuracy. However, the integration of incremental motion information over time leads inevitably to the accumulation of errors, due to, for instance, wheel slippage. This accumulation may cause large pose estimation errors which increase proportionally with the distance travelled by the robot [33]. To mitigate this problem, a fusion algorithm was used that merged the robot linear velocity calculated from the encoder data with the robot angular velocity calculated from the gyroscopic data of the IMU, providing a more reliable and robust pose estimation [34]. Localization refers to estimating the position of the MOBOT rollator on the created map. This was achieved through the Adaptive Monte Carlo Localization, which is an established technique for probabilistic mobile robot localization in 2D maps based on particle filtering [35]. As part of the ROS navigation stack, there is a direct implementation of this method in ROS which provides an estimate of the robot's pose by fusing information from the laser range finder and the odometry.

The navigation assistance system provides prespecified auditory localization information and navigation instructions to the user while he/she has full motion control over the MOBOT rollator. The system assumes a known map with a set of predefined guard points that have audio cues associated with them. Each guard point comprises two states: in and out. The transition to the "in" state is made when the MOBOT rollator enters a circular area of predefined radius centered at the guard point, while the transition to the "out" state is made when the MOBOT rollator exits this area. On entry into the predefined area, a precise directional audio cue is provided that aims to guide the user safely and on a direct route to a prespecified destination. Each audio cue of a guard point is repeated every 3 seconds until the user leaves the predefined area of the specific guard point. The guard points are treated as a directed path, i.e. when the MOBOT rollator exits a guard point, this point and its associated audio cue are dis-carded and only subsequent guard points are further considered. Using the localization algorithm described above, the position of the MOBOT rollator on the map is estimated continuously, and according to its position, the appropriate guard point with its specific audio cue is triggered.

Study Design

The study was designed as a randomized, between-subject, 2x2 factorial experiment with navigation assistance condition (MOBOT-assisted vs. MOBOT-unassisted navigation) and cognitive status (cognitively impaired, CI vs. not cognitively impaired, NCI) as independent variables, and navigation performance as the dependent variable. The ethics committee of the Medical Department of the University of Heidelberg approved the study in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to study inclusion.

Study Population

According to the predefined user group of the MOBOT rollator, study participants were predominantly recruited from rehabilitation and acute care wards of a geriatric hospital and from nursing homes. We also screened members of hospital-associated sports club for geriatric rehabilitation, which includes former in-patients of the geriatric rehabilitation wards, now taking part in outpatient physical rehabilitation. Two groups of participants were recruited: people currently using a rollator (1) with mild-to-moderate cognitive impairment (MMSE 17-26), and (2) without cognitive impairment (MMSE > 26). Further inclusion criteria were: ≥ 65 years; ability to perform the navigation task of the study, to understand study instructions, to hear the audio cues provided by the navigation system, and to see signposts; unfamiliar with the test environment; no severe neurologic, cardiovascular, metabolic, or psychiatric disorders; residence within 15 kilometers of the study center; and written informed consent. The participants enrolled in the study were matched for cognitive status (cognitively impaired vs. not cognitively impaired) and randomly allocated to one of two conditions: (1) with or (2) without MOBOT-assisted navigation.

Descriptive Measures

Demographic and clinical characteristics including age, gender, falls in the previous year, and social status (community-dwelling vs. institutionalized) were documented from patient charts or by standardized interview-administered assessment. A trained interviewer assessed psychological status for depression (Geriatric Depression Scale, GDS, 15 item version, [36]) and fear of falling (Short Falls Efficacy Scale-International, Short-FES-I, [37]). Motor performance was measured by the Performance Oriented Mobility Assessment (POMA) [38] and the 4MWT [27].

Measures of Navigation Performance

Test Environment and Procedure

A navigation path within a standardized real-life test environment was designed at the ground floor of a geriatric hospital. The path had a total length of about 100 meters, subdivided into two sections with different levels of difficulty (figure 2). The shorter and rather less complex section 1 led from the starting position in front of the elevator within the acute care clinic, along a hallway, through the main entrance hall, past at the elevator within the medical center, to the hospital chapel, defined as the interim destination (shortest distance ≈ 45 m). The longer and a bit more complex section 2 included more junctions and critical waypoints and led from the hospital chapel, back through the main entrance and along the hallway, right into another hallway, to the reception area of the hospital's admission center, defined as the final destination (shortest distance ≈ 55 m).

The test procedure was conducted according to a standardized written test protocol. The two sections of the path were performed one by one, with a recovery break of few minutes between the sections. Directly prior to each section, a test administrator informed the participants about the respective destination to be reached for section 1 (chapel) and section 2 (admission center). For both sections, the participants were instructed to navigate to the destination by taking the most direct route possible for them. The test administrator also stated that the prespecified destination is located at the ground floor of the hospital and that there are no closed doors to be opened on the path in order to reach the destination. No instruction was given on the speed of walking. Both sections could be performed at self-selected walking pace.

The destination to be reached for section 1 and section 2 were stated separately to the participants by a test administrator directly prior to each section.

Participants allocated to the condition with MOBOT-assisted navigation were supported in wayfinding by the audio cues (table 1) provided by the navigation system when entering the predefined guard points on each section of the navigation path (figure 3). The prespecified audio cues included direct navigation instructions that were kept as short as possible while still providing sufficient and precise information on the route to be taken to successfully reach the destinations. At some critical waypoints with several junctions (e.g., in the entrance hall), also contextual information on the environment (e.g., "walk towards the elevator") was included to make the audio cues even more precisely and unambiguously. The navigation system was pre-configured and activated by the test administrator. The participants with MOBOT-assisted navigation were instructed to walk to the destinations only by listening and following the directional audio cues given by the system. In contrast, in the condition without MOBOT-assisted navigation, the navigation system was inactive, such that no directional audio cues were provided to the participants. They were asked to reach the destinations as directly as possible by orienting themselves solely by the signposts fixed at the walls and ceilings of the hospital (figure 2). Asking other people (e.g., test administrator, receptionist in the entrance hall, hospital staff) for help in wayfinding was not allowed in both conditions.

All participants were continuously supervised by the test administrator during both sections to ensure participants' safety and to have the opportunity to intervene in critical or unexpected situations as quickly as possible. The navigation trial for each section was continued as long as the participants were motivated to search for the destination and was only stopped in cases they gave up their searching efforts, despite repeated encouragement by the test administrator. Each participant had only one trial for each section to exclude learning effects.

Outcome Parameters

In a first step, the test administrator recorded whether (or not) the participant successfully reached the destination of each section (i.e. success rate). In a second step, for all participants that successfully completed the sections, more qualitative, sensor-based outcome parameters specifically tailored to the participant's navigation performance were extracted from the odometric and localization information that had been recorded by the ROS software infrastructure of the MOBOT rollator during the experiments. For each of the two sections and for each participant, the sensor-based outcome parameters were calculated from the starting position, defined as when the MOBOT rollator first exited the first guard point (t_{start}), to the end position, defined as when the MOBOT rollator first entered the last guard point of the section (t_{end}). Following sensor-based outcomes were calculated:

- Completing time [s]: Time interval from the starting position to the end position (t_{end} – t_{start}).
- Stopping time [s]: Sum of the length of the time periods in which the velocity of the MOBOT rollator was < 0.1 m/s for a duration of at least 1 s.
- Number of stops: Number of the time intervals in which the velocity of the MOBOT rollator was < 0.1 m/s for a duration of at least 1 s.
- Walking distance [m]: Geometric length of the trajectory travelled by the MOBOT rollator from the starting position to the end position.
- Gait speed [m/s]: Mean velocity of the MOBOT rollator, calculated as the walking distance divided by the walking time. Walking time was defined as the sum of the length of time periods in which the velocity of the MOBOT rollator was ≥ 0.1 m/s.

Statistical Analysis

Descriptive data were presented as frequencies and percentages for categorical variables, and means and standard deviations (SD) or medians and ranges for continuous variables as appropriate. According to the distribution of the data, unpaired t-tests, Mann-Whitney U-tests, and Chi-square tests, and Fisher' exact tests were used for comparison between the groups with and without MOBOT-assisted navigation. Fisher's exact tests were also calculated to analyze the success rate for completing the two sections of the navigation path with or without MOBOT-assisted navigation in the CI group, the NCI group, and the total sample. For the sensor-based outcomes, 2-way analyses of variance (2x2 ANOVAs) were performed (1) to examine the interaction of the navigation assistance condition (MOBOT-assisted vs. MOBOT-unassisted navigation) and cognitive status (CI vs. NCI) and (2) to examine the main effect of the navigation assistance condition in the total sample. Post-hoc t-tests with Bonferroni adjustment for multiple pairwise comparisons were performed if a significant interaction effect was obtained. A 2-sided *p*-value of < 0.05 indicated statistical significance. Effect sizes were calculated as partial eta squared (η_p^2) and were interpreted as small ($\eta_p^2 < 0.06$), medium ($0.06 \geq \eta_p^2 < 0.14$), or large effects ($\eta_p^2 \geq 0.14$). The statistical analysis was performed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Participant Characteristics

The study sample included 42 frail older rollator users with mild-to-moderate or without cognitive impairment, who were all in-patients of geriatric rehabilitation or acute care wards (16.7%), nursing home residents (42.9%), or former geriatric in-patients now being members of the outpatient rehabilitation sports club (40.4%). Participants' mean age was 82.5 ± 8.7 years and the mean MMSE score was 25.9 ± 3.6 points. About half of the participants (n = 20, 47.6%) met criteria for cognitive impairment (MMSE ≤ 26). The habitual gait speed averaged 0.56 ± 0.22 m/s and the POMA score averaged 19.2 ± 5.9 points, indicating low motor performance, frailty, and increased risk of falling [38,39]. Five (11.9%) participants showed depressive symptoms (GDS score ≥ 5) [36]. Fear of falling was low (Short-FES-I = 7-8 points) in 15 (35.7%), moderate (Short-FES-I = 9-14 points) in 18 (42.9%), and high (Short-FES-I = 14-28 points) in nine participants (21.4%) [40]. More than the half (n = 26, 61.9%) reported one or more falls in the previous year. Twenty-two participants (52.4%) were living independently at home, partly with supportive care; 20 (47.6%) were institutionalized.

The subgroups of the participants with and without MOBOT-assisted navigation did not differ significantly in age, cognitive status, motor performance, history of falls, fear of falling, depressive symptoms, living situation, and place of recruitment (table 2; *p* = 0.204-0.999). The participants with MOBOT-assisted navigation comprised more females than those without MOBOT-assisted navigation (81.2% vs. 50.0%; *p* = 0.029); however, there were no gender differences for any outcomes of the navigation path between females and males in the MOBOT-assisted navigation condition (*p* = 0.294-0.823).

No clinical critical events (e.g., falls) occurred during testing, and no participant rejected the challenges of the test session. For one participant in the condition with MOBOT-assisted navigation, the navigation system broke down on section 2 of the navigation path (hospital chapel to admission center) due to technical problems and the test session had to be cancelled, which reduced the sample size for that section.

Navigation Performance

Section 1

Except for one participant in the MOBOT-unassisted and two in the MOBOT-assisted navigation condition, all participants successfully completed the first section of the navigation path (table 3). No significant associations were found between the success rate and the navigation assistance condition, neither in the CI or NCI group nor in the total sample (p > 0.999).

For the completion and stopping time, a significant interaction between navigation assistance and cognitive status was found (p = 0.002-0.040), with medium to large effect sizes (η_p^2 = 0.115-0.235) (table 4). The Bonferroni-adjusted post-hoc analysis of simple main effects revealed that in the MOBOT-unassisted condition, the CI group had a significantly longer completion and stopping time compared to the NCI group (p < 0.001-0.003) but not in the MOBOT-assisted condition (p = 0.836-0.866), and that in the CI group, these times were significantly shorter with MOBOT-assisted navigation than that without it (p = 0.003-0.014). In the NCI group, however, MOBOT-assisted navigation had no significant effect on the completion time (p = 0.165). No significant interaction between the independent variables (p = 0.072-0.125; η_p^2 = 0.066-0.089), nor a significant main effect of the navigation assistance (p = 0.117-0.909; η_p^2 < 0.001-0.069) on the number of stops, walking distance, and gait speed was found.

Section 2

The second section of the navigation path also was successfully completed by almost all participants. Only two participants in the MOBOT-unassisted and one in the MOBOT-assisted navigation condition were not able to reach the desired destination (table 3). There were no significant associations between the success rate and the navigation assistance condition, neither in the CI or NCI group nor in the total sample (p = 0.474-0.999).

A significant interaction effect between navigation assistance and cognitive status were observed for the completion time and the number of stops (p = 0.011-0.015). Effect sizes for these outcomes were between medium and large (η_p^2 = 0.165-0.180) (table 4). Post-hoc analysis showed that in the MOBOT-unassisted condition, the CI group had a significantly longer completion time and higher number of stops compared to the NCI group ($p \leq 0.001$) but not in the MOBOT-assisted condition (p = 0.691-0.809), and that MOBOT-assisted navigation led to a shorter completion time and to a reduced number of stops in the CI group ($p \leq 0.001$) but not in the NCI group (p = 0.422-0.925). For stopping time, walking distance, and gait speed, no significant interactions between independent variables were identified (p = 0.112-0.419; η_p^2 = 0.020-0.075); however, there was a significant main effect of navigation assistance on the stopping time (p = 0.016, η_p^2 = 0.162) and walking distance (p =

0.014, $\eta_p^2 = 0.171$), such that participants assigned into the MOBOT-assisted navigation condition showed a shorter stopping time and walking distance compared to the MOBOT-unassisted navigation condition. No significant main effect of navigation assistance was found on participants' gait speed ($p = 0.203$, $\eta_p^2 = 0.049$).

DISCUSSION

In the presented study, a special focus was placed on the design and the methodology to prevent the methodological shortcomings of previous studies on the user-evaluation of RRs [24,25]. A specific impairment-related user group definition was provided that was based on standardized clinical observation and/or established, standardized and validated assessment methods; a reasonable number of adequate participants were recruited, representative of potential end-users of the MOBOT rollator; an "intra-device" comparative study design (i.e., activated vs. inactivated navigation system within the same RR) and an assessment strategy specifically tailored to the navigation functionality of the MOBOT rollator with highly specific outcome measures was used to document the specific effect of the navigation system, and the data obtained were analyzed by statistical methods.

Almost all participants were able to reach the destinations of the navigation path, independent of the navigation assistance provided by the RR or their cognitive status. On both sections at least 90% of the participants were able to reach the specified destination, indicating a ceiling effect for the outcome parameter of success rate. The reason for this can be found in the design of the navigation path. The path included two freely-accessible (i.e., no closed doors to be open to reach the destinations), not too long (≈ 45 to 55 m) sections within a closed environment (i.e. ground floor of the hospital) to increase the likelihood that participants reach the destinations if they are just persistent enough in their searching efforts. As the more specific, qualitative sensor-based outcomes parameters, which have been suggested to be most appropriate for demonstrating the added value of high-tech functionalities of RRs [24], could only be calculated in a standardized manner for participants successfully completing a section, we designed such a path on purpose in order to minimize the number of dropouts (e.g., due to frustration caused by ongoing disorientation) and to maintain an adequate sample size for these outcomes.

On the less challenging section 1, the navigation assistance provided by the MOBOT rollator enabled the CI participants to complete the section significantly faster than without MOBOT-provided navigation assistance. The highly specific and tailored outcome parameters captured by the RR-integrated sensing technology allow for a more detailed and qualitative insight on why the CI participants with activated navigation system were able to complete this section faster, although the participants were not instructed to walk as fast as possible (no testing-the-limits approach). MOBOT-assisted navigation in the CI group was not associated with fewer stops, shorter walking distances, or higher gait speeds on section 1. The shorter completion time on this section was based rather on the significant shorter length of the time periods in which the CI participants substantially slowed down the RR. As this stopping time might be highly related to a participant's disorientation and attempt to (re-)orient his/herself in the environment, this result suggests that navigation assistance provided by a RR can effectively reduce such time periods in CI users. On section 1, no positive effects of the MOBOT's navigation system were found in the NCI participants, indicating that they were still able to orient themselves adequately in less challenging navigation tasks within unknown environments by the conventional signage.

Section 2 of the navigation path was a bit longer and included more junctions than section 1 (figure 2) and, therefore, seemed to be more challenging for participants to complete, as indicated by the smaller success rate, longer completion time, higher number of stops, and larger walking distance observed for this section when compared to section 1. On this more complex section, positive effects of the MOBOT's navigation system was most notably found also in the CI group. The navigation system enabled CI participants to complete section 2 faster and with a substantially smaller number of stops, indicating that the directional audio cues provided by the navigation system at critical waypoints led to less interrupted and smoother walking routes in CI users on this section. As more interrupted walking patterns were reported to be associated with a higher risk of falling in cognitively impaired people [41], the navigation assistance provided by a RR might contribute to increase safety during wayfinding of CI users in unknown indoor environments. On section 2, positive effects of the MOBOT-provided navigation assistance were observed not only in the CI group but also among the total sample that was MOBOT-assisted in navigation. Independent of their cognitive status, the participants completing this section with assistance of the navigation system showed shorter time periods in which the RR was slowed down and they were able to complete the section on a more direct and shorter walking route. The results for section 2 suggest that in more complex navigation tasks not only frail older rollator users with cognitive impairment can benefit from RR-provided navigation assistance but also those without cognitive impairment. In frail older rollator users, providing audio cues by a RR-integrated navigation system seem to be more effective for navigation assistance within complex unknown environments than providing visual cues in terms of conventional signposts, reducing the time required for orientation (i.e., decreased stopping time) and enhancing the wayfinding accuracy (i.e., decreased walking distance). A similar effect of RR-provided navigation assistance on the walking distance in the user group has been suggested in a previous study [42], which reported a shorter walking distance on a navigation path with the RR compared to that with a conventional walker. This finding of the study was, however, solely based on a use case description without statistical analysis of data [42].

Overall, the positive effect of the MOBOT-integrated navigation system on the study outcomes were most frequently observed only in the CI group, which confirms our hypothesis that CI users would profit more from such navigation assistance than NCI users. This positive effect in the CI group might be explained by the reduced cognitive load induced by the system. Completing the sections of the navigation path involved the simultaneous performance ("walking while navigating") of a motor task (i.e., walking with the RR) and an attention-demanding, cognitive task (i.e., orientation and wayfinding). Cognitively impaired older people have been reported to show lower motor and cognitive performances under such "dual-task" conditions [43,44]. Our results presented for the MOBOT-unassisted navigation condition showed similar effects of cognitive impairment on participants' navigation performance, as indicated by the significant longer completion times (both sections), the longer stopping time (section 1), and the higher number of stops (section 2) in the CI group compared to the NCI group under this condition. The detrimental effect of cognitive impairment on the navigation performance was, however, not observed for the participants that completed the sections under the MOBOT-assisted navigation condition. No positive effect of the navigation system was found on the gait speed during the pure walking episodes which would have presented a rather unspecific effect of the cognitive assistance provided by the navigation system on participants' motor performance. However, the more cognitive performances of the CI participants during completing the sections, which might be represented particularly by the number of stops and the stopping time (e.g., due to disorientation and wayfinding problems), have been substantially improved by the navigation system to a level even comparable to that of NCI participants, indicating that the navigation system seem to have compensated for the cognitive deficits in the CI group.

Navigation assistance integrated on a rollator may have the potential to reduce the burden of the staff in healthcare facilities. Accompanying rollator users with difficulty in navigation within geriatric rehabilitation centers, acute care hospital, or nursing homes to medical, therapeutic, social, and cosmetic activities (e.g., medical appointment, physiotherapy treatments, worship, hair dressing appointment), or repetitively during the day to the dining facilities, represents a time-consuming task that often requires human guidance assistance by staff. An RR that effectively provides navigation assistance can take over this task in order to enable the staff to focus and spent more time on higher-priority tasks in health care. Additionally, such navigation assistance might reduce the users with fear of getting lost and of not returning back to their rehabilitation ward, residential unit, or personal room without guidance assistance, which may have prevented them from being more physically and socially active, and thus may enhance independence in mobility, physical activity, and social participation.

LIMITATIONS AND FUTURE RESEARCH

Although our sample size was much larger than that of previous studies on the evaluation of RR-integrated, high-tech functionalities [25], it is rather small for our study design, thus limiting the statistical power to detect significant effects and the study's generalizability. However, significant effects as documented in this study, associated with large effect sizes, indicate a high effectiveness of the MOBOT-integrated navigation system in frail older users with cognitive impairment.

The low difficulty of the navigation path may have caused a ceiling effect on the success rate in the total sample and also on the sensor-based outcomes in the NCI group. This may have limited the impact of the navigation system on the ability to complete the sections in the total sample and also on the navigation performance in the NCI group. The rather low-complex design of the sections, however, reduced the number of dropouts in the already small sample for the more qualitative, sensor-based outcomes, which allowed for a more detailed and qualitative insight on how the navigation system assists and improves participants' navigation performance.

The criteria for moderate motor impairment in the user group definition actually also addressed the STS ability of the potential users. The MOBOT consortium defined this criterion because also a STS assistance functionality was implemented on the MOBOT rollator to support users with difficulty in the STS transfer. The special focus of the presented study was, however, to conduct an evaluation specifically tailored to document the specific effects of the MOBOT-integrated navigation system. For this, all other high-tech assistance functionalities, including the STS assistance, were deactivated during the test procedure. Assuming that the navigation system might also provide an added value to rollator users without need for STS assistance, the STS criterion in the user group definition was therefore not considered for the recruitment of our study participants.

A learning effect on the navigation path from section 1 to section 2 cannot be excluded. However, as the destination to be reached for section 2 was provided to the participants not before completing section 1, it seems unlikely to us that the participants have memorized crucial route information about section 2 already during section 1. In addition, this potential learning effect should have been balanced across the groups with and without MOBOT-assisted navigation.

We only used the MMSE for the assessment of the cognitive status. Although the MMSE is the most commonly used brief cognitive screening instrument in clinical practice [45], it has shown shortcomings in its ability to discriminate between CI and NCI subjects in some populations (for review see [46]). A more comprehensive neuropsychological test battery would improve the accuracy in detecting CI and NCI subjects in future studies.

It remains a future research question whether different types of audio cues (e.g., with [“turn right towards the elevator”] or without contextual information [“turn right”]) have different effects on the navigation performance of specific users. Future studies may compare different types of audio cues in different user groups (e.g., CI and NCI users) to identify which type of audio cues is most effective for which type of specific user.

CONCLUSION

The presented study clearly demonstrated that navigation assistance provided by a RR is effective for supporting wayfinding and navigation of CI end-users within a real-life environment. To the best of our knowledge, this is the first study that provides statistical evidence on the effectiveness of a RR-integrated navigation system in the intended user group of a RR.

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DISCLOSURE STATEMENT

The authors have no conflict of interests to declare.

REFERENCES

1 Cifuentes CA, Frizera A: Human-Robot Interaction Strategies for Walker-Assisted Locomotion. Schwitzerland, Springer International Publishing, 2016.

2 Martins MM, Santos CP, Frizera-Neto A, Ceres R: Assistive mobility devices focusing on Smart Walkers: Classification and review. Robot Auton Syst 2012;60:548-562.

3 Chaudhry SI, McAvay G, Ning Y, Allore HG, Newman AB, Gill TM: Geriatric impairments and disability: the cardiovascular health study. J Am Geriatr Soc 2010;58:1686-1692.

4 Martins M, Santos C, Frizera A, Ceres R: A review of the functionalities of smart walkers. Med Eng Phys 2015;37:917-928.

5 Wolbers T, Hegarty M: What determines our navigational abilities? Trends Cogn Sci 2010;14:138-146.

6 Moffat SD: Aging and spatial navigation: what do we know and where do we go? Neuropsychol Rev 2009;19:478-489.

7 Kirasic KC: Spatial cognition and behavior in young and elderly adults: implications for learning new environments. Psychol Aging 1991;6:10-18.

8 Poynter L, Kwan J, Sayer AA, Vassallo M: Does cognitive impairment affect rehabilitation outcome? J Am Geriatr Soc 2011;59:2108-2111.

9 Boustani M, Baker MS, Campbell N, Munger S, Hui SL, Castelluccio P, Farber M, Guzman O, Ademuyiwa A, Miller D, Callahan C: Impact and recognition of cognitive impairment among hospitalized elders. J Hosp Med 2010;5:69-75.

10 Bjork S, Juthberg C, Lindkvist M, Wimo A, Sandman PO, Winblad B, Edvardsson D: Exploring the prevalence and variance of cognitive impairment, pain, neuropsychiatric symptoms and ADL dependency among persons living in nursing homes; a cross-sectional study. BMC Geriatr 2016;16:154.

11 Cushman LA, Stein K, Duffy CJ: Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. Neurology 2008;71:888-895.

12 Hort J, Laczó J, Vyhnálek M, Bojar M, Bureš J, Vlček K: Spatial navigation deficit in amnestic mild cognitive impairment. Proc Natl Acad Sci USA 2007;104:4042-4047.

13 Chiu YC, Algase D, Whall A, Liang J, Liu HC, Lin KN, Wang PN: Getting lost: Directed attention and executive functions in early Alzheimer's disease patients. Dement Geriatr Cogn Disord 2004;17:174-180.

14 Pai MC, Jacobs WJ: Topographical disorientation in community-residing patients with Alzheimer's disease. Int J Geriatr Psychiatry 2004;19:250-255.

15 Burns PC: Navigation and the mobility of older drivers. J Gerontol B Psychol Sci Soc Sci 1999;54:S49-55.

16 Passini R, Rainville C, Marchand N, Joanette Y: Wayfinding in dementia of the Alzheimer type: planning abilities. J Clin Exp Neuropsychol 1995;17:820-832.

17 Wachaja A, Agarwal P, Zink M, Adame MR, Möller K, Burgard W: Navigating blind people with walking impairments using a smart walker. Auton Robots 2017;41:555-573.

18 Kulyukin V, Kutiyanawala A, LoPresti E, Matthews J, Simpson R: iWalker: toward a rollator-mounted wayfinding system for the elderly; IEEE Int Conf Radio Freq Identif. Las Vegas, NV, USA, , 2008, pp 303-311.

19 Glover J, Holstius D, Manojlovich M, Montgomery K, Powers A, Wu J, Kiesler S, Matthews J, Thrun S: A robotically-augmented walker for older adults. . Pittsburgh, Computer Science Department, Carnegie Mellon University, 2003.

20 Yu H, Spenko M, Dubowsky S: An adaptive shared control system for an intelligent mobility aid for the elderly. Auton Robots 2003;15:53-66.

21 Palopoli L, Argyros A, Birchbauer J, Colombo A, Fontanelli D, Legay A, Garulli A, Giannitrapani A, Macii D, Moro F, Nazemzadeh P, Padeleris P, Passerone R, Poier G, Prattichizzo D, Rizano T, Rizzon L, Scheggi S, Sedwards S: Navigation assistance and guidance of older adults across complex public spaces: the DALi approach. Intelligent Service Robotics 2015;8:77-92.

22 Rodriguez-Losada D, Matia F, Jimenez A, Galan R, Lacey G: Implementing Map Based Navigation in Guido, the Robotic SmartWalker: Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005, pp 3390-3395.

23 Morris A, Donamukkala R, Kapuria A, Steinfeld A, Matthews JT, Dunbar-Jacob J, Thrun S: A robotic walker that provides guidance; IEEE Int Conf Robot Autom. Taipei, Taiwan, , 2003, pp 25-30.

24 Werner C, Ullrich P, Geravand M, Peer A, Bauer JM, Hauer K: A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. Disabil Rehabil Assist Technol 2017:1-12.

25 Werner C, Ullrich P, Geravand M, Peer A, Hauer K: Evaluation studies of robotic rollators by the user perspective: A systematic review. Gerontology 2016;62:644-653.

26 Efthimiou E, Fotinea S-E, Goulas T, Dimou A-L, Koutsombogera M, Pitsikalis V, Maragos P, Tzafestas C: The MOBOT Platform – Showcasing Multimodality in Human-Assistive Robot Interaction; in Antona M, Stephanidis C (eds): Universal Access in Human-Computer Interaction. Interaction. Techniques and Environments. 10th International Conference, UAHCI 2016, Held as Part of HCI International 2016, Toronto, ON, Canada, July 17-22, 2016, Proceedings, Part II. Berlin, Heidelberg, Springer International Publishing, 2016, pp 382-391.

27 Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA, Wallace RB: A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol 1994;49:M85-94.

28 Folstein MF, Folstein SE, McHugh PR: "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975;12:189-198.
29 Quigley M, Conley K, Gerkey B, Faust J, Foote T, Leibs J, Wheeler R, Ng AY: ROS: An open-source robot operating system: IEEE Int Conf Robot Autom. Kobe, Japan, 2009,
30 Navigation - ROS Wiki, 2017, http://wiki.ros.org/navigation.
31 Marder-Eppstein E, Berger E, Foote T, Gerkey B, Konolige K: The Office Marathon: Robust navigation in an indoor office environment: IEEE Int Conf Robot Autom. Anchorage, AK, USA, 2010, pp 300-307.
32 Klancar G, Zdesar A, Blazic S, Skrjanc I: Wheeled Mobile Robotics: From Fundametals Towards Autonomous Systems. Butterworth-Heinemann, 2017.
33 Ballagi Á, Tihamér Á: Fuzzy odometry error approximation of a mobile robot. Annals of Craiova University, Series: Automation, Computers, Electronics and Mechatronics 2007;4 (31):13-17.
34 Peer A, Geravand M, Tzafestas CS, Moustris GP: Deliverable D3.2: Report on autonomous navigation algorithms, online configuration optimization, motion control, and physical human-robot interaction and collaboration, 2015, http://www.mobot-project.eu/userfiles/downloads/Deliverables/MOBOT_WP3_D3.2.pdf,
35 Thrun S, Fox D, Burgard W, Dellaert F: Robust monte carlo localization for mobile robots. Artif Intell 2001;128:99-141.
36 Sheikh JI, Yesavage JA: Geriatric Depression Scale (GDS): Recent evidence and development of a shorter version; in Brink TL (ed): Clinical Gerontology: A Guide to Assessment and Intervention. New York, NY, The Haworth Press, 1986, pp 165-173.
37 Hauer KA, Kempen GI, Schwenk M, Yardley L, Beyer N, Todd C, Oster P, Zijlstra GA: Validity and sensitivity to change of the falls efficacy scales international to assess fear of falling in older adults with and without cognitive impairment. Gerontology 2011;57:462-472.
38 Tinetti ME: Performance-oriented assessment of mobility problems in elderly patients. J Am Geriatr Soc 1986;34:119-126.
39 Fried LP, Tangen CM, Walston J, Newman AB, Hirsch C, Gottdiener J, Seeman T, Tracy R, Kop WJ, Burke G, McBurnie MA: Frailty in older adults: evidence for a phenotype. J Gerontol A Biol Sci Med Sci 2001;56:M146-156.
40 Delbaere K, Close JC, Mikolaizak AS, Sachdev PS, Brodaty H, Lord SR: The Falls Efficacy Scale International (FES-I). A comprehensive longitudinal validation study. Age Ageing 2010;39:210-216.
41 Schwenk M, Hauer K, Zieschang T, Englert S, Mohler J, Najafi B: Sensor-derived physical activity parameters can predict future falls in people with dementia. Gerontology 2014;60:483-492.
42 Graf B: An adaptive guidance system for robotic walking aids. J Comput Inf Technol 2009;17:109-120.
43 Montero-Odasso M, Muir SW, Speechley M: Dual-task complexity affects gait in people with mild cognitive impairment: the interplay between gait variability, dual tasking, and risk of falls. Arch Phys Med Rehabil 2012;93:293-299.
44 Hauer K, Marburger C, Oster P: Motor performance deteriorates with simultaneously performed cognitive tasks in geriatric patients. Arch Phys Med Rehabil 2002;83:217-223.
45 Shulman KI, Herrmann N, Brodaty H, Chiu H, Lawlor B, Ritchie K, Scanlan JM: IPA survey of brief cognitive screening instruments. Int Psychogeriatr 2006;18:281-294.
46 Lonie JA, Tierney KM, Ebmeier KP: Screening for mild cognitive impairment: a systematic review. Int J Geriatr Psychiatry 2009;24:902-915.

Table 1. Audio cues provided by the MOBOT navigation system on section 1 and 2 of the navigation path

Section 1: Starting position to hospital chapel		**Section 2: Hospital chapel to admission center**	
Guard point	**Audio cue**	**Guard point**	**Audio cue**
1.0	"Walk straight ahead along the corridor."	2.0	"Leave the chapel."
1.1	"Keep straight on."	2.1	"Turn right and walk into the entrance hall."
1.2	"Keep straight on."	2.2	"Turn diagonally to the right and walk to the end of the entrance hall."
1.3	"Turn diagonally to the right and walk through the entrance hall."	2.3	"Turn left and walk straight ahead along the corridor."
1.4	"Turn left and walk towards the elevator."	2.4	"Turn right and walk straight ahead."
1.5	"Turn left in front of the elevator and walk into the chapel."	2.5	"Keep straight on."
1.6	"You have reached your destination."	2.6	"You have reached your destination."

Table 2. Participants' characteristics for the group with and without MOBOT-assisted navigation

Variables	**MOBOT-unassisted navigation** (*n* = 20)	**MOBOT-assisted navigation** (*n* = 22)	***p*-value**
Age, years, mean ± SD[a]	80.7 ± 9.5	84.1 ± 7.7	0.204
Gender, female, *n* (%)[b]	10 (50.0)	18 (81.2)	0.029
MMSE, score, mean ± SD[a]	25.9 ± 3.3	25.9 ± 4.0	0.958
Habitual gait speed[c], m/s, mean ± SD[a]	0.60 ± 0.21	0.54 ± 0.22	0.381
POMA, score, mean ± SD[a]	18.9 ± 5.6	19.5 ± 6.4	0.766
Recent history of falls, *n* (%)[b]	11 (55.0)	14 (63.6)	0.707
Short-FES-I, score, median (range)[d]	10.0 (7-17)	9.5 (7-20)	0.731
GDS, score, median (range)[d]	1.5 (0-9)	2.0 (0-11)	0.912
Living situation, n (%)[b]			0.768
Community-dwelling	10 (45.5)	12 (54.5)	
Institutionalized	10 (50.0)	10 (50.0)	
Place of recruitment, n (%)[e]			> 0.999
Rehabilitation/acute care wards	3 (42.9)	4 (57.1)	
Nursing home	9 (50.0)	9 (50.0)	
Outpatient rehabilitation sports club	8 (47.6)	9 (52.4)	

MMSE, Mini-Mental State Examination; [c]assessed by the 4-meter walk test; POMA, Performance Oriented Mobility Assessment; Short-FES-I, Short Falls Efficacy Scale-International; GDS, Geriatric Depression Scale (15-item version); p-values are given for t-tests[a], Chi-square tests[b], Mann-Whitney U-tests[d], and Fisher's exact test[e] applied to test for differences between the MOBOT-assisted and unassisted condition.

Table 3. Success rate for section 1 and 2 of the navigation path

Navigation path	Cognitive Status		Success rate, *n* (%) MOBOT-unassisted navigation	MOBOT-assisted navigation	*p*-value[a]
Section 1	CI (*n*=20)	Yes	9 (90.0)	9 (90.0)	> 0.999
		No	1 (10.0)	1 (10.0)	
	NCI (*n*=22)	Yes	10 (100.0)	11 (91.7)	> 0.999
		No	0 (0.0)	1 (8.3)	
	Total (*n*=42)	Yes	19 (95.0)	20 (90.9)	> 0.999
		No	1 (5.0)	2 (9.1)	
Section 2	CI (*n*=20)	Yes	8 (80.0)	10 (100.0)	0.474
		No	2 (20.0)	0 (0.0)	
	NCI (*n*=21)	Yes	10 (100.0)	10 (90.9)	> 0.999
		No	0 (0.0)	1 (9.1)	
	Total (*n*=41)	Yes	18 (90.0)	20 (95.2)	0.606
		No	2 (10.0)	1 (4.7)	

[a]*p*-value for Fisher's exact test.

Table 4. Effects of the navigation assistance condition and cognitive status on sensor-based outcome parameters of section 1 and 2

Variables	MOBOT-unassisted navigation *n*	Mean ± SD	MOBOT-assisted navigation *n*	Mean ± SD	Difference[a]	*p*-value	Effect size
Section 1							
Completion time, s						0.185[b]	0.050[c]
CI	9	139.9 ± 60.6	9	84.1 ± 28.1	-55.8	0.002[d]	0.235[e]
NCI	10	63.7 ± 9.9	11	86.9 ± 35.7	+23.2		
Stopping time, s						0.107[b]	0.072[c]
CI	9	10.4 ± 12.3	9	2.4 ± 5.1	-8.0	0.040[d]	0.115[e]
NCI	10	0.7 ± 1.5	11	1.7 ± 3.0	+1.0		
Number of stops, n						0.286[b]	0.033[c]
CI	9	2.2 ± 2.4	9	0.9 ± 1.8	-1.3	0.125[d]	0.066[e]
NCI	10	0.3 ± 0.7	11	0.6 ± 0.9	+0.3		
Walking distance, m						0.117[b]	0.069[c]
CI	9	84.1 ± 28.1	9	55.3 ± 19.8	-28.8	0.072[d]	0.089[e]
NCI	10	43.7 ± 0.5	11	44.4 ± 0.6	+0.7		
Gait speed, m/s						0.909[b]	<0.001[c]
CI	9	0.47 ± 0.17	9	0.57 ± 0.11	+0.10	0.104[d]	0.074[e]
NCI	10	0.70 ± 0.11	11	0.61 ± 0.27	-0.09		
Section 2							
Completion time, s						0.011[b]	0.180[c]
CI	8	225.9 ± 134.5	10	104.9 ± 28.1	-121.0	0.015[d]	0.165[e]
NCI	9	100.3 ± 28.5	10	97.2 ± 39.1	-3.1		
Stopping time, s						0.016[b]	0.162[c]
CI	8	26.7 ± 34.6	10	4.0 ± 6.7	-22.7	0.112[d]	0.075[e]
NCI	9	4.9 ± 6.1	10	0.0 ± 0.0	-4.9		
Number of stops, n						0.001[b]	0.307[c]
CI	8	10.4 ± 9.3	10	0.8 ± 1.3	-9.6	0.011[d]	0.180[e]
NCI	9	1.7 ± 2.1	10	0.0 ± 0.0	-1.7		
Walking distance, m						0.014[b]	0.171[c]
CI	8	69.8 ± 20.9	10	55.9 ± 4.3	-13.9	0.221[d]	0.045[e]
NCI	9	59.3 ± 9.3	10	54.4 ± 1.0	-4.9		
Gait speed, m/s						0.203[b]	0.049[c]
CI	8	0.46 ± 0.18	10	0.59 ± 0.14	+0.13	0.419[d]	0.020[e]
NCI	9	0.63 ± 0.07	10	0.67 ± 0.30	+0.03		

[a]Difference is calculated as: (assisted score – unassisted score); [b]*p*-value for effect of navigation assistance; [c]Effect size η_p^2 for effect of navigation assistance; [d]*p*-value for interaction effect between navigation assistance and cognitive status; [e]Effect size η_p^2 for interaction effect between navigation assistance and cognitive status.

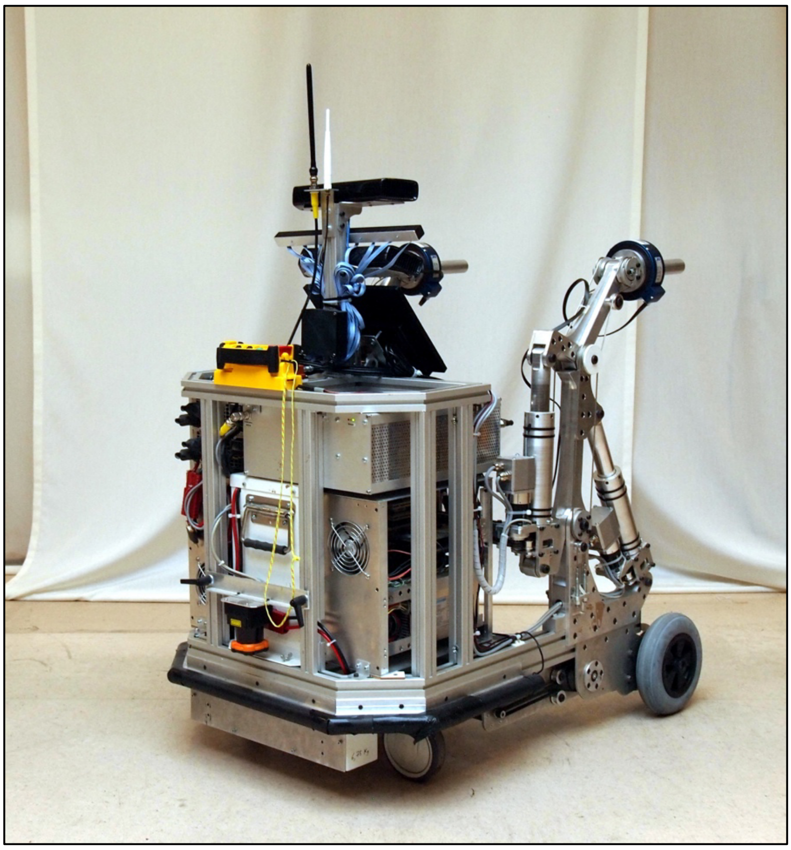

Fig. 1. The MOBOT rollator-type mobility assistant

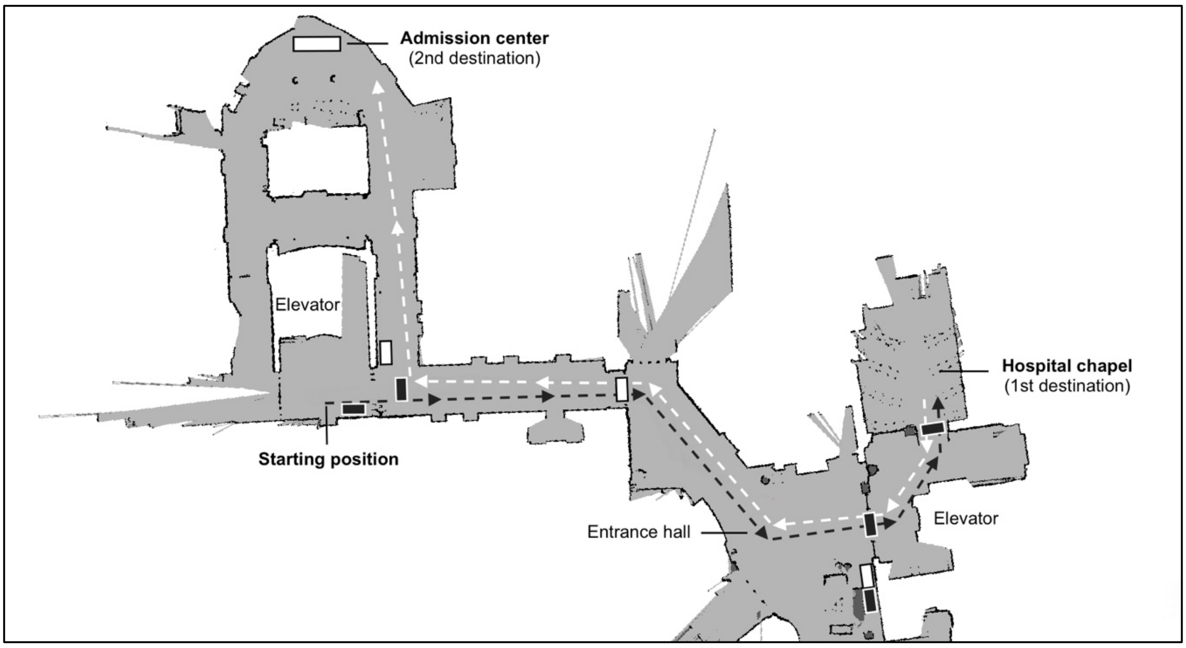

Fig. 2. Layout of the navigation path at the ground floor of the hospital.
The gray area visualizes the test environment. The dashed dark-gray line indicates the route from the starting position to the hospital chapel (section 1); the dashed white line indicates the route from the hospital chapel to the admission center (section 2). Dark-gray squares represent signposts to the hospital chapel; white squares represent signposts to the admission center.

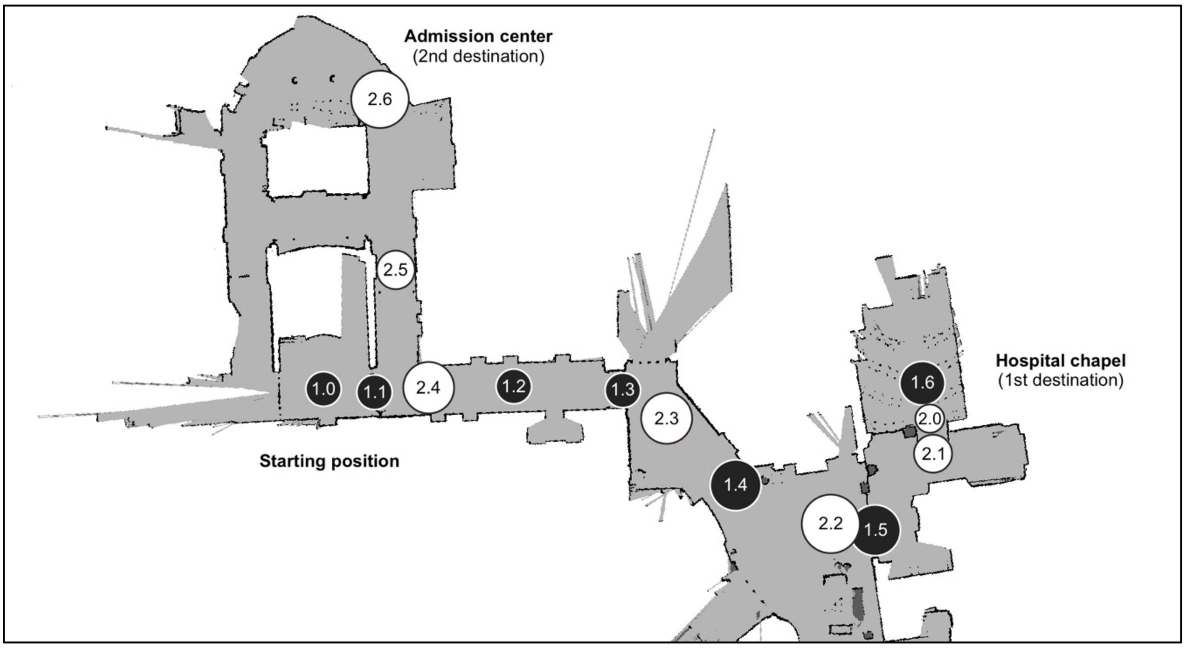

Fig. 3. Position of the guard points on the navigation path.
Dark-gray circles represent the guard points for section 1 (starting position to chapel); white circles represent the guard points for section 2 (hospital chapel to admission center). The size of the circles indicates the area in which the audio cues were provided.

Manuskript IV

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Assessing the concurrent validity of a gait analysis system integrated into a smart walker in older adults with gait impairments

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Abstract

Objective: To assess the concurrent validity of a smart walker–integrated gait analysis system with the GAITRite® system for measuring spatiotemporal gait parameters in potential users of the smart walker.
Design: Criterion standard validation study.
Setting: Research laboratory in a geriatric hospital.
Participants: Twenty-five older adults (⩾65 years) with gait impairments (habitual rollator use and/or gait speed <0.6 m/s) and no severe cognitive impairment (Mini-Mental State Examination ⩾17).
Main measures: Stride, swing and stance time; stride length; and gait speed were simultaneously recorded using the smart walker–integrated gait analysis system and the GAITRite system while participants walked along a 7.8-m walkway with the smart walker. Concurrent criterion-related validity was assessed using the Bland–Altman method, percentage errors (acceptable if <30%), and intraclass correlation coefficients for consistency ($ICC_{3,1}$) and absolute agreement ($ICC_{2,1}$).
Results: Bias for stride, swing and stance time ranged from −0.04 to 0.04 seconds, with acceptable percentage errors (8.7%–23.0%). Stride length and gait speed showed higher bias ($mean_{bias}$ (SD) = 0.20 (0.11) m; 0.19 (0.13) m/s) and not acceptable percentage errors (31.3%–42.3%). Limits of agreement were considerably narrower for temporal than for spatial-related gait parameters. All gait parameters showed good-to-excellent consistency ($ICC_{3,1}$ = 0.72–0.97). Absolute agreement was good-to-excellent for temporal ($ICC_{2,1}$ = 0.72–0.97) but only poor-to-fair for spatial-related gait parameters ($ICC_{2,1}$ = 0.37–0.52).
Conclusion: The smart walker–integrated gait analysis system has good concurrent validity with the GAITRite system for measuring temporal but not spatial-related gait parameters in potential end-users

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of the smart walker. Stride length and gait speed can be measured with good consistency, but with only limited absolute accuracy.

Keywords
Smart walker, gait analysis, elderly, validity, assistive devices

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Introduction

Recent technological developments in gait analysis focus on ambulatory solutions that allow for unobtrusive and continuous gait monitoring in real-life environments outside the laboratory such as wearable sensors.[1] However, these sensors require an individual's willingness to wear them and may cause discomfort and adherence issues. In addition, to our knowledge, the validity of body-worn sensors for measuring spatiotemporal gait parameters in older adults with walking aids is still unknown. Considering that walkers or rollators are prescribed routinely to patients during geriatric rehabilitation and that many older adults with mobility limitations have to use them for ambulation, there is the need for valid gait analysis systems to unobtrusively and continuously capture spatiotemporal gait parameters also in these walking aid users.

Technological advances have led to the development of 'smart walkers' with various high-tech functionalities such as monitoring a user's gait.[2] Different sensor types (e.g. vision-based sensors,[3] inertial measurement units,[4] force sensors[5]) have been used to implement gait analysis on a smart walker. Independent of the technical implementations, to our knowledge, previous validation studies of smart walker–integrated gait analysis systems suffered from methodological shortcomings such as small sample sizes, participants not representative of potential users, no criterion standard comparisons and/or no statistical analyses.[3–5]

The study aim was to assess the concurrent validity of a smart walker–integrated gait analysis for measuring spatiotemporal gait parameters with a criterion standard (GAITRite® system) in a reasonable number of potential smart walker users.

Methods

The study was conducted between 1 November and 5 December 2014, with approval of the ethics committee of the Medical Faculty of the Heidelberg University (S-358/2013) and in accordance with the Declaration of Helsinki. All participants gave written informed consent.

Participants were recruited from rehabilitation wards of a geriatric hospital, from nursing homes and from a hospital-associated sports club for geriatric outpatient rehabilitation. According to the defined users of our smart walker,[6] inclusion criteria were age $\geqslant$65 years, moderate gait impairments (rollator use in daily life and/or 4 m usual gait speed[7] $<$0.6 m/s) and no severe cognitive impairment (Mini-Mental State Examination[8] score $\geqslant$17 points).

The GAITRite system (CIR Systems Inc., Havertown, PA, USA) is an electronic walkway with embedded pressure sensors, representing a well-established and validated method for automated gait analysis in clinical settings.[9] The GAITRite system used in this study was 5.79 m long and 0.89 m wide (active area: 4.88 m $\times$ 0.61 m; sampling rate 120 Hz).

The smart walker integrates innovative functionalities such as sit-to-stand assistance, obstacle avoidance, navigation assistance and gait monitoring. A detailed description of all its functionalities has been provided previously.[6,10] For this study, only the gait analysis system of the smart walker was activated and all other innovative functionalities were deactivated. The smart walker–integrated gait analysis system is based on a standard laser range finder (UBG-04LX-F01; Hokuyo Automatic Co., Ltd, Osaka, Japan; sampling period 28 ms/scan) mounted at the rear side of the four-wheeled smart walker at a fixed height of 35 cm from the ground with a viewing direction towards the user's legs to record their motion at a horizontal plane below the knee level. Gait parameters were extracted by pre-processing the laser data using a Probabilistic Data Association Particle Filtering system and subsequent modelling of the user's walking pattern based on a Hidden Markov Model approach, as previously described.[11] The overall goal of this gait analysis system is not only to validly measure gait parameters continuously during smart walker use but also to serve as a basis for future development of a context-aware smart walker that generates and provides real-time assistive actions (e.g. distance/velocity adjustments) according to the user‘s current walking pattern.

After a familiarization phase, in which participants freely moved around with the smart walker for approximately 2–5 minutes, they were instructed to walk along a GAITRite instrumented walkway with the smart walker at self-selected maximum gait speed. Each walk was initiated and terminated 1 m before and after the walkway (total length = 7.79 m) to account for acceleration and deceleration. No practice trials were performed on the instrumented walkway. After data recording, each walk was checked to ensure that the same steps, and the same number of steps, were used to calculate mean values for spatiotemporal gait parameters (stride, swing and stance time; stride length; and gait speed) by both processing methods. Mean values were used because average gait parameters are usually of clinical interest.

Between-method differences (bias) and 95% limits of agreement ($mean_{bias} \pm 1.96 \times SD_{bias}$) were determined using the Bland–Altman method.[12] Percentage errors, calculated as $100 \times (1.96 \times SD_{bias})/((mean_{smart\ walker} + mean_{GAITRite})/2)$, were considered to be clinically acceptable if $<30\%$.[13] Intraclass correlation coefficients (ICCs) with 95% confidence intervals were calculated to determine the consistency ($ICC_{3,1}$) and absolute agreement ($ICC_{2,1}$) between the mean gait parameters measured by the two methods. ICCs were interpreted as poor (<0.40), fair to good (0.40–0.75) and excellent (>0.75).[14] The sample size for this study was estimated to be $\geqslant 23$ participants, based on an acceptable ICC of 0.70 and an expected ICC of 0.90 for two measurements (smart walker and GAITRite), a significance level (α) of 0.05 and a statistical power ($1-\beta$) of 0.80.[15] A two-sided P-value of <0.05 indicated statistical significance. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

Results

The sample included 25 older adults with a mean (SD) age of 84.1 (5.4) years, moderate gait impairments (usual gait speed = 0.48 (0.15) m/s) and no severe cognitive impairment (Mini-Mental State Examination score = 24.5 (4.1) points). Sixteen (64%) participants were geriatric rehabilitation patients, seven (28%) were members of the sports club for geriatric outpatient rehabilitation, and two (8%) were nursing home residents.

Mean bias for the stride, swing and stance time ranged from –0.04 to 0.04 seconds, with clinically acceptable percentage errors (8.7%–23.0%) (Table 1). Stride length and gait speed showed both a substantially higher bias ($mean_{bias}$ (SD) = 0.20 (0.11) m; 0.19 (0.13) m/s) and a clinically not acceptable percentage error (31.3%–42.3%). Limits of agreement were considerably narrower for the stride (–0.10 to 0.11 seconds), swing (–0.07 to 0.16 seconds) and stance time (–0.12 to 0.20 seconds) than for the stride length (–0.07 to 0.44 m) and gait speed (–0.02 to 0.42 m/s) (Figure 1). Consistency between both methods was good to excellent for all gait parameters ($ICC_{3,1}$ = 0.72–0.97). Absolute agreement was also good to excellent for the stride, swing and stance time ($ICC_{2,1}$ = 0.72–0.97), but only poor to fair for the stride length ($ICC_{2,1}$ = 0.37) and gait speed ($ICC_{2,1}$ = 0.52).

Discussion

This initial validation study showed that the smart walker–integrated gait analysis system provides comparable data to the GAITRite system for the temporal gait parameters of stride, swing and stance time in potential smart walker users. Although also a good consistency for the stride length and gait speed

Table 1. Mean values (±SD), mean difference scores (bias ± SD), limits of agreement, mean percentage errors and intraclass correlation coefficients for consistency and absolute agreement for each gait parameter.

Gait parameter	GAITRite®	Smart walker	Bias	95% LOA	PE	Consistency $ICC_{3,1}$ (95% CI)	Absolute agreement $ICC_{2,1}$ (95% CI)
Stride time (s)	1.21 ± 0.24	1.21 ± 0.22	–0.01 ± 0.05	–0.10 to 0.11	8.7	0.97 (0.94 to 0.99)	0.97 (0.94 to 0.98)
Swing time (s)	0.48 ± 0.09	0.52 ± 0.10	–0.04 ± 0.06	–0.07 to 0.16	22.8	0.80 (0.59 to 0.91)	0.72 (0.27 to 0.89)
Stance time (s)	0.73 ± 0.18	0.69 ± 0.13	0.04 ± 0.08	–0.12 to 0.20	23.0	0.86 (0.70 to 0.93)	0.83 (0.62 to 0.93)
Stride length (m)	0.80 ± 0.17	0.60 ± 0.13	0.20 ± 0.11	–0.02 to 0.42	31.3	0.72 (0.45 to 0.86)	0.37 (–0.10 to 0.73)
Gait speed (m/s)	0.70 ± 0.22	0.51 ± 0.15	0.19 ± 0.13	–0.07 to 0.44	42.3	0.76 (0.53 to 0.89)	0.52 (–0.10 to 0.82)

LOA: limits of agreement; PE: percentage error; ICC: intraclass correlation coefficient; CI: confidence interval.
All ICCs for consistency and absolute agreement were significant at $P < 0.001$.

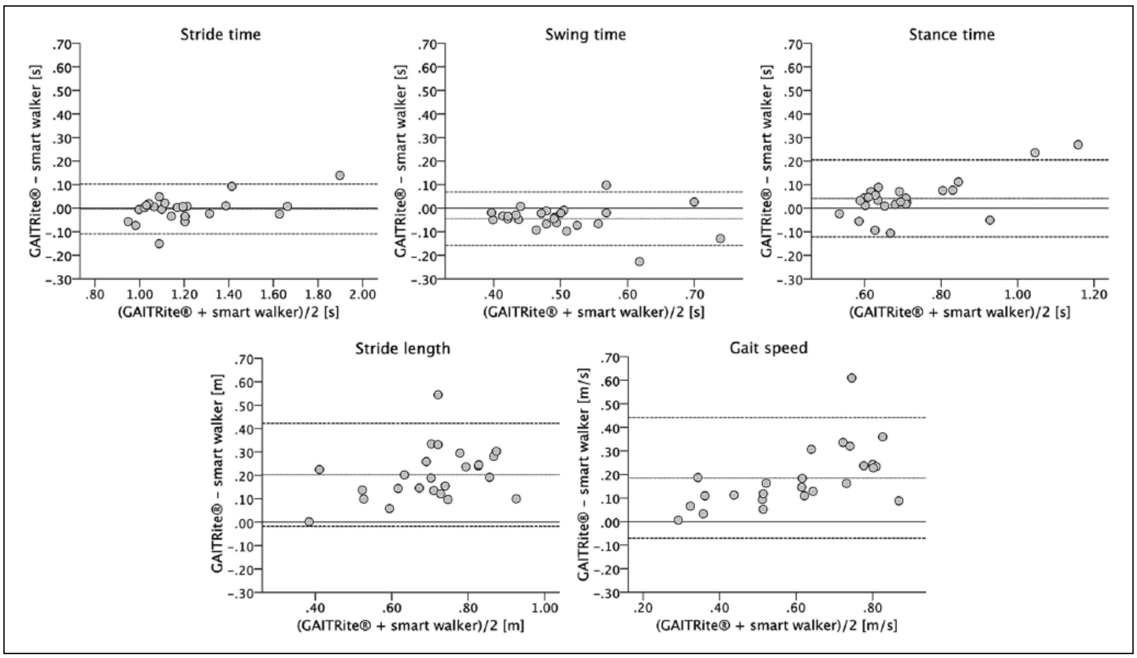

Figure 1. Bland–Altman plots for comparison between the GAITRite® system and the smart walker–integrated gait analysis system. Dotted lines indicate bias and dashed lines indicate upper and lower 95% limits of agreement (±1.96 SD of the bias).

was found between these two systems, they cannot be used interchangeably when absolute values of these spatial-related gait parameters are required (e.g. for comparison with normative values).

The low absolute agreement for spatial-related gait parameters can be explained by the fact that the GAITRite system refers to the distance between heel contacts on the electronic walkway for measuring the stride length, while the smart walker–integrated gait analysis system refers to the distance between leg placements recorded by the laser range finder 35 cm above the walkway. The reference points of the laser range finder are closer to the pivot of the lower legs (i.e. knee joint) and thus travel a shorter distance during the gait cycle, resulting in the shorter stride length and also the lower gait speed. While absolute agreement for these spatial-related parameters seems lacking, the extent to which they agree with the GAITRite system on the relative values (i.e. consistency) was good to excellent, suggesting that the stride length and gait speed of the smart walker–integrated gait analysis system may be themselves reliable and as good as those of the GAITRite system in determining meaningful changes in a user's walking pattern.

Compared to previous validation studies of smart walker–integrated gait analysis systems, the strengths of this study are that a reasonable number of participants representative of potential smart walker users were recruited, a well-established, validated gait analysis system was used as criterion standard for comparison, and the data obtained were analysed by adequate statistical methods. However, this study also has some limitations. Only short straight walking in a controlled laboratory environment was evaluated, as limited by our criterion standard. Future studies should assess the validity of the smart walker-gait analysis system in less constrained movement situations. Our participants were predominantly females, limiting the generalizability of the results to males. However, we did not expect gender to affect the concurrent validity between the two systems.

The smart walker–integrated gait analysis system can provide clinicians and researchers the ability to unobtrusively capture gait parameters of smart walker users, without any sensors being attached to the user's body. Our study represents a first step towards a continuous gait analysis of smart walker users in natural environments. The applicability of the system for such long-term gait monitoring needs to be confirmed in future studies.

Clinical Messages

- The smart walker–integrated gait analysis system has good concurrent validity with the GAITRite® system for measuring temporal gait parameters in potential smart walker users.
- Stride length and gait speed can also be measured consistently; however, modifications are recommended to improve the absolute measurement accuracy for these spatial-related gait parameters.

Author contributions

C.W. was responsible for study concept, design and management, test administration, data collection, statistical analysis and interpretation of data, and preparation of manuscript. G.C., X.S.P., and C.S.T. were involved in study concept and design, analysis and interpretation of data, and preparation of manuscript. J.M.B. contributed to interpretation of data and preparation of manuscript. K.H. was responsible for study concept, design and management, interpretation of data and preparation of manuscript. All authors contributed to interpretation of data, drafting the manuscript and final approval of the manuscript to be published.

Declaration of conflicting interests

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References

1. Chen S, Lach J, Lo B, et al. Toward pervasive gait analysis with wearable sensors: a systematic review. *IEEE J Biomed Health Inform* 2016; 20(6): 1521–1537.
2. Martins M, Santos C, Frizera A, et al. A review of the functionalities of smart walkers. *Med Eng Phys* 2015; 37(10): 917–928.
3. Paulo J, Peixoto P and Nunes UJ. ISR-AIWALKER: Robotic walker for intuitive and safe mobility assistance and gait analysis. *IEEE Trans Hum Mach Syst* 2017; 47(6): 1110–1122.
4. Wang T, Merlet J-P, Sacco G, et al. Walking analysis of young and elderly people by using an intelligent walker ANG. *Rob Auton Syst* 2016; 75: 96–106.
5. Ballesteros J, Urdiales C, Martinez AB, et al. Automatic assessment of a rollator-user's condition during rehabilitation using the i-Walker platform. *IEEE Trans Neural Syst Rehabil Eng* 2017; 25(11): 2009–2017.
6. Werner C, Moustris GP, Tzafestas CS, et al. User-oriented evaluation of a robotic rollator that provides navigation assistance in frail older adults with and without cognitive impairment. *Gerontology* 2018; 64(3): 278–290.
7. Guralnik JM, Ferrucci L, Pieper CF, et al. Lower extremity function and subsequent disability: consistency across studies, predictive models, and value of gait speed alone compared with the short physical performance battery. *J Gerontol A Biol Sci Med Sci* 2000; 55(4): M221–M231.
8. Folstein MF, Folstein SE and McHugh PR. 'Mini-mental state'. A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res* 1975; 12(3): 189–198.
9. Webster KE, Wittwer JE and Feller JA. Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. *Gait Posture* 2005; 22(4): 317–321.
10. Efthimiou E, Fotinea S-E, Goulas T, et al. The MOBOT platform – showcasing multimodality in human-assistive robot interaction. In: Antona M and Stephanidis C (eds) *Universal access in human-computer interaction techniques and environments 10th international conference, UAHCI 2016, held as part of HCI International 2016, Toronto, ON, Canada, July 17–22, 2016, proceedings, part II*. Berlin: Springer International Publishing, 2016, pp.382–391.
11. Chalvatzaki G, Papageorgiou XS and Tzafestas CS. Towards a user-adaptive context-aware robotic walker-with a pathological gait assessment system: first experimental study. In: *2017 IEEE/RSJ international conference on intelligent robots and systems (IROS)*, Vancouver, BC, Canada, 24–28 September 2017, pp.5037–5042. New York: IEEE.
12. Bland JM and Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1(8476): 307–310.
13. Critchley LA and Critchley JA. A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. *J Clin Monit Comput* 1999; 15(2): 85–91.
14. Fleiss JL. *The design and analysis of clinical experiments*. New York: John Wiley & Sons, 1986.
15. Zou GY. Sample size formulas for estimating intraclass correlation coefficients with precision and assurance. *Stat Med* 2012; 31(29): 3972–3981.

Manuskript V

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An Integrated Decision Making Approach for Adaptive Shared Control of Mobility Assistance Robots

Milad Geravand · Christian Werner · Klaus Hauer · Angelika Peer

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Abstract Mobility assistance robots (MARs) provide support to elderly or patients during walking. The design of a safe and intuitive assistance behavior is one of the major challenges in this context. We present an integrated approach for the context-specific, on-line adaptation of the assistance level of a rollator-type mobility assistance robot by gain-scheduling of low-level robot control parameters. A human-inspired decision-making model, the Drift-Diffusion Model, is introduced as the key principle to gain-schedule parameters and with this to adapt the provided robot assistance in order to achieve a human-like assistive behavior. The mobility assistance robot is designed to provide a) cognitive assistance to help the user following a desired path towards a predefined destination as well as b) sensorial assistance to avoid collisions with obstacles while allowing for an intentional approach of them. Further, the robot observes the user long-term performance and fatigue to adapt the overall level of c) physical assistance provided. For each type of assistance a decision-making problem is formulated that affects different low-level control parameters. The effectiveness of the proposed approach is demonstrated in technical validation experiments. Moreover, the proposed approach is evaluated in a user study with 35 elderly persons. Obtained results indicate that the proposed gain-scheduling technique incorporating ideas of human decision-making models shows a general high potential for the application in adaptive shared control of mobility assistance robots.

Keywords Mobility Assistance Robot · Adaptive Shared Control · Decision Making

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1 Introduction

A sufficient motor performance that allows performing physical daily activities is a critical requirement for maintaining mobility and vitality, especially for elderly people and patients. Changes due to aging or disease may result in the limitation of human motor performance, sensing capabilities and cognitive functions, and thus reduce the ability to perform activities of daily living such as walking, transferring or performing personal hygiene. This again often leads to less autonomy and a decreased quality of life and self-esteem. Thus, the constantly increasing elderly population, especially in industrialized countries, has led to a strong demand for healthcare specialists and assistive devices. Mobility assistance robots (MARs) can partly cover this demand by providing physical, sensorial, and cognitive assistance [31, 44, 55].

How to adapt the provided assistance depending on the actual context is a major challenge in the controller design of assistive robots. An assistive robot under direct user control can have difficulties guaranteeing acceptable performance and safety due to cognitive, sensorial and physical weaknesses of target users being elderly or disabled people. On the other hand, a fully autonomous system that ignores the user's intention can result in user dissatisfaction and dangerous situations in case of human and robot disagreement. The latter can highly affect acceptability of such systems by their end-users (elderlies and patients) [1, 3, 12, 14, 20]. Therefore, a shared control approach allowing human and robot to share the control over resulting actions is typically employed.

Shared control has been studied for different applications of human-machine interaction: For example [2, 4, 28, 40, 53] investigated shared control for teleoperation, space and aviation systems, [35–38] explored similar principles for surgery applications, while [7] and [54] report on shared control for powered wheelchairs.

In literature most adaptive shared control mechanisms attempt to tune the level of assistance to improve metrics related to the task. Thus, an inherent difficulty lies in deciding on suitable metrics and adaptation strategies such that the overall robot assistance results in a natural behavior to the user. In this context *natural* refers to an intuitive cooperative control scheme that considers human and robot to collaborate as *peers*, meaning that the robot is allowed to make own decisions to online adjust its level of assistance taking current and past information on the user and environment into account. We believe that an intuitive and natural behavior can be achieved if the robot can decide on the provided level of assistance in a similar way to humans. Thus, we formulate the problem of the allocation of control authority as a decision-making problem and employ human-inspired decision-making models. We use the Drift-Diffusion (DD) model, firstly proposed by [9], that describes the decision-making mechanism in humans as a process in which decisions are based on past decisions and the decision criteria are continuously adjusted in order to maximize the reward obtained throughout task execution. Following the principles of the DD model, we propose a mathematical formulation for an integrated control architecture to adapt the parameters of the shared control system of a rollator-type MAR. The proposed architecture allows to intuitively adapt the short-term a) *cognitive assistance* helping the user to follow a desired path towards a predefined destination, the robot b) *sensorial assistance* to avoid collisions with obstacles and to allow an intentional approach of them, and the more long-term adaptation of the robot c) *physical assistance* based on measured user performance and fatigue. We illustrate the effectiveness of the proposed architecture in experiments and evaluate its performance by conducting a user study with elderly. Obtained results indicate an acceptable user satisfaction and show a general high potential of the proposed adaptive shared control architecture for MARs.

This paper is organized as follows: Section 2 reviews related work. Section 3 introduces the MAR and the implemented admittance control approach. The integrated adaptive shared control architecture is presented in Section 4, while Section 5 provides details on the implementation of the adaptation policies for the sensorial, cognitive and physical assistance. Finally, Section 6 discusses the experimental setup and reports on technical validation experiments and the performed user study with elderly users. Section 7 concludes the work.

2 Related Work

This section reviews literature on adaptive shared control of MARs as well as studies on decision making in humans and related models.

2.1 Adaptive Shared Control for MARs

Variable admittance control is the most common control scheme in MARs. An admittance model defines the sensitivity of the device to the applied human forces according to a specified desired mass and damping that should be rendered by the device. The behavior of the system can be modified by adapting this admittance, or by manipulation of the force applied by the user. In [32, 33, 57] the authors for example improve maneuverability by applying a transformation on the user force that allows to online modify the center of rotation of the mobility assistant. In [24, 26, 27] authors propose to include also a braking force to the admittance law and to achieve the robot desired behavior such as fall prevention, gravity compensation on slopes or step avoidance by proper activation of the brakes. Different environment-adaptive approaches, mainly based on the inclusion of additional forces/torques to the admittance model for obstacle avoidance and goal-seeking (generated based on environment information) can be found in [23–25, 34, 48, 49, 56]. These approaches can result in an active robot behavior which can lead to dangerous situations, for example in case the human releases the handles and the robot continuous to move or the human plans to walk on a straight path, while the system accidently turns to circumvent an obstacle.

Only few works consider the history of the human performance during the interaction with the robot in the adaptation law of the admittance controller. In [64] the author proposes a cost function with forgetting factor evaluating the user's performance by combining multiple criteria like the proximity to obstacles, the deviation from the planned trajectory and human stability criteria. This allows to realize an adaptive shared control with varying force gains, which provides more authority to the human or the robot assistant depending on the accumulated human performance. Similarly, in [62] the authors propose to shift authority from the human user to the robotic system or vice versa depending on the specific context and logical rules allowing e.g. for the implementation of a no assist mode, an assist mode (human and robot share the execution of the task), a safety mode (robot acts fully autonomous) or an override mode (robot is under full control of the human). In [30, 61] again a logical rule-based method is proposed that evaluates the interaction force to estimate the human intentional direction which is defined as "the direction into which a person intends to move" and then select the admittance parameters among some defined values. Different admittance parameters are studied to provide the user a comfortable feeling while walking and to avoid manoeuvres in unintended directions.

Apart from the use of variable admittance control, few other approaches exist that address the problem of shared control. A Bayesian network approach that combines sensor information with user inputs (read by an interface with three buttons for moving forward, turn left or right) and that activates respective autonomous robot behavior is proposed in [41]. An autonomous path planning and obstacle avoidance approach is discussed in [15–17, 42] that lets the user decide on the robot velocity leaving partial authority of modifying the path with the user. The author employs advanced methods for dynamic path planning (e.g. elastic bands [51]) to allow for dynamic obstacle avoidance and smooth path planning and modifications according to user inputs. In [56] three robot guiding behaviours including obstacle avoidance, wall following, and goal seeking are designed for an omni-directional mobile robot by evaluating laser sensor data and by fusing these three behaviors by means of a Fuzzy Kohonen Clustering Network. In [29] the authors use forces and moments a user applies to a walker's handle in addition to information on the local environment and the walker's state to derive the most likely human intention, respectively path to follow. Depending on the identified intention, the angle of the robot front wheel is set by the mobility assistant, leaving the user the freedom to decide on the velocity to move on the identified path. Finally, a switching controller to avoid human forward fall and human-robot collision is proposed in [13].

Summarizing, although a series of adaptive shared control approaches for mobility assistance robots were studied in literature as mentioned above, to the best of the authors knowledge none of the aforementioned approaches used human-inspired decision making models to define adaptation policies for the provided level of assistance, which is expected to result in a natural and safe human-robot interaction. Thus, for the first time we study human decision making models as mechanism to gain-schedule low-level control parameters and with this to vary the level of assistance provided and evaluate the effectiveness of this approach for real end-users.

2.2 Human Decision Making Models

In cognitive science, human decision making has been widely studied in so called two-alternative forced-choice (TAFC) tasks. TAFC tasks require a human to make a sequence of choices between two predefined alternatives. After every choice, the subject is given a reward based on the current choice and the previous N choices. The subject's goal is to maximize the accumulated reward over a sequence of choices. TAFC tasks were used to study optimal decision strategies, see [9, 47], or sub-optimal strategies, see [21, 22]. In human subject experiments, it was observed that for a majority of human subjects working with particular reward structures, decisions are centered around particular points, termed matching points, where the reward return curves for the two options cross.

Mathematical investigations focusing on potential underlying mechanisms of human decision making have involved among others Markov decision processes (MDP) and drift-diffusion (DD) models. Authors in [58] consider TAFC tasks and a DD model together as a Markov process and show that, under certain assumptions, the DD model analytically exhibits matching behavior as observed in human subjects. In [5], convergence to a matching point is proven for a particular task called the matching-shoulders-type task and using the DD model with a time decay extension. In [47] and [59], a combination of a DD model and MDP is used to address empirical and analytical effects of social context (decisions and rewards of other people) on decision making.

Although several extensions to the concept of decision making based on the DD model in TAFC tasks exist, see for example [50, 63], its application to assistive robotics has not received lots of attention. In this work we extend our previous work [8] and explore the applicability of the DD model to MARs supporting elderly and patients.

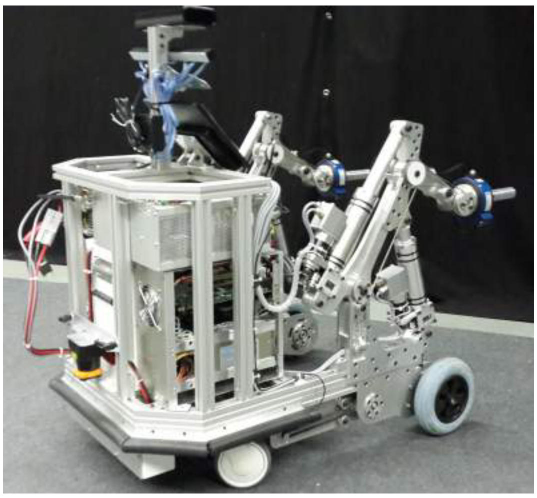

Fig. 1 Mobility assistance platform.

3 MAR Low-Level Control

3.1 System Description

Our rollator-type MAR consists of rear and front wheels, chassis, supportive handle bars and a range of sensors to measure environment and human data, see Fig. 1. The prototype has two actuated rear wheels and two front castors and is equipped with two 6 DoF *JR3* force-torque sensors at the handles, a Hokuyu laser range finder at the front to monitor the environment, one at the back to observe human gait patterns and two Kinect to monitor the human posture. The system is further equipped with an Inertia Measurement System (IMU), XSens MTi-G-700 GPS/INS, in order to estimate the robot angular acceleration and two 2 DoF arms to support sit-to-stand transfers. The rollator is of active and non-holonomic type, meaning that the translational motion of the robot along the heading direction as well as rotational motion along its center of rotation are possible, while motions in lateral direction are restricted. With reference to Fig. 2, the non-holonomic constraint is given by

$$\dot{x}_r \sin\theta_r - \dot{y}_r \cos\theta_r = 0,$$

and therefore the kinematic model can be written as follows,

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\theta}_r \end{bmatrix} = \begin{bmatrix} cos\theta_r & 0 \\ sin\theta_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} = \boldsymbol{J}\boldsymbol{u}, \quad (1)$$

where v and ω are two available control inputs for the linear and angular velocities around the vertical axis and $\boldsymbol{q} = [x_r,\, y_r,\, \theta_r]^T$ the states of the robot.

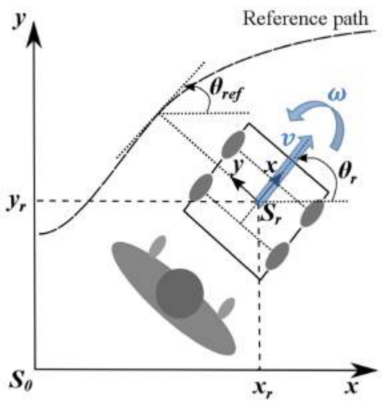

Fig. 2 Human and MAR in the world frame.

3.2 Admittance Control

Two force/torque sensors mounted at the handles of the rollator are used to drive the differential drive MAR. Force components along and around the heading direction are used for motion control[1]. An admittance control is implemented, which allows to design the desired dynamic behavior of the system with respect to the user's applied force by selecting proper admittance parameters. The admittance controller emulates a dynamic system and gives the user a feeling as if he/she were interacting with the system specified by the admittance model. A mass-damper system for the linear and angular motion is considered

$$\boldsymbol{M}_d\dot{\boldsymbol{u}} + \boldsymbol{D}_d\boldsymbol{u} = \boldsymbol{F}_h, \quad (2)$$

where $\boldsymbol{M}_d$ and $\boldsymbol{D}_d$ are the desired inertia and damping matrices, respectively, and $\boldsymbol{F}_h = [f_{h_x}, f_{h_y}, \tau_h]$ the driving forces applied by the user. Therefore, the desired reference velocity for the robot is specified by the desired admittance parameters and is based on the human input in terms of applied force. The robot reference velocity is then controlled by a low-level controller.

4 Shared Control Architecture

We propose an integrated architecture that allows to adapt the robot's short-term *cognitive* and *sensorial* assistance as well as the long-term *physical* assistance provided. The cognitive assistance provides required support to the user in path following situations guiding the user from an initial to a desired destination. The sensorial assistance reduces the risk of the robot colliding with obstacles and allows for the intentional approach of obstacles. The physical assistance tunes the robot contribution according to the long-term user performance, which may be affected due to fatigue. The latter is particularly important since considerable changes in performance are observed due to user fatigue after continuous activity, which may render performing daily activities at a desired level of performance difficult, see [10, 52].

With reference to Fig. 3, we propose an integrated adaptive shared control framework for MARs. Three decision-maker blocks for sensorial, cognitive and physical assistance are responsible for online adapting the parameters of the admittance controller in order to achieve the desired system behavior. The *Decision on cognitive assistance* block evaluates the planned path towards the goal which is generated by the path planner block, the human navigational intention in form of force and torque applied to the robot handles as well as the actual human performance. The *Decision on sensorial assistance* block uses human input and the information provided by the *Environment state* block, which provides information on the position of obstacles around the robot. Finally, the *Decision on physical assistance* block processes

[1] Please note that in a holonomic system also the force component in sidewards direction is used for motion control.

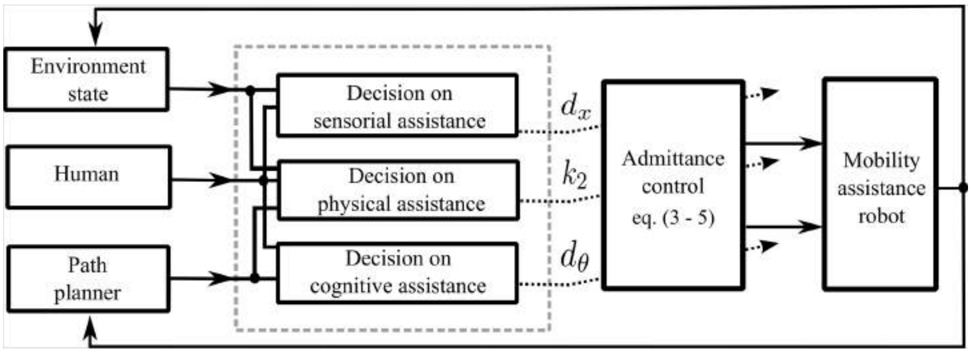

Fig. 3 MAR adaptive shared control architecture.

all inputs and adjusts the level of active support provided accordingly.

The concept of the robot assistance is implemented by manipulating the admittance control parameters. We decompose and extend the admittance controller (2) as follows:

$$m_x\dot{v} + d_x v = f_{h_x}, \tag{3}$$

$$I_\theta\dot{\omega} + d_\theta\omega = k_1\tau_h + k_2\tau_{assis}, \tag{4}$$

$$k_1 + k_2 = 1, \tag{5}$$

where the parameters m_x, d_θ and f_{h_x} are the mass, damping and human force components along the heading direction of the robot (in alignment with the unitary vector x of the robot in Figure 2). The variables I_θ, d_θ and τ_h are the inertia, damping and human torque components. The parameters d_x, d_θ and k_2 are tuned to satisfy the aforementioned sensorial, cognitive and physical assistance. Increasing the value of d_x decelerates the robot motion in heading direction and knowing that the robot is of non-holonomic nature this effect can be used for the purpose of robot sensorial assistance. Manipulation of d_θ influences the felt resistance when aiming to change the robot orientation and thus, can help preventing deviations from the desired path towards the destination. Finally, an increase of k_2 increases the robot active contribution to the control of the orientation of the robot. This effect is used for varying the physical assistance provided by the robot. The adaptation of the d_x and d_θ parameters results in a passive and thus, intrinsically safe support strategy. The advantage of active support is used to tune the parameter k_2, whenever the passive support strategy alone cannot provide the desired system behavior, e.g. when the user is exhausted and can hardly guide the robot towards his/her desired destination.

The decision making systems that decide on the specific tuning of these parameters are discussed in the following sections.

5 Decision Making for MARs

The individual decision making policies that decide on the specific level of robot assistance provided are formulated based on the DD model to achieve an intuitive online adaptation of the robot assistance. In the following sections, we first introduce the DD model, and then detail its application for designing an adaptive robot assistance for a MAR.

5.1 Decision Making Principle based on DD Model

In a two-alternative forced-choice (TAFC) task a human has to take a decision between two alternative choices and is asked to continuously choose between them. Each choice is associated with a specific reward. The human not knowing about the underlying reward structures typically explores the options and gradually optimizes the overall intake. Different reward structures have been proposed in literature to study human decision-making behavior. In this paper, we mainly focus on the matching shoulder reward structure. The matching shoulder structure consists of two reward functions with inverse relationships as encountered for example whenever two goals are conflicting and a decision has to be taken for either improving the one or the other. The specific form of the two crossing reward functions is a design factor and allows to program different kind of behaviors allowing to favour one goal over another in some situations, while favouring the other in other situations. Thus, in general the matching shoulder structure consists of two intersecting curves that diminish with increasing/decreasing performance. Consider p_A and p_B human performance measures associated with the choices A and B and the associated rewards r_A and r_B. Further, and only assumed in the context of this manuscript, the general relationship of a reward r and a performance measure p should be given by:

$$r_z = k_z(p_z - p_{offset,z})^{n_z} + r_{0,z}, \tag{6}$$

where $p_{offset,z}$, $r_{0,z}$, k_z, and n_z are the user and task-defined tunable variables for each specific reward structure ($z \in A,\ B$).

The Drift Diffusion (DD) model has proven to implement the optimal mechanism for TAFC decision making tasks and accounts for an impressive amount of behavioral and neuroscientific data. The DD model characteristic can be formulated as soft-max model firstly introduced by [9] to describe human decision making in TAFC tasks. The soft-max model as a main component in human decision-making processes was also shown by [45] and formulated using a sigmoidal function

$$\mathbb{P}_A(t+1) = \frac{1}{1 + exp^{-\mu(w_A(t) - w_B(t))}}. \quad (7)$$

According to this model, the probability of the human preference for choice A at time $t+1$ is $\mathbb{P}_A(t+1)$ which is computed using (7), where $w_A(t)$ and $w_B(t)$ are the accumulated evidences for choosing option A or B, respectively. The parameter μ is used to manipulate the slope of the sigmoid function, and therefore the level of certainty in making a decision.

The values $w_A(t)$ and $w_B(t)$ are updated with the help of a learning rule. Authors in [46] have proposed a discrete-time linear update rule. Considering the decision set $z \in [A, B]$ at each time t, then

$$w_z(t+T) = (1-\lambda)w_z(t) + \lambda r_z(t) \quad (8)$$

where z is the decision just made, $r_z(t)$ the obtained reward for z, $\lambda \in [0\,1]$ a forgetting factor and T the sample time in the system. We consider the same initial value for the weightings w_z which implies no preference for each of the two choices.

In the following sections we employ the DDM as a key element for the gain-scheduling of low-level control parameters resulting in varying levels of physical, sensorial and cognitive assistance. Doing so, the problem of fulfilling two conflicting goals is formulated for each type of assistance studied. Then, associated performance metrics are defined and the corresponding matching shoulder reward structures are introduced. Next, the level of the provided assistance is decided upon by evaluating the DDM (7), which finally determines which of the two conflicting goals should be prioritized according to the accumulated evidence to improve the overall intake. Finally, a linear homotopy is applied for gain scheduling respective low-level control parameters c between a pre-defined minimum and maximum value based on the determined probabilities for deciding on either of the two choices:

$$c(t) = \mathbb{P}_A(t+1)c_{min} + (1 - \mathbb{P}_A(t+1))c_{max}. \quad (9)$$

5.2 Decision on Cognitive Assistance

In this section, we formulate the problem of providing adaptive, passive cognitive assistance as a human decision making problem. We employ the DD model for gain-scheduling of the low-level control parameter d_θ to online adjust the level of the provided robot cognitive assistance.

5.2.1 Problem Formulation

An important functionality of the MAR is guiding the user from an initial to a target destination, especially for users who are cognitively impaired and have thus, difficulties in locating themselves and finding their way. An ideal robot assistance makes the user feel comfortable by giving him/her enough control over the platform, while the user is safely guided towards the desired destination. In particular, we aim at improving human-robot agreement by providing the user enough freedom in controlling the platform as long as the deviation from the desired path stays within acceptable limits and at shifting priority towards improving task performance by reducing the human control authority in case the task deviation is slowly approaching its allowed maximum, but the user performs no proper reaction to prevent this. This trade-off is formulated as decision-making problem. The assistance is realized by a passive guidance that prevents movements in directions perpendicular to the desired path and giving the user freedom to control the robot when moving along the reference path.

Consider a task of path following from an initial to a final location where the desired path is known for the robot assistant. The human forces ($\boldsymbol{f}_h = [f_{h_x},\, f_{h_y}]^T$), represented by the linear components (two first entries) of $\boldsymbol{F}_h$ in (2) are used to control the linear robot motion along the robot reference frame. They can be split into two main components, the human force along the reference path ($\boldsymbol{f}_\parallel$) and perpendicular to it ($\boldsymbol{f}_\perp$). With reference to Fig. 2, the magnitudes of these forces are given as follows,

$$f_\parallel = \parallel \boldsymbol{f}_h \parallel cos(\theta_e), \quad f_\perp = \parallel \boldsymbol{f}_h \parallel sin(\theta_e), \quad (10)$$

where $\theta_e = \theta_{ref} - \theta_r$ and θ_{ref} is the desired orientation between the reference path and the global x-axis.

We believe that the proper control of the robot orientation error is satisfactory for the purpose of providing cognitive assistance. To ensure a safe robot behavior, we propose a passive assistance by adapting the damping parameter d_θ and thus, indirect manipulation of the robot angular velocity and orientation error while giving the user the freedom to move freely along the path. This reduces the problem to the adaptation of only one parameter, namely the damping parameter d_θ. The adaptation law for this parameter is formulated as a decision making problem using the DD model.

5.2.2 Performance Measures

Task performance is measured using the rotational and translational tracking error formulated with respect to the desired path over an observation windows N_C

$$p_{T,C} = \frac{\sum_{i=1}^{N_C} k_{C,e} e_i + k_{C,\theta_e} \theta_{ei}}{N_C \cdot \max(k_{C,e} e + k_{C,\theta_e} \theta_e)}, \tag{11}$$

where the subscript i refers to the value of the variable at the sample i and e is the robot position error given by

$$e = \sqrt{(x_{ref} - x_r)^2 + (y_{ref} - y_r)^2}, \tag{12}$$

and $p_{T,C}$ means the normalized task performance computed over N_C samples, and $k_{C,e}$ and k_{C,θ_e} are two user-defined factors distributing the weightings between orientation and translation. The max value is initialized with the maximum acceptable error with respect to the task and is updated if a larger value is observed during the interaction process.

Disagreement is assumed to occur when the user and robot assistant apply forces in opposite directions leading to so called internal forces. These internal forces provide important information on haptic interaction, see e.g. [18]. Minimizing disagreement can enhance the quality of human-robot interaction as the robot then behaves according to human expectations. Considering the task of providing cognitive assistance described in the previous section, we define the internal moment τ_{int} as follows

$$\tau_{int} = \begin{cases} \tau_h + l_f f_\perp & sign(\tau_h + l_f f_\perp) \neq sign(\tau_{robot}) \wedge \\ & |\tau_h + l_f f_\perp| \leq |\tau_{robot}|, \\ -\tau_{robot} & sign(\tau_h + l_f f_\perp) \neq sign(\tau_{robot}) \wedge \\ & |\tau_h + l_f f_\perp| > |\tau_{robot}|, \\ 0 & \text{otherwise}, \end{cases} \tag{13}$$

where l_f is a variable representing the Euclidean distance between the robot position and the reference point on the desired path which allows the manipulation of $\tau_h + l_f f_\perp$, especially for cases when the human does not apply enough torque to correct the robot deviation, but instead the deviation is increasing due to applied forces. The value of τ_{robot} can be computed by any orientation controller, similar to the one proposed for τ_{assis} in (26). The disagreement metric is then computed over N_C samples and is further normalized to define the following agreement performance $p_{A,C}$,

$$p_{A,C} = 1 - \frac{\sum_{i=1}^{N_C} |\tau_{int,i}|}{N_C \cdot \max(|\tau_{int}|)}. \tag{14}$$

The final performance set to be considered for each decision is $p_C \in [p_{T,C}, p_{A,C}]$.

5.2.3 Reward Structure and Decision Making

Following ideas of the DD model in TAFC tasks, a reward function is associated with each performance measure. For the considered decision making problem, we propose a matching shoulder structure with two intersecting reward functions as depicted in Fig. 4 and both functions expressed using (6).

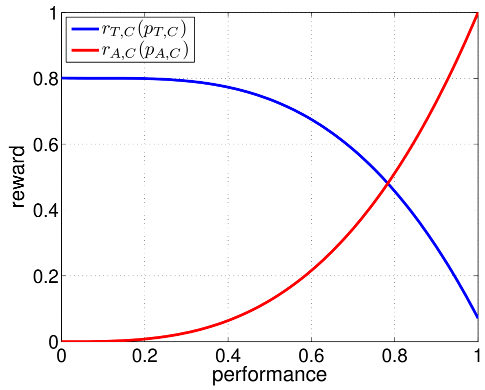

Fig. 4 Reward structure for adapting the cognitive assistance. The blue function is the reward $r_{T,C}$ associated to the task performance measure $p_{T,C}$ and the red function is the reward $r_{A,C}$ associated to the agreement performance measure $p_{A,C}$.

The proposed reward structure is designed to fit to the requirements introduced in Section 5.2.1. The assistant faces a trade-off between providing low assistance to improve human-robot agreement and providing high assistance to improve task performance. When the user is following the desired path, high agreement (agreement measure at its maximum) and high task performance (task performance measure at its minimum) are typically observed and thus, the maximum corresponding rewards are associated for both choices. The maximum reward associated to human-robot agreement is designed to be larger than the maximum reward for improving task performance. This implies an assistant's preference for improving agreement over task performance whenever the user's deviation from the reference path is acceptable. When both performances are decreasing, the reward for task performance decreases with a slower rate than the one for human-robot agreement. This allows a faster change of the preference from improving agreement to task performance. On the other hand, when both rewards are improving from very low performance, even a small increase of human-robot agreement results in a quick change of the preference towards improving human-robot agreement because of the higher rate of change in the reward associated to it (compare the change of slopes in both curves for example in $0.6 <$performance< 1).

The probability to assist the human to improve human-robot agreement at time $t+1$ is calculated using the DD model represented by (7) and considering $\mathbb{P}_A = \mathbb{P}_{A,C}$, $w_A = w_{A,C}$ and $w_B = w_{T,C}$ and $\mu = \mu_C$. The values of $w_{A,C}$ and $w_{T,C}$ are updated according to (8) considering $z \in [A_C, T_C]$.

Finally, the level of the provided cognitive assistance is adapted with the help of a linear homotopy defined as follows

$$d_\theta(t) = \mathbb{P}_{A,C}(t+1)d_{\theta,min} + (1-\mathbb{P}_{A,C}(t+1))d_{\theta,max} \quad (15)$$

where $d_{\theta,min}$ and $d_{\theta,max}$ are the minimum and maximum considered values of the damping factor.

5.3 Decision on Sensorial Assistance

The formulation of the sensorial assistance problem and the proposed adaptation policy for gain-scheduling of the low-level control parameter d_x based on the described decision making approach is discussed in the following sections.

5.3.1 Problem Formulation

Although typically a collision-free path is planned for robot assistants, reducing the risk of colliding with dynamic obstacles unknown at the time of planning the path has to be considered in the design of the robot control architecture. Further, an intentional approach to objects (detected as obstacle by the robot) can be desirable, e.g, when aiming to approach a table to grasp an object. This requires the robot to determine the user's intention and to decide on a proper support taking the specific context into account. Specifically, we aim at improving task performance in terms of collision avoidance by reducing the human control authority as well as allowing the intentional approach of objects by shifting the control authority to the human if large human-robot disagreement is detected. This is formulated as decision-making problem.

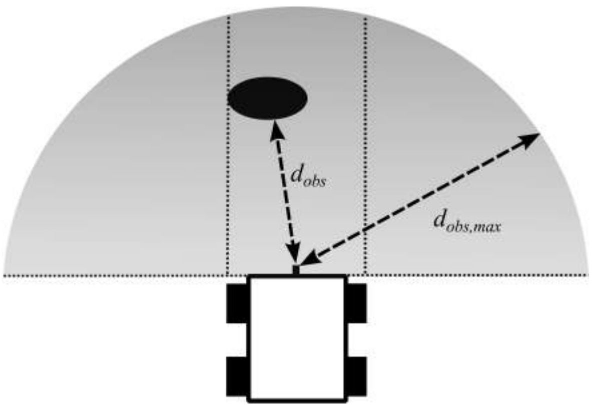

Fig. 5 Concept of the distance definition between robot and obstacle detected by the laser range finder.

Since the most critical collisions occur between obstacles and the front part of the robot, we aim for collision avoidance by adapting the robot heading velocity towards obstacles. Considering the distance between robot and a detected obstacle, virtual forces/moments can be generated based on an artificial potential field, see [39]. We consider the following artificial potential field ($U(\boldsymbol{q})$),

$$U(\boldsymbol{q}) = \begin{cases} \frac{k}{2}\left(\frac{1}{\|\boldsymbol{d}_{obs}(\boldsymbol{q})\|} - \frac{1}{d_{obs,max}}\right)^2 & \| \boldsymbol{d}_{obs}(\boldsymbol{q}) \| \leq d_{obs,max}, \\ 0 & \| \boldsymbol{d}_{obs}(\boldsymbol{q}) \| > d_{obs,max}, \end{cases}$$

where $\boldsymbol{d}_{obs}$ is defined as the shortest distance between the nearest obstacle in front of the robot to a representative point on the robot, see Fig. 6, $d_{obs,max}$ the radius of the area in which the potential field becomes active and k a positive constant gain. Therefore, the value of $U(\boldsymbol{q})$ is increased whenever the robot is approaching an obstacle, and its value is zero if $\| \boldsymbol{d}_{obs}(\boldsymbol{q}) \|$ is larger than $d_{obs,max}$.

Artificial forces applied by the robot are defined as $\boldsymbol{F}(\boldsymbol{q}) = -\nabla(U(\boldsymbol{q}))$ where ∇U is the gradient vector of U. Then $\boldsymbol{F}(\boldsymbol{q})$ is transformed to the robot frame to determine virtual forces and moments $\boldsymbol{F}_{obs} = [\boldsymbol{f}_{obs}, \tau_{obs}]$ applied by the obstacle to the center of rotation of the MAR.

In a fully autonomous system, forces $\boldsymbol{F}_{obs}$ are typically used to actively drive the MAR and avoid collision with obstacles. However, in a shared control system where the robot is (at least partially) under human control and knowing that we aim for a passive support, direct usage of $\boldsymbol{F}_{obs}$ can result into an active and unsafe behavior and thus, we aim for only evaluating it and passively tuning the robot heading velocity v. Here this problem is simplified to the decision on the adaptation of d_x, which allows decelerating the robot whenever an obstacle is detected.

5.3.2 Performance Measures

Considering the task of collision avoidance, task performance is defined according to the distance to the nearest obstacle in front of the robot over an observation window of N_S samples

$$p_{T,S} = 1 - \frac{\sum_{i=1}^{N_S} \| \boldsymbol{d}_{obs,i} \|}{N_S \cdot d_{obs,max}} \quad (16)$$

where $\boldsymbol{d}_{obs,i}$ is the respective vector for sample i.

Similar to Section 5.2.2, internal forces are considered to provide important information on the quality of interaction during collision avoidance. Internal forces $\boldsymbol{f}_{int}$, which represent the level of disagreement between the force applied by a human ($\boldsymbol{f}_h$) as well as the repulsive force generated by the detected obstacle ($\boldsymbol{f}_{obs}$), are computed as follows

$$\boldsymbol{f}_{int} = \begin{cases} \boldsymbol{f}_h & \boldsymbol{f}_h \cdot \boldsymbol{f}_{obs} \leq 0 \wedge \| \boldsymbol{f}_h \| \leq \| \boldsymbol{f}_{obs} \|, \\ -\boldsymbol{f}_{obs} & \boldsymbol{f}_h \cdot \boldsymbol{f}_{obs} \leq 0 \wedge \| \boldsymbol{f}_h \| > \| \boldsymbol{f}_{obs} \|, \\ 0 & \text{otherwise}, \end{cases} \quad (17)$$

whereby human-robot agreement A_S is determined over N_S samples and is normalized as follows

$$p_{A,S} = 1 - \frac{\sum_{i=1}^{N_S} \| \boldsymbol{f}_{int,i} \|}{N_S \cdot \max(\| \boldsymbol{f}_{int} \|)} \quad (18)$$

where $\boldsymbol{f}_{int,i}$ refers to sample i. Thus, the set of performances to be considered for the sensorial assistance is $p_S \in [p_{T,S}, p_{A,S}]$.

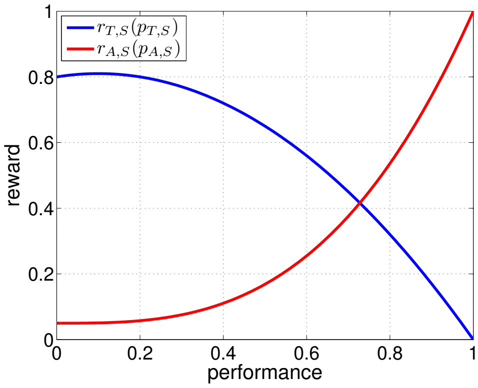

Fig. 6 Reward structure for adapting the sensorial assistance. The blue function is the reward $r_{T,S}$ associated to the task performance measure $p_{T,S}$ and the red function is the reward $r_{A,S}$ associated to the agreement performance measure $p_{A,S}$.

5.3.3 Reward Structure and Decision Making

Fig. 6 presents two reward functions which are defined corresponding to the two performance measures presented in Section 5.3.2.

Again the DD model is adopted for decision making. The probability to improve human-robot agreement $\mathbb{P}_{A,S}$ is calculated by (7) where $w_A = w_{A,S}$ and $w_B = w_{T,S}$ are the evidences for choosing to improve human-robot agreement or task performance (as defined in section 5.3.2). The evidences are calculated using (8) and considering the set of decisions $z \in [T_S, A_S]$ for each time t. Finally, the level of the robot sensorial assistance is modified by means of the following homotopy for the damping parameter d_x

$$d_x(t) = \mathbb{P}_{A,S}(t+1)d_{x,min} + (1-\mathbb{P}_{A,S}(t+1))d_{x,max} \quad (19)$$

where $d_{x,min}$ and $d_{x,max}$ are the minimum and maximum considered values of the damping factor.

We believe that the proposed reward structure satisfies the objectives for providing sensorial assistance as introduced in Section 5.3.1. When no obstacle is detected in front of the robot, the task performance measure is at its minimum (see (16)) and therefore a high reward is associated to it. On the other hand, no obstacles implies no disagreement between human and robot (based on the definition of the performance measures), which results in a large value for the measure of human-robot agreement and therefore a high reward. The maximum value of the reward for human-robot agreement has been decided to be slightly larger than the maximum value of the reward for task performance, which implies a preference to improve human-robot agreement whenever no risk of collision is detected. In other words, the value of $\mathbb{P}_{A,S}$ is close to one due to the fact that the evidence $\Delta w_S = w_{A,S} - w_{T,S}$ is at its maximum according to the rewards defined.

As soon as an obstacle is detected, the reward for improving task performance decreases with a slower rate with respect to the reward for human-robot agreement. This allows a faster change from preferring human-robot agreement to task performance, the value of Δw_S decreases, which results in an increase of the level of assistance. Finally, if the human insists on continuing the motion forward despite the provided resistance of the robot (which can imply the user's interest to approach the obstacle), the task performance measure tends to its maximum value (corresponding to the lowest reward), while the human-robot agreement measure tends to its lowest value (also corresponding to a low reward). In this case the overall preference turns back again towards improving human-robot agreement since its minimum reward is larger than the minimum reward for task performance. This results in an increase of Δw_S allowing the user to approach the obstacle. However, approaching the obstacle has very low risk of collision since the robot velocity has been reduced significantly and the human remains under partial robot assistance.

5.4 Decision on Physical Assistance

Individualization of the robot support is considered by adapting the physical robot assistance by gain-scheduling the parameter k_2 as detailed in the following sections.

5.4.1 Problem Formulation

The demand for assistance of elderly and patients may increase with continuing activity due to fatigue. An assistance strategy that adapts to the current physiological state can meet the aforementioned demand and thus, can result in a higher user satisfaction during interaction with the robot. This requires that the MAR not only evaluates the user performance with respect to the desired task, but also estimates the physiological state of the user in order to decide on the level of the provided robot assistance. Specifically, we aim at shifting the control authority to the robot if task performance is low and human fatigue high and at gradually returning authority to the user when task performance improves and human fatigue decreases. Again, this is formulated as decision-making problem.

We propose an active support by applying an assistive torque to the admittance model. Considering (4) and (5), the input torque can be manipulated by a proper selection of the parameter k_2.

5.4.2 Performance Measures

In general two different types of human fatigue are studied in literature: mental and physical. Physical fatigue, which we focus on in this paper, presents the maximum level of exhaustion at which the human cannot exert any more work.[2] In literature, medical indicators of human fatigue are mostly discussed based on heart rate or the total performed work. Since the former requires an external monitoring system, e.g. heart rate sensor, we mainly focus on the latter. Physical fatigue is directly related to the total power consumed in the human muscles and therefore total work performed as presented by [11]. The total work performed by a person during walking is related to the user's walking velocity and the total weight of the user. Authors in [6] propose the following formula that relates consumed calories per kilogram per hour l_{cal} to the user's velocity v_h during walking

$$l_{cal}(v_h) = 14.326 \frac{v_h}{0.362 + 0.257 v_h}(0.136 v_h + 0.066 v_h^2). \tag{20}$$

We use the aforementioned formula to formulate the level of the human fatigue during walking. Considering a person with total weight of M pushing a MAR with apparent mass m_x and moving with linear velocity of $v_h = v(t)$ at time t, the normalized level of human fatigue is estimated as

$$F(t+1) = F(t) + \frac{l_{cal}(v(t))(M + m_x)\Delta t}{l_{cal,fat}}, \tag{21}$$

where $p_{F,O}$ represent the level of human fatigue, Δt the sampling time of the system and $l_{cal,fat}$ the maximum possible consumed calories resulting in human fatigue. [3] We define

$$p_{F,O} = 1 - F \tag{22}$$

to be the performance measure correlating with the estimated human fatigue.

The overall task performance is defined based on the tracking error of the desired path as well as the distance to the nearest obstacle in front of the robot which is computed as follows

$$p_{T,O} = \frac{\sum_{i=1}^{N_O} |\delta_i|}{N_O \delta_{max}}, \tag{23}$$

$$\delta = k_{O,\theta_e} \cdot \theta_e + k_{O,e} \cdot e + k_{O,obs} \cdot \frac{1}{\| \boldsymbol{d}_{obs} \|}, \tag{24}$$

where δ_i is defined as a measure of total task performance at sample i, δ_{max} the maximum value of δ, $p_{T,O}$ the observed task performance over the observation window with length N_O. We consider a larger value for N_O than N_S and N_C (defined in Sec. 5.2.2 and 5.3.2 respectively) for a better estimation of the more long-term changes in human task performance rather than specific reactions to a given situation. The values of k_{O,θ_e}, $k_{O,e}$ and $k_{O,obs}$ are weighting factors, which can be tuned according to the importance of following the path or avoiding obstacles.

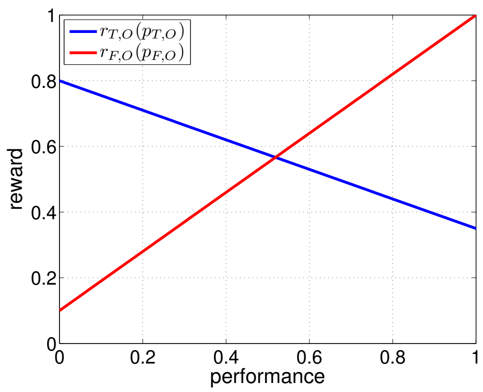

Fig. 7 Reward structure for adapting the physical assistance. The blue function is the reward $r_{T,O}$ associated to the overall task performance measure $p_{T,O}$ and the red function is the reward $r_{F,O}$ associated to the performance measure correlating with estimated human fatigue $p_{F,O}$.

5.4.3 Reward Structure and Decision Making

The reward structure for the two performance measures is shown in Fig. 7.

The linear structure has been chosen as there is no specific preference on improving the overall task performance or increasing the support because of human fatigue. This structure allows to change the decision (gradually) whenever human fatigue or performance changes are detected.

The level of the physical assistance is finally tuned according to the DD model. The estimated level of the robot physical assistance $\mathbb{P}_O$ is computed using (7) with $w_A = w_{F,O}$ and $w_B = w_{T,O}$. The evidences are computed using (8) and assuming the decision set $z \in [F_O, T_O]$ at each time t. Thus, the level of the robot overall assistance is adapted by

[2] Please note that the natural definition of mental and physical fatigue are closely related and it is commonly known that physical fatigue impairs mental fatigue. However, [43] has only recently shown that mental fatigue can also imply physical fatigue. Therefore, we just consider the effect of physical fatigue since this is the most probable cause of fatigue in a mobility assistance scenario.

[3] The work performed by a human to maneuver the platform has not been considered in the computation of human fatigue for the sake of simplicity.

tuning the weighting factor k_2 presented in (4) as follows,

$$k_2(t) = \mathbb{P}_O(t+1)k_{2,min} + (1 - \mathbb{P}_O(t+1))k_{2,max} \quad (25)$$

where $k_{2,min}$ and $k_{2,max}$ are the minimum and maximum considered values for k_2. We propose a very smooth softmax function by considering a small value for the μ parameter in (7). This allows to gradually shift the preference between the human or assistant to control the robot steering velocity.

Finally, to recover the orientation error a robot assistive moment can be generated using the following control law

$$\tau_{assis} = K_{p_1}e + K_{p_2}\theta_e, \quad (26)$$

where K_{p1}, K_{p2} are user-specific defined gains.

6 Experimental Results

This section illustrates the effectiveness of the proposed approach, first by means of experiments aiming for a technical validation with a healthy user interacting with the platform and then by means of a user study involving 35 elderly persons.

6.1 Technical Validation

In the following sections we technically validate the proposed decision making algorithm realizing adaptive shared control in MARs.

6.1.1 Experimental Setup

The robotic platform as shown in Fig. 1 was used for validation of the presented adaptive shared control approach. The controller of the robot mobile base was implemented using MATLAB/Simulink Real-Time Workshop. The robot velocity was controlled using a low-level high gain PD controller. The control loop was set to run at $T = 1\,ms$ sampling time. The robot handles were not actuated and kept at a constant height during the whole experiments.

A static map of the experimental room was build in the Robot Operating System (ROS) using the OPENSLAM Gmapping library package based on captured laser scanner, IMU and robot's odometry data. A path planner as part of the `move_base` package in ROS was implemented that provides a fast interpolated path planning function used to create plans for the mobile base.

For determining the closest point, we used a planner that assumes a circular robot and operates on a cost map, which produces a global path from a starting robot pose to an end pose in a grid. Then, an algorithm was used that searches iteratively on the global path to find the closest points to the current robot position. To solve ambiguity in case two or more closest points are found, we implemented a look-ahead checker, which processes past closest points and returns the next closest point which is located ahead of the robot and has the maximum orientation alignment with the current robot pose.

Robot localization was performed using an Adaptive Monte Carlo Localization (amcl) approach, which was implemented in ROS as part of the `nav_stack` package and provides an estimate of the robot's pose against a known map. It continuously registers the robot pose on the map and corrects possible odometry errors.

An obstacle map based on the front laser scanner was constructed in order to provide information about the closest obstacle in defined zones around the robot. We splitted the area in front of the robot into 5 zones and computed the distance of the nearest obstacle in each zone to the robot, see Fig. 8 for a snapshot.

6.1.2 Test Scenarios

The presented approach was tested using two scenarios. In the first scenario the integration of the cognitive, sensorial and physical assistance was tested, while in the second scenario we specifically investigated the performance of the realized sensorial assistance and its ability to avoid obstacles or allow their intentional approach.

Scenario I: The user was asked to define a desired destination on the map of the experimental area shown on the screen mounted on the robot frame. According to the user's choice, a reference path was automatically generated to the final destination. The user was asked to follow the path while trying to deviate from the path at least once. At half way, another human was asked to pass in front of the robot simulating a dynamic obstacle. The user was instructed to not pay attention to this dynamic obstacle, pretending of not having noticed it. Towards the end of the path the user was asked to keep the robot orientation slightly off the reference path to test the effect of the robot physical assistance.

The parameters used for realizing the cognitive assistance were as follows: $N_C = 2500$, $k_{C,e} = 5$ and $k_{C,\theta_e} = 10$. We considered $\mu_C = 0.6$ in order to increase certainty in the decision making and to avoid chattering. For the sensorial assistance functionality, we set $d_{obs,max} = 0.85m$, $N_S = 2500$ and $\mu_S = 10$. For the overall assistance we exaggerated the value of $l_{cal,fat} = 1000$ for the sake of presentation to be able to detect human fatigue after a short duration of walking, although the real value of $l_{cal,fat}$ is much higher and can be determined from literature. We mostly focused on the error of the robot orientation with respect to the reference path in order to actively point the human towards the destination. Therefore, we set $k_{O,\theta_e} = 8$, $k_{O,e} = 5$ and

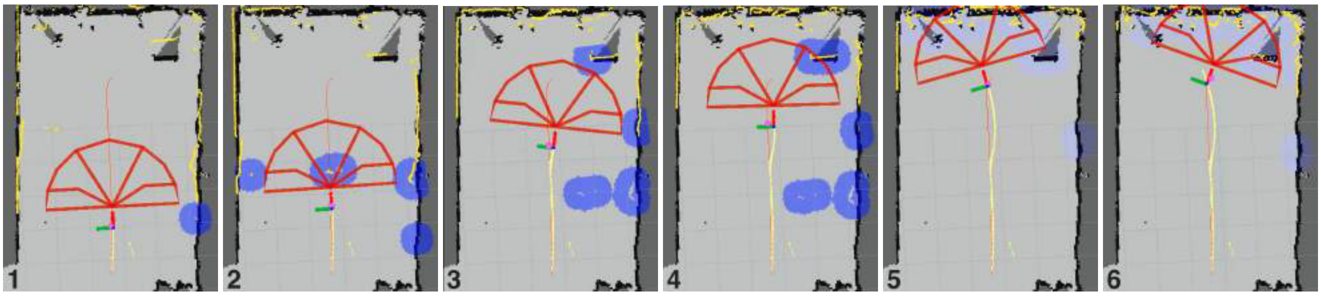

Fig. 8 Snapshots taken during human-robot cooperation in scenario I. The map of the area is depicted in gray, while the dark gray areas show the occupied static obstacles found during the map building. The yellow points indicate the location of observed obstacles during the experiment. The blue point clouds are clusters around each obstacle in the vicinity of the robot (this is only for presentation purposes and has no application in the presented approach). The area in front of the robot is divided into 5 zones as shown in thick red lines. The generated reference path is presented by thin red, while the path the robot passed is shown with yellow line (can be seen near the reference path behind the robot). Each snapshot presents the following information from left to right, 1: initial phase of walking where no obstacles are detected and the user is well following the path, 2: a dynamic obstacle moves in front of the robot, 3: the user is deviating from the reference path, 4: increase of the user's deviation is restricted by the robot and therefore the user comes back to the path, 5: the user keeps an orientation error at the end of the experiment, and 6: the robot overall assistance recovers the orientation error.

Table 1 Defined reward functions for robot assistance.

	reward function
cognitive assistance	$r_{T,C}(p_{T,C}) = {p_{T,C}}^3 - 0.1$ $r_{A,C}(p_{A,C}) = -{p_{A,C}}^3 + 0.8$
sensorial assistance	$r_{T,S}(p_{T,S}) = 0.95{p_{T,S}}^3 + 0.05$ $r_{A,S}(p_{A,S}) = -(p_{A,S} - 0.1)^2 + 0.81$
physical assistance	$r_{T,O}(p_{T,O}) = 0.9p_{T,O} + 0.1$ $r_{F,O}(p_{F,O}) = -0.45p_{F,O} + 0.8$

$k_{O,obs} = 1$. Further, the values of $N_O = 10^4$ and $\mu_O = 12$ were selected. The value of the forgetting factor $\lambda = 0.6$ was considered for all cases. To fulfill the requirements of the desired robot assistance in all three cases, the reward functions were defined as presented in Table 1. Moreover, the parameters for the desired inertia of the admittance controller were considered to be $m_x = 15$ kg and $I_\theta = 5$ kgm^2.

Figure 8 shows some snapshots taken during the experiment. The map of the experimental area, the robot and defined obstacle zones, detected obstacles at the front and around the robot as well as the desired and traveled path are shown.

At the beginning of the experiment a dynamic obstacle (another person) was passing in front of the robot ($\approx 30 < t < 32$s). As depicted in Fig. 9, when the robot approaches the obstacle the task performance measure increases. Moreover, since the user was asked to not react to the obstacle, the agreement measure between the robot being interested in avoiding the obstacle and the human not reacting properly decreases. Taking into account the defined reward structure, the human receives a quite low reward which results in triggering the robot decision to increase the robot assistance which was achieved by automatically increasing the damping factor and therefore reducing the robot approaching velocity to the obstacle. As soon as the dynamic obstacle passed the robot and the risk of collision reduced again, the robot decided to return the authority of controlling the motion of the robot to the user, which happened quite smooth, but fast (with respect to the first decision of increasing the assistance) in order to avoid the user pushing against a blocked robot while there is no obstacle in front of it.

When trying to deviate from the path ($\approx 35 < t < 37$ s) as shown in Fig. 10 the task performance measure increases, while the agreement measure decreases as the robot preferred to stay on the path, while the human was deviating from it. Therefore the robot assistance hindering the user from further deviating from the path is activated and the value of the damping d_θ is increased. This notifies the user that the current direction of motion is not aligned with the desired reference path. However, as soon as the user adapts his input and aligns the robot with the desired path, the robot assistance quickly returns the authority to control the platform to the user.

For the last part of the path when the user was simulating fatigue, we considered a value of $l_{cal,fat} = 10^4$ in order to visualize the effect of the realized algorithm even after only 50 s of walking, see Fig. 11. With increasing duration of the human walking, the estimation of the human fatigue, and thus the corresponding performance measure, increased, while the overall human task performance measure varies according to the distance of the human to obstacles and the overall deviation from the path and orientation error [4]. By increasing the orientation error in the last phase

[4] Please note that emphasizing mostly on the orientation error in the overall task performance measure was assumed only for the sake of presentation. However, one may associate different values for the contribution of each of the terms to the overall task performance.

of the experiment, the corresponding performance measure was influenced and therefore a lower reward was associated. This resulted in a change of the decision towards increasing the level of active assistance by increasing the robot contribution to the control of the robot's orientation. Therefore the value of k_2 was increased to its maximum which we considered to be 0.6 for the sake of safety.

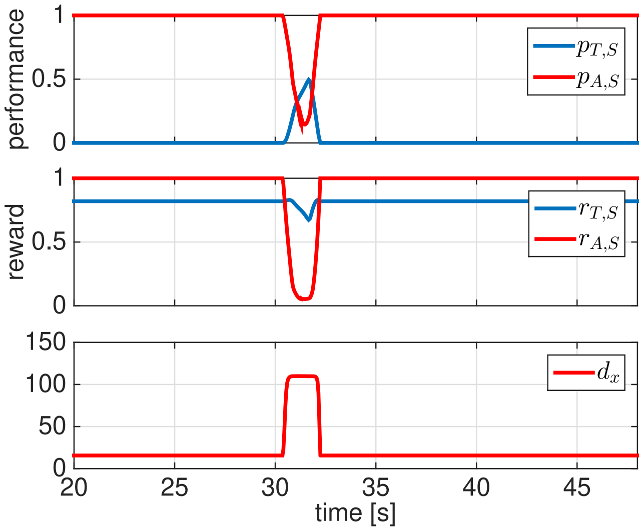

Fig. 9 Results of the sensorial assistance during human-robot cooperation in scenario I.

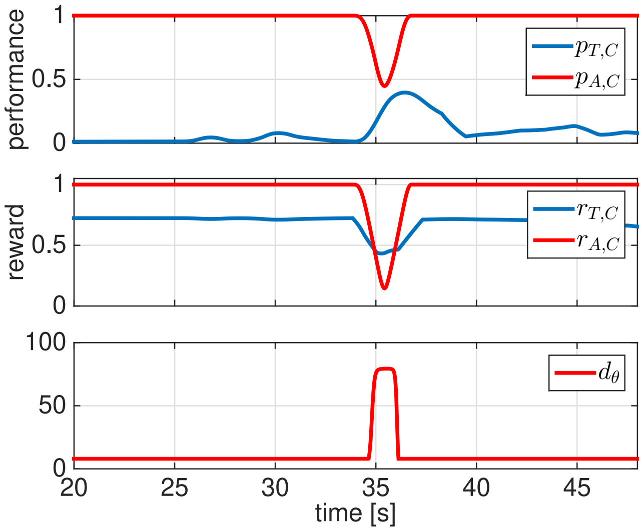

Fig. 10 Results of the cognitive assistance during human-robot cooperation in scenario I.

Scenario II: In this scenario we focused on the evaluation of the robot sensorial assistance and tested the functionality of distinguishing between approaching obstacles either intentionally or accidentally. To be able to focus on the sensorial

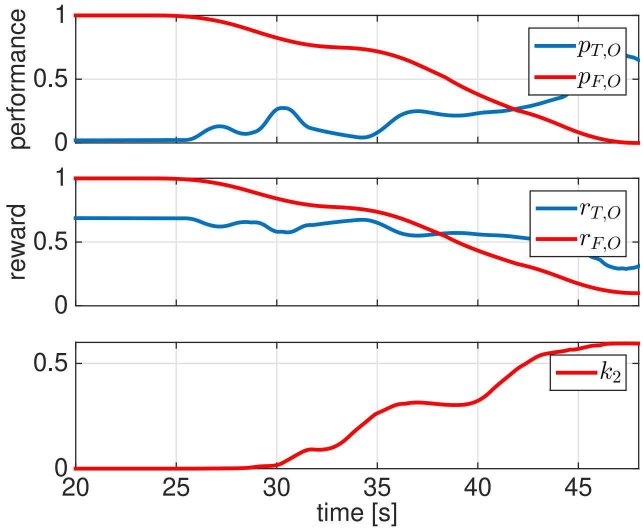

Fig. 11 Results of the physical assistance during human-robot cooperation in scenario I.

assistance functionality, the cognitive and overall assistance were deactivated to prevent the results being influenced by these other assistances. Figure 12 shows the snapshots taken during the experiment.

Two static obstacles were positioned in front of the robot, one after the other in heading direction. A third obstacle (table) was further considered as an intentional goal. The user was asked to approach the table and grasp an object located on it assuming the two obstacles are initially not detected due to e.g. bad sight. As shown in Fig. 13, when approaching the first two obstacles (the first at $\approx 36 < t < 37.5$ s and the second at $\approx 40 < t < 43$ s), the robot task performance measure is increased while the agreement measure is decreased, which implies a risk of collision. The robot correctly decides to prevent the collision with obstacles as the value of the damping factor d_x is increased and only returns the authority to the human once he/she changed the orientation of the robot and thus, the risk of collision decreased (damping factor d_x was decreased fast). However, in the third case where the human pushed the robot towards the intentional obstacle (at $\approx 46 < t < 52$ s), the robot initially reduced the approaching velocity (value of the damping factor d_x was increased), but then it returned the authority to the human to allow for further safe approach to the intentional obstacle (value of the damping factor d_x was reduced to 30). This change in the authority allocation happened even though task performance was low (task performance measure high) as the robot was in a very close distance to the obstacle.

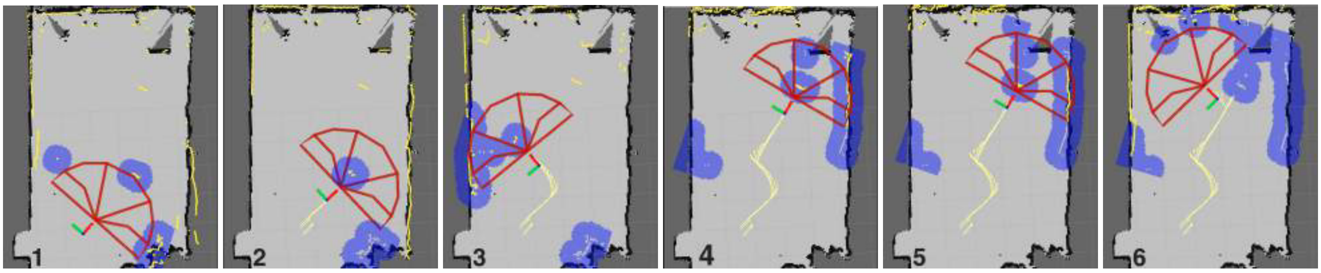

Fig. 12 Snapshots taken during human-robot cooperation in scenario II. The map of the area is depicted in gray, while the dark gray areas show the occupied static obstacles found during the map building. The yellow points indicate the location of observed obstacles during the experiment. The blue point clouds are clusters around each obstacle in the vicinity of the robot (this is only for presentation purposes and has no application in the presented approach). The area in front of the robot is divided into 5 zones as shown in thick red lines. The path that the robot passed is shown with yellow line behind the robot. Each snapshot presents the following information from left to right, 1: initial phase of walking where an obstacle is detected in front of the robot, 2: close distance between the robot and obstacle which increases the risk of collision resulting in the robot reaction to avoid collision, 3: the second obstacle is detected and the robot reacts to avoid collision, 4: the user is guiding the robot towards a new obstacle he wants to approach intentionally, 5: the robot allows for a very close approach of the intentional obstacle, and 6: the user leaves the intentional obstacle.

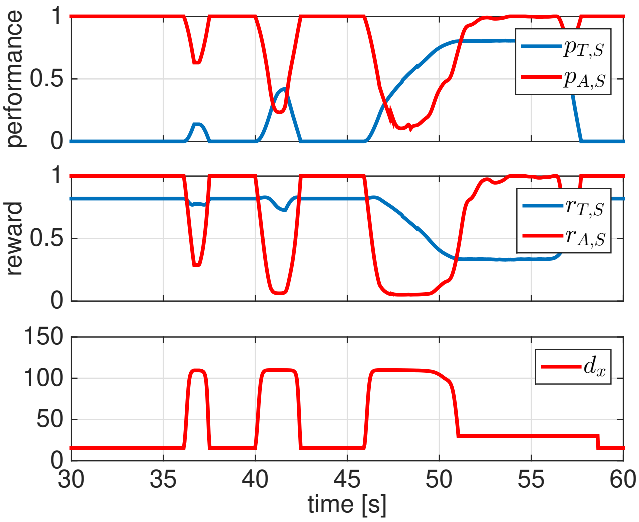

Fig. 13 Results of the sensorial assistance during human-robot cooperation in scenario II.

6.2 User Study

An intensive evaluation with 35 elderly subjects was performed to assess the effectiveness of the proposed adaptive shared control approach. Thirty one women and four men participated in the evaluation which took place for six weeks at the rehabilitation centre of the Agaplesion Bethanien Hospital/Geriatric Centre at the University of Heidelberg. The average age of subjects was 84.3 ±5.4, ranging from 71 to 94 years. The study sample comprised frail older persons as expressed by impaired motor status (Performance Oriented Mobility Assessment, [60]: 20.3 ±5.4; gait speed, 5-chair stand test [19]: 0.48 ±0.16 m/s, 19.2 ±7.5 s) and high risk of falling (63 % of subjects reported one or more falls in the last year). All subjects currently used conventional walkers in their daily routine. The experiments were performed under ethical approval by the ethics committee of the Medical Department of the University of Heidelberg, Alte Glockengießerei 11/1, 69115 Heidelberg, Germany. Written informed consent was obtained from all subjects participating in the study.

6.2.1 Test Conditions

The adaptive shared control approach for sensorial assistance has been implemented on the robotic platform and was compared with an existing approach in literature. We considered three different conditions:

- C1: Walking assistance without obstacle avoidance functionality implementing a constant virtual inertia and damping.
- C2: Walking assistance with obstacle avoidance based on the approach presented by [24].
- C3: Walking assistance with obstacle avoidance based on the decision-making algorithm presented in this manuscript.

The main reason for focusing on the evaluation of the sensorial assistance in the user study is that beside the baseline C1 there is hardly any directly comparable algorithm available for the other two modes.

For a fair comparison, base values of $m_x = 15$ kg and $I_\theta = 5$ kgm^2, and of $d_x = 10$ Ns/m and $d_\theta = 10$ Nms/rad were considered for each condition. These values were selected after discussion with rehabilitation experts. Although the above mentioned values were considered constant for condition C1, the value of d_x and d_θ were adapted up to their maximum of $d_{x,max} = 110$ Ns/m and $d_{\theta,max} = 80$ Nms/rad in C2 and C3. The maximum values were selected following discussions with rehabilitation experts as well as tests to achieve a good maneuverability of the device with respect to a standard non-motorized walker. We considered 70 cm distance between the robot and obstacles as the activation distance, i.e. the base values were considered in C2 and C3 only for distances larger than 70 cm, while the adaptation laws were applied for distances less than 70 cm.

6.2.2 Experimental Setup

A special test environment was prepared within the Bethanien rehabilitation center to test the proposed adaptive shared control approach. Figure 14 shows the map of the test environment and a representative example of a test path. The test environment covered an area of about 10×9 m with an approximate length of 40 meters of test path starting from an initial position, passing through the narrow corridor by avoiding obstacles and coming back to the same initial position. The height of obstacles varied in different sections of the area. The considered round trip allowed us to record the same number of left and right turns. Over the whole trial the user was faced to 17 obstacles, and a minimum amount of 16 turns either to avoid collisions with obstacles or to perform turns along the path. No reference path was marked on the ground during tests.

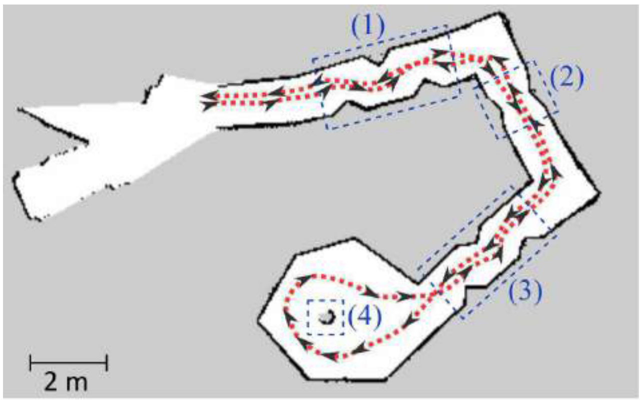

Fig. 14 Map of the evaluation course. The main walking area has a size of about 10 x 9m. The corridor included three sections with obstacles and one turning area in which participants had to drive round a pillar (area (4)) before driving back to the very beginning of the course. The height of obstacles varied in the different sections as follows: 90 cm (1), 50 cm (2)+(3).

6.2.3 Evaluation Method

Before participants completed the test trials, each of them was asked to drive freely through the course. For this first run, no instructions concerning obstacle avoidance and walking speed were given by the test supervisor, and no sensorial assistance was provided by the robot platform. This trial was intended to familiarize the participants with the device and course.

Each participant then completed the obstacle course under three different conditions mentioned in Section 6.2.1. The order of the conditions tested with each participant was randomized to exclude learning effects. The participants were not told which condition was used during the three different trials. Before starting each trial, the participants were instructed to complete the course as fast as possible. After each trial, a sufficient recovery phase was provided to the participants in order to prevent fatigue.

6.2.4 Evaluation Results

Two performance metrics were considered in order to verify the effectiveness of the proposed sensorial assistance: number of collisions (with the front of the robotic platform) and task completion time.

Differences in the number of collisions and task completion time between the three conditions were statistically analysed by a one-way analyses of variance (ANOVA) and obtained results are shown in Figs. 15, 16 and 17. No significant differences between conditions C1, C2 and C3 were identified in terms of task completion time. However, significant differences were found for the number of collisions and approaching velocity to obstacles. Post-hoc tests (Bonferroni corrected) showed a reduced number of collisions and reduced approaching velocity for C3 (sensorial assistance based on decision making algorithm) compared to condition C1 ($p < .05$), but no significant differences between other conditions (C2 vs. C1 / C3: $p = .07/.99$). The lowest approaching velocity to obstacles was found for C3.

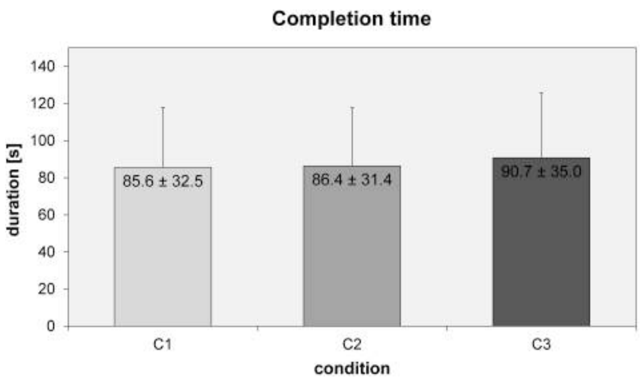

Fig. 15 Completion time in the user study under three conditions (C1, C2, and C3).

6.3 Discussion

The technical performance of the proposed approach was tested in two scenarios and resulted in the desired robot behavior as the robot cognitive, sensorial and physical assistance were activated as needed. The effectiveness of the proposed approach was demonstrated in the performed user

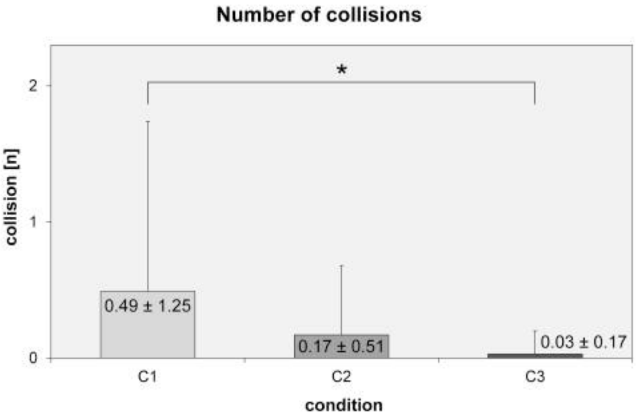

Fig. 16 Recorded number of collisions in the user study under three conditions (C1, C2, and C3).

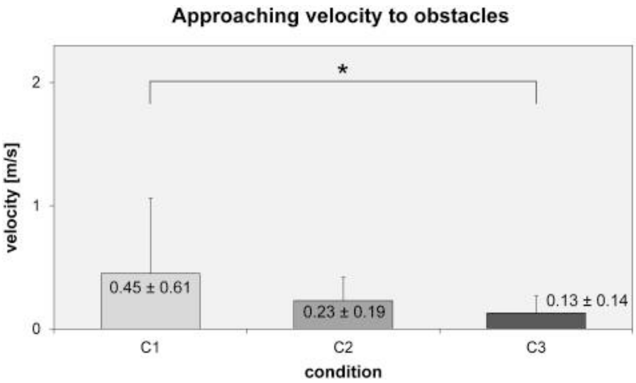

Fig. 17 Recorded average approaching velocity to obstacles in the user study under three conditions (C1, C2, and C3).

study with end-users. The lowest number of collisions, alongside with the lowest approaching velocity to obstacles was found when the user was passing the obstacle course using our newly proposed algorithm. However, similar task completion times for all conditions indicated that the proposed sensorial assistance approach does not interfere with the normal activity of the patients and furthermore guarantees a safe intentional approach to obstacles if needed.

One of the main practical challenges in the presented work was tuning basic and maximum values of adjustable parameters. We finally agreed on the chosen values based on discussions with experts. Further, the selection of suitable performance metrics and reward structures strongly affects the performance of the algorithm and a series of alternative performance metrics and related reward structures could have been chosen instead. We don't argue that our selection is the best, but that it fulfills the desired purpose of improving sensorial, cognitive and physical assistance.

7 Conclusion

An integrated approach for the context-specific, on-line adaptation of the assistance provided by a rollator-type MAR is presented. The shared control architecture distinguishes between short-term adaptations providing a) cognitive assistance to support the user to follow a desired path towards a predefined destination and b) sensorial assistance to avoid collisions with obstacles and to allow for an intentional approach of them. Further, it considers a long-term adaptation of c) the physical assistance based on long-term user performance and observed fatigue. To achieve an intuitive and human-like adaptation policy of the provided assistance, a decision making model explored in cognitive science, the Drift-Diffusion model, was employed.

We illustrated the effectiveness of the proposed architecture by means of experiments technically validating each of the three aforementioned functionalities of the architecture. Moreover, the performance of the algorithm with real end-users was demonstrated by conducting a user study with 35 elderly focusing specifically on the sensorial assistance functionality. Obtained results indicate that the required functionalities can be realized with the proposed decision making algorithm showing a general high potential of the proposed adaptive shared control architecture for MAR.

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References

1. Bedaf, S., Draper, H., Gelderblom, G.J., Sorell, T., Witte, L.: Can a service robot which supports independent living of older people disobey a command? The views of older people, informal carers and professional caregivers on the acceptability of robots. International Journal of Social Robotics pp. 1–12 (2016)
2. Borenstein, J., Koren, Y.: Teleautonomous guidance for mobile robots. IEEE Trans. Syst., Man Cybern. **20**(6), 1437–1443 (1990)
3. Broadbent, E., Stafford, R., MacDonald, B.: Acceptance of healthcare robots for the older population: Review and future directions. International Journal of Social Robotics **1**(4), 319–330 (2009)
4. Bruemmer, D.J., Few, D.A., Boring, R.L., Marble, J.L., Walton, M.C., Nielsen, C.W.: Shared understanding for collaborative control. IEEE Trans. Syst., Man Cybern. **19**(4) (2005)
5. Cao, M., Stewart, A., Leonard, N.E.: Convergence in human decision-making dynamics. Systems & Control Letters **59**(2), 87–97 (2010)
6. Cavagna, G., Margaria, R.: Mechanics of walking. J Appl Physiol **21**(1), 271–8 (1966)
7. Cooper, R.A.: Intelligent control of power wheelchairs. IEEE Engineering in Medicine and Biology Magazine **14**(4), 423–431 (1995)
8. Corredor, J., Sofrony, J., Peer, A.: Deciding on optimal assistance policies in haptic shared control tasks. In: IEEE Int. Conf. on Robotics and Automation, pp. 2679–2684 (2014)
9. Egelman, D.M., Person, C., Montague, P.R.: A computational role for dopamine delivery in human decision-making. J. of Cognitive Neuroscience **10**(5), 623–630 (1998)

10. Eldadah, B.A.: Fatigue and fatigability in older adults. PM&R **2**(5), 406–413 (2010)
11. Fenn, W.O.: The relation between the work performed and the energy liberated in muscular contraction. The Journal of physiology **58**(6), 373–395 (1924)
12. Frennert, S., Östlund, B.: Review: Seven matters of concern of social robots and older people. International Journal of Social Robotics **6**(2), 299–310 (2014)
13. Geravand, M., Peer, A.: Safety constrained motion control of mobility assistive robots. In: IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics. Brazil (2014)
14. Glende, S., Conrad, I., Krezdorn, L., Klemcke, S., Krätzel, C.: Increasing the acceptance of assistive robots for older people through marketing strategies based on stakeholder needs. International Journal of Social Robotics pp. 1–15 (2015)
15. Graf, B.: Reactive navigation of an intelligent robotic walking aid. In: IEEE international Workshop on Robot and Human Interactive Communication (2001)
16. Graf, B.: An adaptive guidance system for robotic walking aids. Journal of Computing and Information Technology - CIT (1), 109–120 (2009)
17. Graf, B., Schraft, R.D.: Behavior-based path modification for shared control of robotic walking aids. In: IEEE 10th International Conference on Rehabilitation Robotics. Noordwijk, Netherlands (2007)
18. Groten, R., Feth, D., Goshy, H., Peer, A., Kenny, D.A., Buss, M.: Experimental analysis of dominance in haptic collaboration. In: IEEE Int. Symp. on Robo. and Hum. Interac. Communic., pp. 723–729 (2009)
19. Guralnik, J., Simonsick, E., Ferrucci, L., Glynn, R., Berkman, L., Blazer, D., Scherr, P., Wallace, R.: A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol **49**(2), 387–392 (1994)
20. Heerink, M., Kröse, B., Evers, V., Wielinga, B.: Assessing acceptance of assistive social agent technology by older adults: the almere model. International Journal of Social Robotics **2**(4), 361–375 (2010)
21. Herrnstein, R.J.: Rational choice theory: Necessary but not sufficient. American Psychologist **45**(3), 356 (1990)
22. Herrnstein, R.J.: Experiments on stable suboptimality in individual behavior. American Economic Review pp. 360–364 (1991)
23. Hirata, Y., Hara, A., Kosuge, K.: Motion control of passive-type walking support system based on environment information. In: IEEE Int. Conf. on Rob. and Aut. ICRA (2005)
24. Hirata, Y., Hara, A., Kosuge, K.: Motion control of passive intelligent walker using servo brakes. IEEE Transaction on Robotics **23**(5) (2007)
25. Hirata, Y., Jr, O.C., Hara, A., Kosuge, K.: Human-adaptive motion control of active and passive type walking support system. In: IEEE Work. on Ad. Rob. and its Social Imp. (2005)
26. Hirata, Y., Komatsuda, S., Kosuge, K.: Fall prevention control of passive intelligent walker based on human model. In: IEEE/RSJ Int. Conf. on Intell. Robo. and Syst. (2008)
27. Hirata, Y., Muraki, A., Kosuge, K.: Motion control of intelligent passive-type walker for fall-prevention function based on estimation of user state. In: IEEE Int. Conf. on Rob. and Aut. (2006)
28. Hirzinger, G., Brunner, B., Dietrich, J., Heindl, J.: Sensor-based space robotics rotex and its telerobotic features. IEEE Trans. Robot. Autom. **9**(5), 649–661 (1993)
29. Huang, C., Wasson, G., Alwan, M., Sheth, P., Ledoux, A.: Shared navigational control and user intent detection in an intelliginet walker. In: AAAI Fall 2005 Symposium (EMBC) (2005)
30. Huang, J., Di, P., Fukuda, T., Matsuno, T.: Motion control of omnidirectional-type cane robot based on human intention. In: IEEE/RSJ Int. Conf. Intell. Robots Syst (2008)
31. Jenkins, S., Draper, H.: Care, monitoring, and companionship: Views on care robots from older people and their carers. International Journal of Social Robotics **7**(5), 673–683 (2015)
32. Jr., O.C., Hirata, Y., Kosuge, K.: Environment feedback for robotic walking support system control. In: IEEE Int. Conf. on Robo. and Aut. (2007)
33. Jr., O.C., Hirata, Y., Wang, Z., Kosuge, K.: A new control approach for a robotic walking support system in adapting user characteristics. IEEE Trans. on Sys., Man, and Sybern. part C: Applications and Reviews **36**(6) (2006)
34. Jr., O.C., Hirata, Y., Wang, Z., Kosuge, K.: A control approach based on passive behaviour to enhance user interaction. IEEE Trans. on Robotics **23**(5) (2007)
35. Khademian, B., Apkarian, J., Hashtrudi-Zaad, K.: Assessment of environmental effects on collaborative haptic guidance. Presence: Teleoperators and Virtual Environments **20**(3), 191–206 (2011)
36. Khademian, B., Hashtrudi-Zaad, K.: Performance issues in collaborative haptic training. In: IEEE Int. Conf. on Robo. and Auto., pp. 3257–3262 (2007)
37. Khademian, B., Hashtrudi-Zaad, K.: Shared control architectures for haptic training: Performance and coupled stability analysis (2011). DOI 10.1177/0278364910397559
38. Khademian, B., Hashtrudi-Zaad, K.: Dual-user teleoperation systems: New multilateral shared control architecture and kinesthetic performance measures. IEEE/ASME Transactions on Mechatronics **17**(5), 895–906 (2012)
39. Khatib, O.: Real-time obstacle avoidance for manipulators and mobile robots. The International Journal of Robotics Research **5**(1), 90–98 (1986)
40. Kofman, J., Wu, X., Luu, T., Verma, S.: Teleoperation of a robot manipulator using a vision-based human-robot interface. IEEE Trans. Ind. Electron. **52**(5), 1206–1219 (2005)
41. Lacy, G., MacNamara, S.: Context-aware shared control of a robot mobility aid for the elderly blind **19**(11), 1054 – 1065 (2000)
42. Manuel, J., Wandosell, H., Graf, B.: Non-holonomic navigation system of a walking-aid robot. In: IEEE int. Work. on Robo. and Hum. Interac. Communic. (2002)
43. Marcora, S.M., Staiano, W., Manning, V.: Mental fatigue impairs physical performance in humans. Journal of Applied Physiology **106**(3), 857–864 (2009)
44. Mitzner, T.L., Chen, T.L., Kemp, C.C., Rogers, W.A.: Identifying the potential for robotics to assist older adults in different living environments. International Journal of Social Robotics **6**(2), 213–227 (2013)
45. Montague, P.R., Berns, G.S.: Neural economics and the biological substrates of valuation. Neuron **36**(2), 265–284 (2002)
46. Montague, P.R., Dayan, P., Sejnowski, T.J.: A framework for mesencephalic dopamine systems based on predictive hebbian learning. The Journal of neuroscience **16**(5), 1936–1947 (1996)
47. Nedic, A., Tomlin, D., Holmes, P., Prentice, D.A., Cohen, J.D.: A decision task in a social context: Human experiments, models, and analyses of behavioral data. Proceedings of the IEEE **100**(3), 713–733 (2012)
48. Nejatbakhsh, N., Kosuge, K.: A human adaptive path tracking method for omnidirectional passive walking aid system. In: IEEE/RSJ Int. Conf. on Int. Robo. and Syst. (2005)
49. Nejatbakhsh, N., Kosuge, K.: User-environment based navigation algorithm for an omnidirectional passive walking aid system. In: Int. Conf. on Rehab. Robo. (2005)
50. Oishi, M.M.: Assessing information availability for user-interfaces of shared control systems under reference tracking. In: American Control Conference, pp. 3474–3481 (2014)
51. Quinlan, S., Khatib, O.: Elastics bands: Connecting path planning and control. IEEE Transactions on Robotics and Automation (1993)

52. Schnelle, J.F., Buchowski, M.S., Ikizler, T.A., Durkin, D.W., Beuscher, L., Simmons, S.F.: Evaluation of two fatigability severity measures in elderly adults. Journal of the American Geriatrics Society **60**(8), 1527–1533 (2012)
53. Sheridan, T.B.: Telerobotics, automation, and human supervisory control. MIT press (1992)
54. Simpson, R.C.: Smart wheelchairs: A literature review. Journal of rehabilitation research and development **42**(4), 423–436 (2004)
55. Smarr, C.A., Mitzner, T.L., Beer, J.M., Prakash, A., Chen, T.L., Kemp, C.C., Rogers, W.A.: Domestic robots for older adults: Attitudes, preferences, and potential. International Journal of Social Robotics **6**(2), 229–247 (2013)
56. Song, K.T., Jiang, S.Y.: Force-cooperative guidance design of an omni-directional walking assistive robot. In: IEEE Int. Conf. on Mechatr. and Autom. (2011)
57. Song, K.T., Lin, C.Y.: A new compliant motion control design of a walking-help robot based on motor current and speed measurment. In: IEEE Int. Conf. on Intell. Robo. and Syst. (2009)
58. Stewart, A., Cao, M., Leonard, N.E.: Steady-state distributions for human decisions in two-alternative choice tasks. In: American Control Conference, pp. 2378–2383 (2010)
59. Stewart, A., Cao, M., Nedic, A., Tomlin, D., Leonard, N.E.: Towards human–robot teams: Model-based analysis of human decision making in two-alternative choice tasks with social feedback. Proceedings of the IEEE **100**(3), 751–775 (2012)
60. Tinetti, M.E.: Performance-oriented assessment of mobility problems in elderly patients. J Am Geriatr Soc **34**(2), 119–126 (1986)
61. Wakita, K., Huang, J., Di, P., Sekiyama, K., Fukuda, T.: Human-walking-intention-based motion control of an omnidirectional-type cane robot. IEEE/ASME Trans. on Mechatro. **18**(1) (Feb. 2013)
62. Wasson, G., Gunderson, J.: Variable autonomy in a shared control pedestrian mobility aid for the elderly. In: Proceedings of the IJCAI01 Workshop on Autonomy, Delegaiton, and Control (2001)
63. Woodruff, C., Vu, L., Morgansen, K.A., Tomlin, D.: Deterministic modeling and evaluation of decision-making dynamics in sequential two-alternative forced choice tasks. Proceedings of the IEEE **100**(3), 734–750 (2012)
64. Yu, H., Spenko, M., Dubowsky, S.: An adaptive shared control system for an intelligent mobility aid for the elderly. Autonomous Robots **15**(1), 53–66 (2003)

Manuskript VI

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Evaluating the sit-to-stand transfer assistance from a smart walker in older adults with motor impairments

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Running title

STS assistance from a smart walker

ABSTRACT

Aim: To evaluate the effectiveness and user satisfaction with the sit-to-stand (STS) assistance system of a smart walker (SW) and to identify factors associated with them in potential users.

Methods: Thirty-three older adults (29 females, ≥65 years) with motor impairments (habitual rollator use) and no severe cognitive impairment (Mini-Mental State Examination ≥17 pt.) performed a five-chair stand test (5CST) without assistance and five STS transfers with the STS assistance system. Based on the number of successfully completed STS transfers, success rates were calculated for the 5CST and the SW-assisted STS transfers and compared using Wilcoxon signed-rank test. User satisfaction was assessed using the Telehealthcare Satisfaction Questionnaire-Wearable Technology (TSQ-WT = 0-80 pt., higher score = higher satisfaction). Bivariate correlations and multiple linear regression analyses were used to identify participant characteristics associated with the success rate and user satisfaction with the STS assistance system.

Results: Success rate for the SW-assisted STS transfers was significantly higher than for the 5CST (93.3 ±12.9% vs. 54.5 ±50.6%; P <0.001). User satisfaction was high (TSQ-WT = 62.5 ±11.2 pt.). Success rate with the STS assistance system was not significantly associated with any participant characteristics. Higher body mass index was a significant independent predictor of higher user satisfaction.

Conclusions: The SW-integrated STS assistance system can provide effective STS support with high user satisfaction for a wide range of potential users. Our findings suggest the high potential of the STS assistance system for promoting mobility, independence and quality of life in older adults with motor impairments.

Keywords: elderly, evaluation studies, mobility limitation, robotics, walkers.

INTRODUCTION

The ability to transfer from a sitting to a standing position is a prerequisite for mobility, independence, and quality of life (QoL) in older adults.[1,2] However, personal determinants for the sit-to-stand (STS) transfer such as muscle strength, motor planning and control, joint mobility, and balance[3,4] decline during the aging process,[5,6] and many older adults show STS difficulties, which have been associated with increased risk of falling and subsequent disability, institutionalization and mortality in older adults.[2,7] In nursing home residents, the STS transfer has even been identified as the activity most frequently performed prior to falling.[8] Assisting the STS transfer might therefore be highly beneficial for older adults with STS difficulties to reduce their risk of falling and to promote their mobility, independence and QoL.

Recent technological advances have led to the development of smart walkers (SWs), which are no longer limited to only providing walking assistance but integrate smart functionalities such as obstacle avoidance, navigation assistance, fall prevention, and/or gait tracking.[9] Some SWs can also provide STS assistance. Different technical solutions have been proposed for implementing such STS assistance into a SW, ranging from (1) basic, passive solutions, in which the braking system of the SW are activated while they grasp the handles and pull themselves up from the sitting position, through (2) more active solutions, in which the SW motion is controlled in the forward direction to pull up the user from sitting while grasping the handles, to (3) more complex, active solutions, in which the user is assisted during the entire STS motion by specifically designed trajectories of a manipulated STS supporting element (e.g., forearm or chest support) to achieve optimal transfer characteristics.[9] Independent of the technical implementation, previous evaluation studies of SW-integrated STS assistance systems suffer from methodological limitations, including small sample sizes, inadequate selection of participants, lack of assessment strategies specifically tailored to the STS assistance system, lack of user satisfaction measures, and/or lack of inferential statistical analyses.[10-13] To our knowledge, factors predictive for the effectiveness and user satisfaction have also not yet been investigated.

In a previous paper,[11] we described the technical details of the SW-integrated STS assistance system to be evaluated in this study. We also presented initial descriptive data on the effectiveness and user satisfaction with the system in potential SW users; however, we did not provide more detailed statistical analyses of these results and did not analyze participant characteristics that might have affected the effectiveness or user satisfaction.

In summary, the aim of this study was to evaluate the effectiveness and user satisfaction with a SW-integrated STS assistance system and to identify factors associated with them in potential SW users.

METHODS

This study was conducted between 1st November and 5th December 2014, with approval from the Ethics Committee of the Medical Faculty of the University of Heidelberg (S-358/2013) and in accordance with the Declaration of Helsinki. Written Informed consent was obtained from all participants included in the study.

MOBOT smart walker

The four-wheeled SW used in this study was developed in the MOBOT project ("Intelligent Active MObility Aid RoBOT integrating Multimodal Sensory Processing, Proactive Autonomy and Adaptive Interaction") and integrates innovative functionalities such as STS assistance, obstacle avoidance, navigation assistance, user following, gait tracking, and audio-gestural human-robot interaction into an overall context-aware mobility assistance robot.[14-17] Its STS assistance system is based on two actuated arms providing active assistance during the entire

STS motion via individualized robot handle trajectories (positions, velocities, accelerations) specifically tailored to the user's specific anthropometrics and motor impairment level. A detailed description of the STS assistance system and the optimal assistive strategies used to support the participants in the STS transfer has been provided previously.[11]

Study population

Participants were recruited from rehabilitation wards of a geriatric hospital, from a hospital-associated geriatric rehabilitation sports club, and from nursing homes. Following the criteria for the defined SW users,[17] inclusion criteria were: age ≥65 years, moderate motor impairments (habitual rollator use in daily life and/or 4-m usual gait speed[18] <0.6 m/s), and no severe cognitive impairment (Mini-Mental State Examination[19] [MMSE] score ≥17 pt.).

Measurements

Descriptive measures included age, sex, Body Mass Index (BMI), MMSE,[19] Barthel Index,[20] Performance Oriented Mobility Assessment (POMA),[21] 4-meter usual gait speed test,[18] falls in the previous year, Short Falls Efficacy Scale-International,[22] 15-item Geriatric Depression Scale,[23] 12-item Short-Form Health Survey,[24] and living situation (community dwelling vs. institutionalized).

STS measurements started with the Five-Chair Stand Test (5CST)[2] to assess the participants' general ability to stand up from a sitting position without assistance. As a standardized pre-test of the 5CST, participants were initially instructed to complete one chair stand (1CS). If they were unable to complete the 1CS after several trials, the 5CST was not performed. Participants who successfully completed the 1CS, were instructed to perform the actual 5CST (i.e. five STS transfers as fast as possible without assistance) once. The number of successful STS transfers in the 5CST and, if possible, the completion time for all five STS transfers in the 5CST were recorded. After the 5CST, participants tested the SW-integrated STS assistance system, which was initially adapted to the anthropometrics and motor impairment level of each participant to provide a user-specific optimal robot handle trajectory for the STS assistance. The SW was placed in front of the seated participants and the SW handles was brought into the starting position such that they were in line with the participants' trochanter major. Participants were then instructed to grip the handles and to trigger the STS assistance system by applying a small downward force on the handles, whenever they felt ready for the STS transfer. Each participant performed five STS trials with assistance of the SW, including short pauses in between to avoid exhaustion and in which the handles of the SW were brought back to the initial starting position. Figure 1 shows a sequence of snapshots taken during a STS transfer with the STS assistance system. The number of successful STS transfers with assistance of the SW was recorded. For all STS measurements, participants were seated on an arm- and backless, height-adjustable chair with the seat placed at 100% knee height, measured as the distance from the left medial tibia plateau to the floor.

User satisfaction with the STS assistance system was evaluated using the Telehealth-care Satisfaction Questionnaire-Wearable Technology (TSQ-WT; see Supplementary Document 1).[25] The TSQ-WT consists of six dimensions evaluating the benefit, usability, self-concept, privacy & loss of control, QoL and wearing comfort of a system. Each dimension includes five items rated on a 5-point Likert scale (0-4 pt.), with higher scores indicating more positive ratings. The TSQ-WT has already been successfully used to evaluate the navigation assistance system of the SW[26] and other robotic devices.[27,28] It can be adapted to several systems and was customized to the STS assistance system by deleting the inappropriate dimensions of wearing comfort, which focuses on wearable technology, and privacy & loss of control, which focuses on long-term technology use.

Main study outcomes were the (1) success rates [%] for the 5CST without assistance (SR_{5CST}) and the STS trials assisted by the SW (SR_{SW}), both calculated as (100 × (number of successful STS transfers / 5); (2) TSQ-WT dimension scores (range 0-20 pt.), calculated as the sum of item scores, and (3) TSQ-WT total score (range 0-80 pt.), calculated as the sum of the TSQ-WT dimension scores.

Statistical analysis

Descriptive data were presented as frequencies and percentages, means and standard deviations (SD), or medians and interquartile ranges (IQR). McNemar tests were used to compare the number of participants successfully completing the 1CS with those successfully completing the individual STS trials with the SW. Difference between the $SR5_{CST}$ and the SR_{SW} was analyzed using the Wilcoxon signed-rank test. Effect size (ES) was calculated as ($Z/\sqrt{N}$) and interpreted as small (<0.3), moderate (0.3<0.5), and large (≥0.5).[29] To identify potential predictors of the effectiveness and user satisfaction with the STS assistance system, bivariate associations of participant characteristics with the SR_{SW} and TSQ-WT total score were examined using Spearman rank or point-biserale correlations (*r*). The association of the TSQ-WT total score with the SR_{SW} was also analyzed by Spearman rank correlation. Participant characteristics that showed significant correlations were entered into multiple linear regression models (stepwise backward) to determine independent predictors of SR_{SW} and TSQ-WT total score. A two-sided *P*-value of <0.05 indicated statistical significance. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

RESULTS

The sample included 33 older persons (females: *n* = 29, 87.9%) with a mean age of 84.6 ±5.0 years and no severe cognitive impairment (MMSE score = 24.9 ±3.9 pt.) who all used a rollator as a mobility aid in everyday life (Table 1). Functional status was slightly impaired, with a median Barthel Index of 80.0 [67.5-95.0] points. Habitual gait speed averaged 0.47 ±0.13 m/s and the mean POMA score was 20.0 ±5.4 points, indicating low motor performance and increased risk of falling.

Fifteen participants (45.5%) were not able to complete the unassisted 1CS. Already in the first trial with the STS assistance system, the number of participants who successfully completed the STS transfer was significantly higher than in the unassisted 1CS (*n* = 28, 84.8% vs. *n* = 15, 45.5%, *P* = 0.003) and further increased over the subsequent trials (2nd: *n* = 29, 87.9% vs. *n* = 15, 45.5%, *P* = 0.003; 3rd: *n* = 31, 93.9% vs. *n* = 15, 45.5%, *P* <0.001), with all participants achieving the standing position in the fourth and fifth trial (*n* = 33, 100.0%). All participants who performed the unassisted 5CST (*n* = 18, 54.5%) completed five repeated STS transfers, with a mean completion time of 19.6 ±7.6 seconds. The SR_{SW} was significantly higher than the SR_{5CST} (93.3 ±12.9% vs. 54.5 ±50.6%, *P* <0.001), with a large effect size (ES = 0.62). User satisfaction with the STS assistance system was high, with all median TSQ-WT scores in the upper quartile of the scoring range (Table 2).

None of the participant characteristics significantly correlated with the SR_{SW} (*r* = |0.01-0.24|, *P* = 0.183-.999). BMI (*r* = 0.45, *P* = 0.009) and age (*r* = -0.38, *P* = 0.031) showed significant moderate correlations with the TSQ-WT total score, such that a higher BMI and younger age were associated with higher user satisfaction. All other correlations between the TSQ-WT total score and participant characteristics were not significant (*r* = |0.01-0.29|, *P* = 0.156-.905). No significant correlation was also found between the TSQ-WT total score and the SR_{SW} (*r* = -0.26, *P* = 0.148). In the linear regression model, only a higher BMI was identified as a significant independent predictor of higher user satisfaction (β = 0.48, R^2 = 0.23, *P* = 0.005).

DISCUSSION

This study shows that the SW-integrated STS assistance system was highly effective for supporting the STS transfer in older adults with motor impairments. To our knowledge, this is the first study that provides statistical evidence on the effectiveness of such system in the intended user group of a SW. Our results further demonstrate high user satisfaction with the STS assistance system among potential SW users, with those having higher BMI being more satisfied.

The general STS ability of the participants was low, with only about half of them able to stand up unassisted. Already in the first trial with the STS assistance system, a significantly higher proportion of participants achieved the standing position, suggesting that the system can initially provide an easy-to-handle and effective STS assistance for potential users. Participants initially not able to stand up with the STS assistance system became also quickly familiar, as indicated by the finding that all participants achieved the standing position with its assistance not later than with the fourth trial. As documented by the significantly higher success rate with the STS assistance system than without its assistance, the added value of this system for the intended user group is evidenced by statistical analysis, which was lacking in previous evaluation studies of SW-integrated STS assistance systems.[10-12]

Based on a comprehensive questionnaire, our results revealed high user satisfaction with the STS assistance system in several dimensions. To our knowledge, such multidimensional subjective evaluation measure has not yet been used in previous studies for evaluating such SW-integrated systems. High scores across the different dimensions emphasized that (1) the STS assistance system provided a benefit for the participants by helping them to stand up; (2) it was perceived as easy-to-use, not requiring much effort and not causing feelings of insecurity or indisposition; (3) its use was an interesting challenge for them, and they were not reminded of losing their independence nor would they feel embarrassed when using it in public, and (4) it could have the potential for promoting the user's well-being, social contacts, independence and QoL.

The user satisfaction with the STS assistance system was comparably high to that previously reported for the SW-integrated navigation assistance system, as also assessed using the TSQ-WT in a similar study population.[26] Concerning the satisfaction in different dimensions, it even seems that potential users might perceive a SW-integrated STS assistance system as being more beneficial and having a greater potential to improve their QoL than a SW-integrated navigation assistance system.

The success rate with the STS assistance system was not related to specific participant characteristics, suggesting that it may be effective for a wide range of potential SW users. The individualized assistive STS strategy in terms of adapting the robot handle trajectory of the STS assistance system to the specific participant may explain this finding.

Higher user satisfaction was found to be independently associated with higher BMI. A potential explanation for this might be that participants with higher BMI had to exert more physical effort to successfully complete the unassisted STS transfer and therefore perceived the reduction of physical exertion from the STS assistance system more clearly than participants with lower BMI, who usually perceived less physical exertion when completing functional tasks.[30] Measuring the perceived physical exertion in future studies evaluating SW-integrated STS assistance systems may provide further support for this explanation.

User satisfaction was not related to the success rate with the STS assistance system, indicating that participants who initially had difficulties in standing up with the SW were still satisfied with the STS assistance system. The failed trials in the initial phase of using the system seem to have been well-accepted by the participants and did not negatively affect their user satisfaction.

The strength of this study was its approach to avoid the methodological limitations of previous studies evaluating STS assistance systems or other innovative SW functionalities.[13] It extends the previous research by including a reasonable number of representative SW users; using a comparative study design for effectiveness testing (i.e. unassisted vs. assisted STS transfer) and an assessment strategy specifically tailored to the STS assistance system to document its specific effect; using a comprehensive questionnaire on the user satisfaction with the STS assistance system; investigating potential factors associated with the effectiveness and user satisfaction, and analyzing data obtained by statistical methods.

The study also has some limitations. Although our sample size was much larger than in previous studies evaluating SWs and integrated STS assistance systems, it was relatively small, which may have limited the statistical power. However, post-hoc power analyses revealed a power of 92.3-92.9% for the McNemar tests (OR = 11.1-12.1, α = 0.05, π_D = 0.363-0.364), 98.6% for the Wilcoxon signed-rank test (d_z = 0.77, α = 0.05), and 86.0% for the linear regression model (R^2 = 0.23, α = 0.05, number of predictors = 1). Our participants were predominantly females, limiting the generalizability of the results to males. Consequently, the finding that gender was not related to the effectiveness and user satisfaction with the STS assistance system may have also be limited by the small number of male participants. The five STS trials with the STS assistance system included short pauses in between, while the 5CST had to be performed as fast as possible without pauses. This could have led to a reduced SR_{5CST} due to exhaustion; however, all participants able to perform the 5CST achieved the maximum SR_{5CST} of 100% despite maximum STS pace. The STS assistance system was tested only for a small number of trials within a controlled laboratory environment, as limited by the prototype status of the SW. Future studies with a more advanced version should include evaluations after prolonged use in more natural environments.

In conclusion, the present study highlights that the SW-integrated STS assistance system can provide effective support for the STS transfer of potential SW users, with high user satisfaction. Our findings suggest the high potential of the STS assistance system to promote mobility, independence and QoL in older adults with motor impairments. Future SW developments may consider the implementation of STS assistance systems that allow for individual adaption to the user.

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Disclosure statement

The authors declare no conflict of interest.

References

[1] Fusco O, Ferrini A, Santoro M, Lo Monaco MR, Gambassi G, Cesari M. Physical function and perceived quality of life in older persons. Aging Clin Exp Res 2012; 24: 68-73.
[2] Guralnik JM, Simonsick EM, Ferrucci L, et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol 1994; 49: M85-94.
[3] Lindemann U, Muche R, Stuber M, Zijlstra W, Hauer K, Becker C. Coordination of strength exertion during the chair-rise movement in very old people. J Gerontol A Biol Sci Med Sci 2007; 62: 636-40.
[4] Schenkman M, Hughes MA, Samsa G, Studenski S. The relative importance of strength and balance in chair rise by functionally impaired older individuals. J Am Geriatr Soc 1996; 44: 1441-46.
[5] Ferrucci L, Cooper R, Shardell M, Simonsick EM, Schrack JA, Kuh D. Age-related change in mobility: Perspectives from life course epidemiology and geroscience. J Gerontol A Biol Sci Med Sci 2016; 71: 1184-94.
[6] Whipple R, Wolfson L, Derby C, Singh D, Tobin J. Altered sensory function and balance in older persons. J Gerontol 1993; 48 Spec No: 71-76.
[7] Ward RE, Leveille SG, Beauchamp MK, et al. Functional performance as a predictor of injurious falls in older adults. J Am Geriatr Soc 2015; 63: 315-20.
[8] Rapp K, Becker C, Cameron ID, Konig HH, Buchele G. Epidemiology of falls in residential aged care: analysis of more than 70,000 falls from residents of bavarian nursing homes. J Am Med Dir Assoc 2012; 13.
[9] Page S, Saint-Bauzel L, Rumeau P, Pasqui V. Smart walkers: an application-oriented review. Robotica 2016; 35: 1243-62.
[10] Chugo D, Asawa T, Kitamura T, Jia S, Takase K. A motion control of a robotic walker for continuous assistance during standing, walking and seating operation. Intelligent Robots and Systems, 2009 IROS 2009 IEEE/RSJ International Conference on, 2009; 4487-92.
[11] Geravand M, Korondi PZ, Werner C, Hauer K, Peer A. Human sit-to-stand transfer modeling towards intuitive and biologically-inspired robot assistance. Auton Robots 2017; 41: 575-92.
[12] Rumeau P, Pasqui V, Vigourou N. A generic method for the assessment of smart walkers. Gerontechnology 2012; 11: 345.
[13] Werner C, Ullrich P, Geravand M, Peer A, Hauer K. Evaluation studies of robotic rollators by the user perspective: A systematic review. Gerontology 2016; 62: 644-53.
[14] Geravand M, Werner C, Hauer K, Peer A. An integrated decision making approach for adaptive shared control of mobility assistance robots. Int J Soc Robot 2016: 1-18.
[15] Werner C, Chalvatzaki G, Papageorgiou XS, Tzafestas CS, Bauer JM, Hauer K. Assessing the concurrent validity of a gait analysis system integrated into a smart walker in older adults with gait impairments. Clinl Rehab 2019; 33:1682-1687.
[16] Efthimiou E, Fotinea S-E, Goulas T, et al. The MOBOT Platform – Showcasing Multimodality in Human-Assistive Robot Interaction. In: Antona M, Stephanidis C, eds. Universal Access in Human-Computer Interaction Interaction Techniques and Environments 10th International Conference, UAHCI 2016, Held as Part of HCI International 2016, Toronto, ON, Canada, July 17-22, 2016, Proceedings, Part II. Berlin, Heidelberg: Springer International Publishing, 2016; 382-91.
[17] Werner C, Moustris GP, Tzafestas CS, Hauer K. User-oriented evaluation of a robotic rollator that provides navigation assistance in frail older adults with and without cognitive impairment. Gerontology 2018; 64: 278-90.
[18] Ostir GV, Volpato S, Fried LP, Chaves P, Guralnik JM. Reliability and sensitivity to change assessed for a summary measure of lower body function: results from the Women's Health and Aging Study. J Clin Epidemiol 2002; 55: 916-21.
[19] Folstein MF, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975; 12: 189-98.

[20] Mahoney FI, Barthel DW. Functional evaluation: The Barthel Index. Md State Med J 1965; 14: 61-5.
[21] Tinetti ME. Performance-oriented assessment of mobility problems in elderly patients. J Am Geriatr Soc 1986; 34: 119-26.
[22] Kempen GI, Yardley L, van Haastregt JC, et al. The Short FES-I: a shortened version of the Falls Efficacy Scale-International to assess fear of falling. Age Ageing 2008; 37: 45-50.
[23] Sheikh JI, Yesavage JA. Geriatric Depression Scale (GDS): Recent evidence and development of a shorter version. In: Brink TL, ed. Clinical Gerontology: A Guide to Assessment and Intervention. New York, NY: The Haworth Press, 1986; 165-73.
[24] Ware J, Jr., Kosinski M, Keller SD. A 12-Item Short-Form Health Survey: Construction of scales and preliminary tests of reliability and validity. Med Care 1996; 34: 220-33.
[25] Chiari L, van Lummel R, Pfeiffer K, Lindemann U, Zijlstra W. Deliverable 2.2: Classification of the user's needs, characteristics and scenarios - update. [Unpublished report from the EU Project (6th Framework Program, IST Contract no. 045622) Sensing and Action to support mobility in Ambient Assisted Living]. Department of Health. (2009) Prevention Package for Older people. London: Crown Copyright, 2009.
[26] Hauer K. Bewertung von AAL-Ambient-Assisted-Living-Systemen bei Personen mit kognitiver Schädigung: Match vs. Mismatch. In: Bendel O, ed. Pflegeroboter. Wiesbaden: Springer Fachmedien Wiesbaden, 2018; 89-111.
[27] Schwickert L, Klenk J, Stahler A, Becker C, Lindemann U. Robotic-assisted rehabilitation of proximal humerus fractures in virtual environments: a pilot study. Z Gerontol Geriatr 2011; 44: 387-92.
[28] Ambrosini E, Ferrante S, Rossini M, et al. Functional and usability assessment of a robotic exoskeleton arm to support activities of daily life. Robotica 2014; 32: 1213-24.
[29] Cohen J. Statistical power analysis for the behavioral sciences. New York: Routledge, 1988.
[30] Hageman PA, Pullen CH, Dizona P, Schmidt K, Boeckner LS. Obesity and Physical Function in Rural Women who enroll in a Lifestyle Modification Intervention for Reducing Blood Pressure. Cardiopulm Phys Ther J 2013; 24: 4-11.

Table 1 Participant characteristics

Variables	*n* = 33
Age, years	84.6 ± 5.0
Sex, females	29 (87.9)
Body Mass Index, kg/m^2	26.8 ± 3.3
Mini-Mental State Examination, score	24.9 ± 3.9
Barthel Index	80.0 [67.5-95]
Performance Oriented Mobility Assessment, score	20.1 ± 5.4
4-meter walk test, m/s	0.47 ± 0.13
Fall in the previous year	21 (63.6)
Short Falls Efficacy Scale-International, score	9 [7-12]
15-item Geriatric Depression Scale, score	2 [1-3]
12-item Short Form Health Survey, score	
Physical component	34.4 ± 9.6
Mental component	53.6 ± 9.4
Living situation	
Community-dwelling	26 (78.8)
Institutionalized	7 (21.2)

Data presented as mean ± SD, *n* (%), and median [IQR].

Table 2 User satisfaction with the sit-to-stand transfer assistance system of the smart walker: Dimension scores and total score of the Telehealthcare Satisfaction Questionnaire – Wearable Technology

TSQ-WT dimension	*n*	Mean ± SD	Median [IQR]
Benefit (0-20 pt.)	33	15.5 ± 4.4	16 [13-19]
Usability (0-20 pt.)	33	16.7 ± 2.9	17 [15-19]
Self-concept (0-20 pt.)	33	14.6 ± 3.7	15 [13-20]
Quality of life (0-20 pt.)	33	15.1 ± 3.2	16 [13-20]
Total score (0-80 pt.)	33	62.5 ± 11.2	62 [56-71]

Data presented as mean ± SD and median [IQR]. TSQ-WT, Telehealthcare Satisfaction Questionnaire – Wearable Technology. Higher scores indicate more positive ratings.

Table 3 Bivariate correlations of participant characteristics with the effectiveness and user satisfaction with the sit-to-stand transfer assistance system of the smart walker

Variables	SR_{SW}	TSQ-WT total score
Age	-0.06	-0.38*
Sex†	0.05	0.07
Body Mass Index	-0.19	0.45**
Mini-Mental State Examination	-0.14	-0.06
Barthel Index	-0.01	-0.12
Performance Oriented Mobility Assessment	0.21	-0.15
4-meter walk test	-0.15	-0.18
Fall in the previous year	<0.01	-0.07
Short Falls Efficacy Scale-International	-0.02	-0.14
15-item Geriatric Depression Scale	0.24	-0.05
12-item Short Form Health Survey		
Physical component	0.09	-0.04
Mental component	-0.10	0.25
Living situation††	0.08	0.02

Correlations given as Spearman rank or point-biserale correlations coefficients. SR_{SW}, success rate for the sit-to-stand transfers with assistance of the smart walker. TSQ-WT, Telehealthcare Satisfaction Questionnaire – Wearable Technology. †0 = female, 1 = male; ††0 = community-dwelling, 1 = institutionalized; *$p < .05$, **$p < .01$.

Figure legends

Figure 1 Sequence of snapshots taken during a sit-to-stand transfer with assistance of the smart walker

List of Supporting information

Supporting Document 1 Telehealthcare Satisfaction Questionnaire – Wearable Technology (TSQ-WT) adapted to the evaluation of the sit-to-stand assistance system of the smart walker

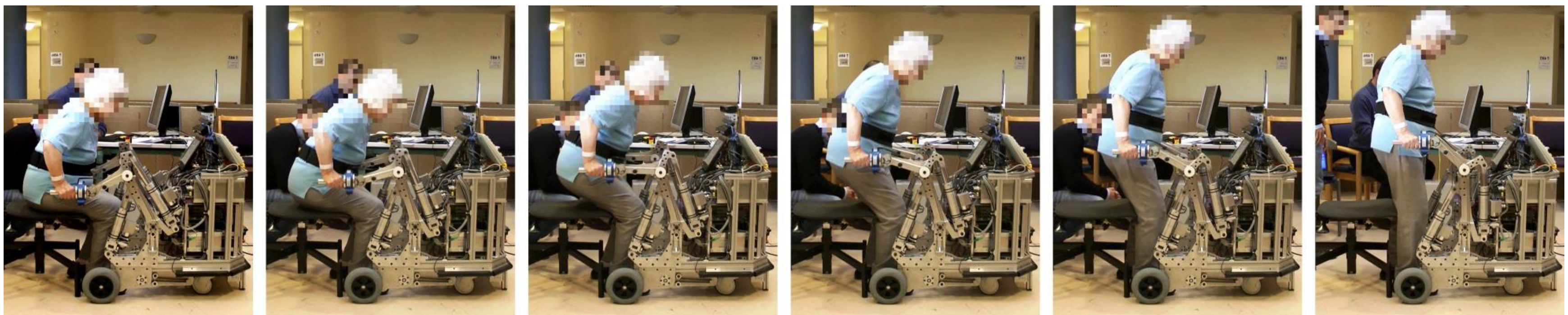

Figure 1 Sequence of snapshots taken during a sit-to-stand transfer with assistance of the smart walker

Supporting Document 1

Telehealthcare Satisfaction Questionnaire – Wearable Technology (TSQ-WT) adapted to the evaluation of the sit-to-stand assistance system of the smart walker

Dimension	Statement		0 Strongly disagree	1 Disagree	2 Neutral	3 Agree	4 Strongly agree
Benefit	1	I can benefit from this sit-to-stand assistance system.	☐	☐	☐	☐	☐
	2	The effort of using this sit-to-stand assistance system is worthwhile for me.	☐	☐	☐	☐	☐
	3	I am confident I'm getting the most out of this sit-to-stand assistance system.	☐	☐	☐	☐	☐
	4	This sit-to-stand assistance system is helping me to stand up from a chair.	☐	☐	☐	☐	☐
	5	I would recommend this sit-to-stand assistance system to other people in my situation.	☐	☐	☐	☐	☐
Usability	1	The use of this sit-to-stand assistance system requires effort.†	☐	☐	☐	☐	☐
	2	The sit-to-stand assistance system is reliable according to my estimation and experience so far.	☐	☐	☐	☐	☐
	3	This sit-to-stand assistance system is easy to use.	☐	☐	☐	☐	☐
	4	I feel safe when using this sit-to-stand assistance system.	☐	☐	☐	☐	☐
	5	I feel good while using this STS assistance system.	☐	☐	☐	☐	☐
Self-concept	1	The use of this sit-to-stand assistance system is an interesting challenge for me.	☐	☐	☐	☐	☐
	2	This sit-to-stand assistance system reminds me of losing my independence.†	☐	☐	☐	☐	☐
	3	The use of this sit-to-stand assistance system is making me feel older than I am.†	☐	☐	☐	☐	☐
	4	I (would) feel embarrassed using this sit-to-stand assistance system visible around others.†	☐	☐	☐	☐	☐
	5	I like to use technological products or systems like this sit-to-stand assistance system.	☐	☐	☐	☐	☐
Quality of life	1	Using this sit-to-stand assistance system could improve my physical well-being.	☐	☐	☐	☐	☐
	2	This sit-to-stand assistance system evokes unpleasant feelings.†	☐	☐	☐	☐	☐
	3	This sit-to-stand assistance system could enhance my social contacts.	☐	☐	☐	☐	☐
	4	This sit-to-stand assistance system could help me to maintain or increase my independence.	☐	☐	☐	☐	☐
	5	The use of this sit-to-stand assistance system has a positive effect on me.	☐	☐	☐	☐	☐

†These items are scored in reverse order (4 = strongly agree, 3 = agree, 2 = neutral, 1 = disagree, 0 = strongly disagree). *Note*. The original version of the Telehealthcare Satisfaction Questionnaire – Wearable Technology (TSQ-WT) is available from https://site.unibo.it/hfrs/en/questionnaires/tsq-wt/tsq-wt.pdf/@@download/file/TSQ-WT.pdf

Manuskript VII

Werner, C., Dometios, A. C., Maragos, P., Tzafestas, C. S., Bauer, J. M. & Hauer, K. Evaluating the task effectiveness and user satisfaction with different operation modes for an assistive bathing robot in older adults with bathing disability. Under Review in *Assistive Technology.*

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Evaluating the task effectiveness and user satisfaction with different operation modes of an assistive bathing robot in older adults with bathing disability

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ABSTRACT

Older adults who require assistance in bathing may wish to be personally independent in this intimate activity. Bathing robots represent an option for them to foster independence while preserving privacy. Making human-robot interaction (HRI) for elderly as easy, effective and user-satisfying as possible is, however, a major challenge in the development of such robots. The study aim was to evaluate the effectiveness (EF) and user satisfaction with three operation modes (autonomous operation, shared control, tele-manipulation) for the HRI with a bathing robot in potential users. Twenty-five older persons with bathing disability tested the robot's operation modes in a water pouring scenario for the upper back. Autonomous operation led to maximum EF. In the shared control and tele-manipulation mode, EF was rather low and worse than in autonomous operation ($p \leq 0.001$). EF decreased with decreasing robot assistance in the user-controlled modes (p=0.009-0.016). User satisfaction with the autonomous operation was higher than with the tele-manipulation mode ($p = 0.003$) and in trend ($p = 0.071$) also than with the shared control mode. Our study suggests that for an effective and highly satisfying HRI with a bathing robot in older users, operation modes with high robot autonomy that require a minimum of user input seem to be necessary.

Keywords: robotics; activities of daily living; baths; aged; human-robot interaction.

INTRODUCTION

Limitations in activities of daily living (ADLs) increase with age (Chatterji, Byles, Cutler, Seeman, & Verdes, 2015) and are significant predictors of loss of independence and mortality (Gill, Allore, & Han, 2006; Luppa et al., 2010; Manton, 1988; Rozzini, Sabatini, Ranhoff, & Trabucchi, 2007). Among ADL limitations, those in bathing activities are one of the first to occur during the aging process (Jagger, Arthur, Spiers, & Clarke, 2001; Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963) and have even been identified as a seminal point in the disabling process for older adults (Gill, Allore, et al., 2006; Gill, Guo, & Allore, 2006). Bathing represents one of the most complex ADLs (Gerrard, 2013), for which institutionalized and non-institutionalized older adults require personal assistance more frequently than for other ADLs (dressing, transferring, toileting, eating) (Wiener, Hanley, Clark, & Van Nostrand, 1990). Prevalence rates for bathing disability (defined as the need for personal assistance) in community-dwelling older adults have been reported to increase with age from 4.6-8.6% in those ≥65 years (Wiener et al., 1990) to 21.0% in those ≥85 years (Dawson, Hendershot, & Fulton, 1984). In institutionalized settings such as nursing homes or personal care facilities, an even much higher prevalence rate of bathing disability (≥90%) has been documented (Jones, Dawyer, Bercovitz, & Strahan, 2009; Wiener et al., 1990). The demographic change towards an aging society will further increase the number of older adults in need for bathing assistance, and thus also the burden of formal and informal care system. As bathing is one of the most sensitive and intimate ADLs, some older adults might wish to be independent from personal assistance in bathing as long as possible (Ahluwalia, Gill, Baker, & Fried, 2010). Addressing these issues, an assistive bathing robot represent an option for older adults with bathing disability to sustain their autonomy in bathing, to reserve their privacy, and to reduce the burden of caregivers.

One of the most crucial challenges in the successful development and application of assistive robots in older adults lies in how to make interaction with the robot as easy, safe and efficient as possible for this user group (Ka, Ding, & Ravishankar, 2015), in which low technology experience and negative attitudes towards robot assistance is not uncommon (Dyck & Smither, 1994; Scopelliti, Giuliani, D'Amico, & Fornara, 2004). Depending on the operation mode, various cognitive abilities (e.g., attention, working memory, information processing) can be relevant for the human-robot interaction (HRI) with the assistive robot. Most of these cognitive abilities, however, show a pronounced decline across the life span into old age (Craik & Salthouse, 2008; Harada, Natelson Love, & Triebel, 2013), and cognitive impairment is frequently observed in older adults with ADL limitations (Gure, Langa, Fisher, Piette, & Plassman, 2013; Hakkinen et al., 2007). If the operation of the assistive robot is cognitively too demanding and too difficult to learn or use the HRI will not be effective and the assistive robot will not be successful in accomplishing the task(s) for which it was developed (Chung, Wang, & Cooper, 2013). In addition, the user's perception of his/her own overload in operating the assistive robot may reduce the self-efficacy and reinforce the feeling of loss of control, which in turn may significantly affect the acceptance of and satisfaction with the robot (Hauer, 2018; Tacken, Marcellini, Mollenkopf, Ruoppila, & Széman, 2005). For developing and implementing well-accepted, easy-to-use and effective operation modes for an assistive robot in older adults, it is therefore crucial to involve their feedback early in the robot design and evaluation process. Furthermore, older adults can be seen as the most heterogeneous population regarding physical, cognitive, sociological and psychological characteristics (Hunter, Pereira, & Keenan, 2016; Nelson & Dannefer, 1992; Yang & Lee, 2010), potentially also leading to a large heterogeneity in their needs and preferences for robot assistance and control. Considering personal characteristics when studying HRI has therefore been strongly recommended in older adults (Zafrani & Nimrod, 2018).

A potential approach to overcome the challenges of HRI in older adults is to reduce their cognitive load when interacting with the assistive robot by increasing its autonomy.

Depending on the level of robot autonomy, operation modes of an assistive robot can be roughly categorized into (1) tele-manipulation, in which the user has full control over the robot to complete a specific task; (2) shared control, in which a synergetic collaboration between the user and the robot exists to complete the task, and (3) autonomous operation, in which the robot fully autonomously completes the task with the user only selecting the task to be executed (Abbink & Mulder, 2010; Amirshirzad, Kaya, & Oztop, 2016; Schirner, Erdogmus, Chowdhury, & Padir, 2013; Vogel et al., 2015; Yanco & Drury, 2004). Having in mind these different levels of robot autonomy, it is reasonable to expect that different operation modes will have an effect on the task effectiveness and the user satisfaction with the assistive robot. To our knowledge, however, there have been no comparative studies between different operation modes within the research field of assistive bathing robots in older adults. Previous studies with other assistive robots (e.g., telemedicine robot, robotic walker, robotic wheelchair) suggest that task effectiveness increases with increasing robot autonomy in young or older adults with physical impairments (Erdogan & Argall, 2017; Kim et al., 2012; Koceska, Koceski, Beomonte Zobel, Trajkovik, & Garcia, 2019; Werner et al., 2018; Yu, Spenko, & Dubowsky, 2003). In contrast to this, it was also observed that the most autonomous operation modes with the highest task effectiveness were not those with the highest user satisfaction, suggesting that users seem to prefer to retain as much control as possible when interacting with an assistive robot (Cooper et al., 2012; Kim et al., 2012; Yu et al., 2003)

In summary, the primary aim of this study was to evaluate the task effectiveness and user satisfaction of older persons with different operation modes (autonomous operation, shared control, tele-manipulation) for a water pouring scenario with a bathing robot. Based on previous studies with other assistive robots, it was hypothesized that (1) task effectiveness with the bathing robot would be highest in the autonomous operation mode and would gradually decrease with lower levels of robot assistance, and (2) user satisfaction would be lower in the autonomous operation mode than in the more user-controlled operation modes (shared control, tele-manipulation). A secondary aim was to explore whether there were interaction effects between personal characteristics of the participants and the different operation modes on the user satisfaction.

METHODS

I-SUPPORT bathing robot and potential users

The bathing robot used in this study was developed in the I-SUPPORT project (ICT-Supported Bath Robots), which aimed to develop an information and communication technology (ICT)-supported domestic service robot that assists frail older or disabled individuals in various bathing tasks (e.g., pouring water, soaping, scrubbing, drying) (http://www.i-support-project.eu/). In brief, the I-SUPPORT bathing robot consists of a motorized chair for supporting stand-to-sit and sit-to-stand transfers and the transition into and out of the shower area, a robotic soft-arm for the specific bathing tasks (e.g., pouring water, soaping, scrubbing, drying), Kinect V2 RGB-D sensors and condenser microphones for natural audio-gestural HRI (human and robot pose estimation, command and action recognition), and a context-aware system for monitoring environmental (water flow and temperature, air temperature, humidity and illumination sensors) and user information (smartwatch for user identification and (in-)activity tracking). Further technical details about the I-SUPPORT bathing robot will be published elsewhere. For this study, the I-SUPPORT bathing robot was installed in a typical bathroom of a rehabilitation clinic at a German geriatric hospital (Figure 1).

Potential users of the I-SUPPORT bathing robot were defined as persons with dependence in bathing activities (Barthel Index [BI] bathing item: 0 pt. = "patient can use a bath tub, a shower, or take a complete sponge bath only with assistance or supervision from another person", Mahoney & Barthel, 1965), and no severe cognitive impairment (Mini-Mental State Examination (MMSE score >17 pt., Folstein, Folstein, & McHugh, 1975).

Operation modes of the I-SUPPORT bathing robot

The use case scenario to be evaluated in this study included the water pouring process of the robotic soft-arm for the user's upper back region (Figure 2) as defined by six target points (Figure 3) with three different operation modes: (1) autonomous operation, (2) shared control and (3) tele-manipulation mode.

In the *autonomous operation mode*, the soft-arm of the I-SUPPORT bathing robot provides water pouring fully automatically for a predefined body area (= upper back region) within a predefined time period and the user has no control over the motion of the soft-arm after starting the robot.

In the shared control mode, the user issues simple motion commands for the soft-arm (i.e., one step left vs. right, up vs. down) using the arrow keys of a commercial waterproof computer keyboard, while the I-SUPPORT bathing robot provides audio assistance via beep signals indicating that (1) the specific user command is registered and (2) the motion of the soft-arm has been successfully executed according to the registered user command, meaning that the user can now issue the next motion command for the soft-arm. Further assistance in the shared control mode is provided by restricting the motion of the soft-arm to the predefined body area (i.e. upper back region cannot be exceeded). Thus, in this mode, the user has predominant, but not full control over the motion of the soft-arm (Dometios, Papageorgiou, Arvanitakis, Tzafestas, & Maragos, 2017).

In the *tele-manipulation mode*, the user issues the motion commands for the soft-arm also using the arrow keys of the commercial waterproof computer keyboard. In this mode, however, no audio assistance for command registration and execution is provided, nor is the motion of the soft-arm restricted to the predefined body area. Consequently, the user has full control over the motion of the soft-arm.

Study design

A within-subject design was used to evaluate differences in the task effectiveness and user satisfaction with the different operation modes of the I-SUPPORT bathing robot. A mixed between- and within-subject design was used to explore the interaction effects between dichotomized participant characteristics (= between-subject factor) and the different operation modes (= within-subject factor) on the user satisfaction. The study was approved by the ethics committee of the Medical Faculty of the Heidelberg University on September 27, 2016 (S-382/2016) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

Study population

Participants were recruited from rehabilitation wards of a German geriatric hospital, from nursing homes, and from a hospital-associated geriatric rehabilitation sports club. Financial incentive was provided to motivate eligible persons for study participation and to address potential barriers associated with the test procedure under wet conditions (e.g. feelings of shame due to wearing only swimsuit suits or swimming trunks). Inclusion criteria were as follows: dependence in bathing activities (BI bathing item = 0 pt.); no severe cognitive impairment (MMSE score >17 pt.); no severe ADL impairment (BI ≥ 50 pt.); independence in bed-chair transfer (BI transfer item = 15 pt.); no severe neurological, cardiovascular, metabolic, or psychiatric disorders; residence within 15 km of the study center, and written informed consent.

Test procedure

Initially, the participant wearing swimming clothes was seated on the motorized chair with the back towards the robotic soft-arm (see Figure 2) and the water temperature was set to his/her preferences. Subsequently, the test administrator explained to the participant that three different operation modes will be tested in the following order: (1) autonomous operation, (2) shared control and (3) tele-manipulation mode.

For the first, autonomous operation mode, the participant was informed that the soft-arm will provide water fully automatically for 1 min following a 6-step path on the upper back with the starting and end point at the top right of the upper body (see Figure 3). To illustrate the movement path of the water stream to the participant, the test administrator showed a poster that indicated the six target points on the upper back region.

After the water pouring scenario with the autonomous operation mode was completed, the test administrator explained that in the next, shared control mode, the participant must control the motion of the soft-arm by his-/herself using the arrow keys of the waterproof computer keyboard. In addition, the participant was told that the I-SUPPORT bathing robot provides some audio assistance as described above (command registration and execution) and that the motion of the soft-arm is restricted to the upper back region. The test administrator then instructed the participant to cover the entire upper back region (i.e. all six target points shown on the poster) with water as fast as possible by using the shared control mode.

Finally, the participants used the tele-manipulation mode for the water pouring scenario. The test administrator explained that in this mode, the soft-arm motion is also controlled by the arrow keys of the waterproof computer keyboard. The participant was informed that in this mode, however, the I-SUPPORT bathing robot does not provide any audio assistance for command registration and execution, nor does it restrict the motion of the soft-arm to the upper back region. Also for this mode, each participant was instructed to cover the entire upper back region as fast as possible.

For both user-controlled modes (shared control, tele-manipulation), the test administrator interrupted the test procedure either after the participant had successfully provided water for the entire upper back region (i.e. all six target points) or after 2 min even if the participant was not successful in water pouring for the entire upper back region. The longer maximum processing time of 2 min in the user-control modes was chosen as for command issuing by the user and command recognition by the I-SUPPOR robot automatically more time is required than in the autonomous operation mode, in which the motion of the robotic soft-arm on the movement path is fully automatically controlled in smooth and constantly progressive way.

Descriptive measures

Demographic and clinical characteristics including age, gender, living situation (community-dwelling vs. institutionalized), falls in the previous year, and ADL status (BI) were documented from patient charts or by standardized interviews. A trained interviewer assessed cognitive status (MMSE), depressive symptoms (15-item Geriatric Depression Scale, GDS-15, Gauggel & Birkner, 1999; Sheikh & Yesavage, 1986), fear of falling (Falls Efficacy Scale-International, FES-I, Dias et al., 2006; Hauer et al., 2010), and technology acceptance (Senior Technology Acceptance Model, [STAM] with subscales for attitude towards technology, perceived usefulness, ease of use, gerontechnology self-efficacy, gerontechnology anxiety, and facilitating conditions Chen & Chan, 2014). Physical performance was measured by the Short Physical Performance Battery (SPPB, Guralnik et al., 1994).

Outcome measures

Task effectiveness

The effectiveness in pouring water on the upper back region with the different operation modes was assessed by the following two outcome parameters: (1) coverage [%], defined as the percentage of the predefined upper back region covered with water (e.g., 4 out of 6 target points covered with water = 66.7 %) during the standardized time period (autonomous operation mode = 1 min, shared control and tele-manipulation mode = 2 min) and (2) step effectiveness [%], calculated as [(coverage ⁄ number of steps required) ⁄ (maximum possible coverage ⁄ minimum possible number of steps required for maximum possible coverage)] × 100. The number of target points covered with water and the number of the steps performed during the standardized time periods were objectively calculated from the visual data obtained from the system's cameras and the kinematics combined with the behavioral-based motion controller of the robotic soft-arm of the I-SUPPORT bathing robot. More technical details on the behavioral-based motion controller can be found elsewhere (Dometios et al., 2017).

User satisfaction

The After-Scenario Questionnaire (ASQ, (Lewis, 1995) was used to assess the user satisfaction with the three different operation modes. The questionnaire contains three statements that address the ease of completing the task, the time taken to complete the task, and the support available when completing the task. For each operation mode, the participants were asked to rate their level of agreement or disagreement on a 7-point scale, with lower scores indicating agreement (1 = strongly agree) and higher scores indicating disagreement (7 = strongly disagree). The scores for the three statements were averaged into a total ASQ score. The lower the ASQ score, the higher the participants' satisfaction with the operation mode.

Statistical analysis

Descriptive data were presented as frequencies and percentages for categorical variables, and medians and ranges or means and standard deviations (SD) for continuous variables. To identify differences in task effectiveness between the operation modes, we calculated Friedman analyses of variance (ANOVAs) with post-hoc Wilcoxon signed-rank tests for paired comparisons. A one-way RM-ANOVA with post-hoc paired-samples t-tests was performed to test for differences in the user satisfaction between the operation modes. To explore whether there was an interaction effect between participant characteristics (age, cognitive status, functional status, physical performance, fall history, fear of falling, and technology acceptance) and the different operation modes, participant characteristics were dichotomized into clinically recognizable subgroups or two subgroups of similar sample size using a median split as follows: age (< 80 years vs. ≥ 80 years, Baltes & Smith, 1999; Iwarsson, Wahl, & Nygren, 2004), cognitive status (cognitively impaired: MMSE ≤ 26 pt. vs. not cognitively impaired: MMSE > 26 pt., Monsch et al., 1995; O'Bryant et al., 2008; Toglia, Fitzgerald, O'Dell, Mastrogiovanni, & Lin, 2011), functional status (high: BI >85 pt. vs. low: BI ≤ 85 pt.), physical performance (low: SPPB ≤ 6 pt. vs. high: SPPB > 6 pt., Pavasini et al., 2016; Vasunilashorn et al., 2009; Veronese et al., 2014), fall history (non-fallers vs. fallers), fear of falling (low: FES-I ≤ 22 pt. vs. high: FES-I > 22 pt., Delbaere et al., 2010), and technology acceptance (STAM total score, low <60% vs. high: ≥ 60%). The STAM total score was defined as the mean of the percentage scores on the STAM subscales, which was each calculated as the score given for the subscale divided by the maximum possible score on the respective subscale multiplied by 100. Two-way RM-ANOVAs were used to examine the interaction effect of subgroups (= between-subject factor) by operation mode (within-subject factor = autonomous operation vs. shared control vs. telemanipulation) on the user satisfaction. Effect sizes were calculated as r (= Z/√N) for Wilcoxon signed-rank tests (r < 0.1 = trivial, 0.1 ≤ r < 0.3 = small, 0.3 ≤ r < 0.5 = moderate, r ≥ 0.5 = large effect), Cohen's d for paired-samples t-tests (d < 0.2 = trivial, 0.2 ≤ d < 0.5 = small, 0.5 ≤ d < 0.8 = moderate, d ≥ 0.8 = large effect), and partial eta squared (ηp2) for RM-ANOVAs ($\eta_p^2 < 0.06$ = small, $0.06 \geq \eta_p^2 < 0.14$ = moderate, $\eta_p^2 \geq 0.14$ = large effect) (Cohen, 1988). A two-sided p-value of < 0.05 indicated statistical significance. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Participant characteristics

Twenty-five older persons (females: n = 20, 80.0%) who all were dependent in bathing (BI, bathing item = 0 pt.) participated in the study. The participants' mean age was 77.9 ± 7.9 years and the MMSE score averaged 25.6 ± 3.1 points, with about half of the participants (n = 13, 52%) having some cognitive impairment (MMSE ≤ 26 pt.). The sample population showed an impaired ADL status (median BI score = 85 [50-95] pt.) and low physical performance (SPPB score = 6.1 ± 2.9 pt.). Fourteen participants (56%) reported at least one fall in the previous year. Clinically relevant depressive symptoms (GDS-15 > 5 pt.) were observed in only three participants (12%). Fear of falling was low (FES-I ≤ 22 pt.) in seven (18%) and high (FES-I > 22 pt.) in 18 (72%) participants. Technology acceptance was fair to good, with mean scores on the different STAM subscales in the upper half of the scoring range (Table 1). Eighteen participants (72%) were living at home, partly with supportive care; seven (28%) were institutionalized.

Due to technical problems with the I-SUPPORT bathing robot in three participants, the test procedure with the bathing robot could be successfully performed with only 22 participants. Additionally, technical data during the test procedure was not properly recorded in one participant; however, data on the user satisfaction in this participant was still available. No significant differences in any descriptive variables were found between the dropouts and the participants with complete data (p = 0.158-0.922).

Task effectiveness with different operation modes

In the autonomous operation mode, maximum coverage of the upper back region and maximum step effectiveness were achieved for all participants. Task effectiveness was substantially lower in the shared control and tele-manipulation modes than in the autonomous operation mode (Table 2). Only seven participants (33.3%) in the shared control mode and two participants (9.5%) in the tele-manipulation mode achieved the maximum possible coverage. Friedman ANOVAs revealed a significant effect of the operation mode on the coverage and step effectiveness (p < 0.001). Post-hoc comparisons showed that task effectiveness was significantly lower in the shared control and tele-manipulation modes than in the autonomous operation mode, with large effect sizes ($p \leq 0.001$, r = 0.74-0.84). Among the two user-controlled modes, the coverage (p = 0.009) and step effectiveness (p = 0.016) were significantly higher in the shared control than in the tele-manipulation mode, with also large effect sizes (r = 0.53-0.57).

User satisfaction with different operation modes

In general, the user satisfaction with all operation modes was positive, as indicated by mean ASQ scores in the lower quartile (autonomous operation, shared control) or lower half (tele-manipulation) of the scoring range (Table 3). RM-ANOVA revealed a significant large effect of the operation mode on the ASQ score (p = 0.037, η_p^2 = 0.16). Post-hoc comparisons showed that the ASQ score for the autonomous operation mode was significantly lower than that for the tele-manipulation mode, with a moderate effect size (p = 0.003, d = 0.70). Compared to the shared control mode, the ASQ score for autonomous operation mode tended to be also lower; however, the difference only approached the level of significance with a moderate effect (p = 0.070, d = 0.50). A non-significant, small effect (p = 0.337, d = 0.23) was observed for the comparison between the two user-controlled modes. No significant interaction effects between subgroups of participants and operation modes were found (p = 0.491-0.826, η_p^2 = 0.01-0.03) (Table 4).

DISCUSSION

The present study aimed to evaluate different operation modes of an assistive bathing robot. Being representative of potential users of this robot, we recruited older persons with bathing disability and analyzed the task effectiveness and user satisfaction with three operation modes providing different levels of assistance during a water pouring task for the user's upper back region. In addition, we explored whether different subgroups of participants were most satisfied with a specific operation mode. Our results indicate that the autonomous operation mode for the robotic soft-arm of the bathing robot is highly effective and reliable in providing water pouring for a predefined body area. Significantly lower task effectiveness was observed in the operation modes in which the robot autonomy was lower and the robotic soft-arm motion was predominantly controlled by the participants. Task effectiveness gradually decreased along with lower assistance provided by the bathing robot. Similar findings were observed for the user satisfaction, with the highest level of satisfaction observed for the autonomous operation mode and also a tendency to a gradually decreasing satisfaction with decreasing robot assistance. Preferences for a specific operation mode were not observed among different subgroups of participants.

Task effectiveness with different operation modes

Our results confirmed the primary hypothesis that task effectiveness with the bathing robot would be highest in the autonomous operation mode and gradually decrease with lower levels of robot assistance. This finding supports previous studies that compared different operation modes of other assistive robots in young or older adults and also found the highest task effectiveness in the most autonomous operation modes (Erdogan & Argall, 2017; Kim et al., 2012; Koceska et al., 2019; Werner et al., 2018; Yu et al., 2003). Although the maximum possible time for completing the water pouring task was allowed to be twice as long as in the autonomous operation mode, the body area covered in the user-controlled modes was significantly lower with only few participants able to provide water pouring for the whole target body area. The lower task effectiveness in the user-controlled modes was also revealed by the significant lower step effectiveness. This suggests that participants issued several inefficient commands not increasing the body are covered by the water and that some target points on the upper back region were passed more than once or the water stream even exceeded this region (tele-manipulation mode). As expected, among the user-controlled operation modes, task effectiveness was significantly higher in the shared control mode than in the tele-manipulation mode, indicating that the audio signals of the I-SUPPORT robot given for command registration and execution as well as the restriction of the robotic soft-arm motion to the predefined upper back region effectively assisted the participants in completing the water pouring scenario. However, as the task effectiveness in the shared control mode was still substantially lower than in the autonomous operation mode, it seems that the robot assistance in this mode was not optimal and the required interaction was too difficult to handle for the participants. This might be explained by the fact that participants did not directly see the robotic soft-arm behind their back during the test procedure but only could imagine its spatial position and movement based on the water stream felt on the skin of their upper back. As spatial and tactile sensory abilities decline with age (Skedung et al., 2018; Techentin, Voyer, & Voyer, 2014), the position determination of the water stream on the upper back might have been particularly difficult in our sample of older adults and hampered their ability to accurately distinguish between the target points on the upper back and to perceive whether all of them were reached. Providing elderly users additional direct visual or audial assistance on the real-time position of the water stream might represent a potential option for increasing their task effectiveness in pouring water on body parts which cannot be directly seen.

User satisfaction with different operation modes

Based on previous studies suggesting that users of assistive robots seem to be more satisfied with operation modes for HRI in which they retain as much control as possible (Cooper et al., 2012; Kim et al., 2012; Yu et al., 2003), we hypothesized that the user satisfaction would be lower in the autonomous operation than in the user-controlled operation modes (shared control, tele-manipulation). Surprisingly and in contrast to this hypothesis, our results revealed that participants were, however, rather less satisfied with the user-controlled operation modes than with the autonomous operation mode, in which they had the least control and the I-SUPPORT robot fully autonomously completed the water pouring task. A potential explanation for these findings might be the higher age of our participants, which may be associated with also a higher request for assistance when using technology than in younger populations (Kressig & Echt, 2002), or the higher differences in the task effectiveness between the operation modes, which could have been perceived much more clearly by our participants during the test procedure. As the water pouring task was interrupted by the test administrator after a maximum of 2 min in the user-controlled operation modes, participants who could not provide water for the whole target body area might have become aware of their low task effectiveness, potentially leading to a feeling of overload that may have affected their satisfaction with these operation modes (Hauer, 2018; Tacken et al., 2005).

Given the recommendation to consider the personal characteristics when studying HRI in the heterogeneous population of older adults (Zafrani & Nimrod, 2018), we explored whether specific subgroups of participants were most satisfied with one of the operation modes. Our results revealed that there were no significant interactions of personal characteristics with the operation modes, indicating the higher user satisfaction with the autonomous operation mode were unspecific for age, cognitive status, functional status, physical performance, fall history, fear of falling, and technology acceptance. Thus, the autonomous operation mode seems to be a promising and highly satisfactory HRI option for a broad range of potential older users of the bathing robot.

Limitations

Our study has some limitations. First, the sample size was rather small, limiting the statistical power and generalizability of our results. Second, participants were predominantly females, limiting the ability to examine gender differences and the generalizability of results to male. Third, the order of the operation modes tested was not randomized but the robot assistance was successively decreased during the test procedure (autonomous operation $\rightarrow$ shared control $\rightarrow$ tele-manipulation mode). However, in the autonomous operation mode, the soft-arm was controlled fully automatically without user input and potential learning effects during the user-controlled operation modes might have rather favored the task effectiveness in the tele-manipulation mode. It might therefore be assumed that a randomization would have even led to more obvious differences in the task effectiveness between the user-controlled operation modes.

CONCLUSIONS

The present study showed that the full autonomous operation of the bathing robot was the most effective and the most satisfying operation mode in our sample of older adults with bathing disability. Giving the participants more control over the bathing robot significantly reduced not only the task effectiveness but also the user satisfaction with the bathing robot. These finding suggest that for an effective and highly satisfying HRI between a bathing robot and potential older users it seems to be necessary to implement operation modes with a high level of robot autonomy that requires a minimum of user input.

Declaration of interest

The authors declare no conflicts of interest.

References

Abbink, D. A., & Mulder, M. (2010). Neuromuscular analysis as a guideline in designing shared control. In M. H. Zadeh (Ed.), Advances in haptics (pp. 499-516): IntechOpen.

Ahluwalia, S. C., Gill, T. M., Baker, D. I., & Fried, T. R. (2010). Perspectives of older persons on bathing and bathing disability: A qualitative study. Journal of the American Geriatrics Society, 58(3), 450-456.

Amirshirzad, N., Kaya, O., & Oztop, E. (2016, 20-23 Sept. 2016). Synergistic human-robot shared control via human goal estimation. Paper presented at the 2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE).

Baltes, P. B., & Smith, J. (1999). Multilevel and systemic analyses of old age : Theoretical and empirical evidence for a fourth age. In P. B. Baltes & K. U. Mayer (Eds.), Handbook of theories of aging (pp. 153 - 173). New York: Springer.

Chatterji, S., Byles, J., Cutler, D., Seeman, T., & Verdes, E. (2015). Health, functioning, and disability in older adults - Present status and future implications. Lancet, 385(9967), 563-575.

Chen, K., & Chan, A. H. (2014). Gerontechnology acceptance by elderly Hong Kong Chinese: A senior technology acceptance model (STAM). Ergonomics, 57(5), 635-652.

Chung, C.-S., Wang, H., & Cooper, R. A. (2013). Functional assessment and performance evaluation for assistive robotic manipulators: Literature review. The Journal of Spinal Cord Medicine, 36(4), 273-289.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences. New York: Routledge.

Cooper, R. A., Grindle, G. G., Vazquez, J. J., Xu, J., Wang, H., Candiotti, J., . . . Beach, S. (2012). Personal mobility and manipulation appliance - Design, development, and initial testing. Proceedings of the IEEE, 100(8), 2505-2511.

Craik, F. I. M., & Salthouse, T. A. (2008). The handbook of aging and cognition (3rd ed.). New York: Psychology Press.

Dawson, D., Hendershot, G., & Fulton, J. (1984). Aging in the eighties. Functional limitations of individuals age 65 years and over. Advance data from Vital and Health Statistics. Public Health Services; 1987. DHHS Pub. No. 133.

Delbaere, K., Close, J. C., Mikolaizak, A. S., Sachdev, P. S., Brodaty, H., & Lord, S. R. (2010). The Falls Efficacy Scale International (FES-I). A comprehensive longitudinal validation study. Age Ageing, 39(2), 210-216.

Dias, N., Kempen, G. I. J. M., Todd, C. J., Beyer, N., Freiberger, E., Piot-Ziegler, C., . . . Hauer, K. (2006). Die deutsche Version der Falls Efficacy Scale-International Version (FES-I) [The German version of the Falls Efficacy Scale-International version (FES-I)]. Zeitschrift für Gerontologie und Geriatrie, 39(4), 297-300.

Dometios, A. C., Papageorgiou, X. S., Arvanitakis, A., Tzafestas, C. S., & Maragos, P. (2017, 24-28 Sept. 2017). Real-time end-effector motion behavior planning approach using on-line point-cloud data towards a user adaptive assistive bath robot. Paper presented at the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

Dyck, J. L., & Smither, J. A.-A. (1994). Age differences in computer anxiety: The role of computer experience, gender and education. Journal of Educational Computing Research, 10(3), 239-248.

Erdogan, A., & Argall, Brenna D. (2017). The effect of robotic wheelchair control paradigm and interface on user performance, effort and preference: An experimental assessment. Robotics and Autonomous Systems, 94, 282-297.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. Journal of Psychiatric Research, 12(3), 189-198.

Gauggel, S., & Birkner, B. (1999). Validität und Reliabilität einer deutschen Version der Geriatrischen Depressionsskala (GDS) [Validity and reliability of a German Version of the Geriatric Depression Scale (GDS)]. Zeitschrift für Klinische Psychologie und Psychotherapie, 28(1), 18-27.

Gerrard, P. (2013). The hierarchy of the activities of daily living in the Katz Index in residents of skilled nursing facilities. Journal of geriatric physical therapy (2001), 36(2), 87-91.

Gill, T. M., Allore, H. G., & Han, L. (2006). Bathing disability and the risk of long-term admission to a nursing home. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 61(8), 821-825.

Gill, T. M., Guo, Z., & Allore, H. G. (2006). The epidemiology of bathing disability in older persons. Journal of the American Geriatrics Society, 54(10), 1524-1530.

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G., . . . Wallace, R. B. (1994). A Short Physical Performance Battery assessing lower extremity function: Association with self-reported disability and prediction of mortality and nursing home admission. Journal of Gerontology, 49(2), M85-94.

Gure, T. R., Langa, K. M., Fisher, G. G., Piette, J. D., & Plassman, B. L. (2013). Functional limitations in older adults who have cognitive impairment without dementia. Journal of Geriatric Psychiatry and Neurology, 26(2), 78-85.

Hakkinen, A., Heinonen, M., Kautiainen, H., Huusko, T., Sulkava, R., & Karppi, P. (2007). Effect of cognitive impairment on basic activities of daily living in hip fracture patients: A 1-year follow-up. Aging Clinical and Experimental Research, 19(2), 139-144.

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. Clinics in Geriatric Medicine, 29(4), 737-752.

Hauer, K. (2018). Bewertung von AAL-Ambient-Assisted-Living-Systemen bei Personen mit kognitiver Schädigung: Match vs. Mismatch [Evaluation of AAL-Ambient-Assisted-Living systems in persons with cognitive impairment]. In O. Bendel (Ed.), Pflegeroboter (pp. 89-111). Wiesbaden: Springer Fachmedien Wiesbaden.

Hauer, K., Yardley, L., Beyer, N., Kempen, G., Dias, N., Campbell, M., . . . Todd, C. (2010). Validation of the Falls Efficacy Scale and Falls Efficacy Scale International in geriatric patients with and without cognitive impairment: Results of self-report and interview-based questionnaires. Gerontology, 56(2), 190-199.

Hunter, S. K., Pereira, H. M., & Keenan, K. G. (2016). The aging neuromuscular system and motor performance. Journal of Applied Physiology, 121(4), 982-995.

Iwarsson, S., Wahl, H.-W., & Nygren, C. (2004). Challenges of cross-national housing research with older persons: Lessons from the enable-age project. European Journal of Ageing, 1(1), 79-88.

Jagger, C., Arthur, A. J., Spiers, N. A., & Clarke, M. (2001). Patterns of onset of disability in activities of daily living with age. Journal of the American Geriatrics Society, 49(4), 404-409.

Jones, A., Dawyer, L., Bercovitz, A., & Strahan, G. (2009). The national nursing home survey: 2004 overview. National Center for Health Statistics. Vital and Health Statistics Series, 13(167).

Ka, H. W., Ding, D., & Ravishankar, S. (2015). Computer access technologies for controlling assistive robotic manipulators: Potentials and challenges. Austin Journal of Robotics & Automation, 2(1), 1007.

Katz, S., Ford, A. B., Moskowitz, R. W., Jackson, B. A., & Jaffe, M. W. (1963). Studies of illness in the aged. The index of ADL: A standardized measure of biological and psychosocial function. Journal of the American Medical Association, 185, 914-919.

Kim, D., Hazlett-Knudsen, R., Culver-Godfrey, H., Rucks, G., Cunningham, T., Portee, D., . . . Behal, A. (2012). How autonomy impacts performance and satisfaction: Results from a study with spinal cord injured subjects using an assistive robot. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, 42(1), 2-14.

Koceska, N., Koceski, S., Beomonte Zobel, P., Trajkovik, V., & Garcia, N. (2019). A telemedicine robot system for assisted and independent living. Sensors (Basel, Switzerland), 19(4), 834.

Kressig, R. W., & Echt, K. V. (2002). Exercise prescribing: Computer application in older adults. Gerontologist, 42(2), 273-277.

Lewis, J. R. (1995). IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. International Journal of Human–Computer Interaction, 7(1), 57-78.

Luppa, M., Luck, T., Weyerer, S., Konig, H. H., Brahler, E., & Riedel-Heller, S. G. (2010). Prediction of institutionalization in the elderly. A systematic review. Age Ageing, 39(1), 31-38.

Mahoney, F. I., & Barthel, D. W. (1965). Functional evaluation: The Barthel Index. Md State Med J, 14, 61-65.

Manton, K. G. (1988). A longitudinal study of functional change and mortality in the United States. Journal of Gerontology, 43(5), S153-161.

Monsch, A. U., Foldi, N. S., Ermini-Funfschilling, D. E., Berres, M., Taylor, K. I., Seifritz, E., . . . Spiegel, R. (1995). Improving the diagnostic accuracy of the Mini-Mental State Examination. Acta Neurologica Scandinavica, 92(2), 145-150.

Nelson, E. A., & Dannefer, D. (1992). Aged heterogeneity: Fact or fiction? The fate of diversity in gerontological research. The Gerontologist, 32(1), 17-23.
O'Bryant, S. E., Humphreys, J. D., Smith, G. E., Ivnik, R. J., Graff-Radford, N. R., Petersen, R. C., & Lucas, J. A. (2008). Detecting dementia with the Mini-Mental State Examination in highly educated individuals. Archives of Neurology, 65(7), 963-967.
Pavasini, R., Guralnik, J., Brown, J. C., di Bari, M., Cesari, M., Landi, F., . . . Campo, G. (2016). Short Physical Performance Battery and all-cause mortality: Systematic review and meta-analysis. BMC Medicine, 14.
Rozzini, R., Sabatini, T., Ranhoff, A. H., & Trabucchi, M. (2007). Bathing disability in older patients. Journal of the American Geriatrics Society, 55(4), 635-636.
Schirner, G., Erdogmus, D., Chowdhury, K., & Padir, T. (2013). The future of human-in-the-loop cyber-physical systems. Computer, 46(1), 36-45.
Scopelliti, M., Giuliani, M. V., D'Amico, A. M., & Fornara, F. (2004). If i had a robot at home... Peoples' representation of domestic robots. In S. Keates, J. Clarkson, P. Langdon, & P. Robinson (Eds.), Designing a more inclusive world (pp. 257-266). London: Springer
Sheikh, J. I., & Yesavage, J. A. (1986). Geriatric Depression Scale (GDS): Recent evidence and development of a shorter version. In T. L. Brink (Ed.), Clinical gerontology: A guide to assessment and intervention (pp. 165-173). New York, NY: The Haworth Press.
Skedung, L., El Rawadi, C., Arvidsson, M., Farcet, C., Luengo, G. S., Breton, L., & Rutland, M. W. (2018). Mechanisms of tactile sensory deterioration amongst the elderly. Scientific Reports, 8(1), 5303-5303.
Tacken, M., Marcellini, F., Mollenkopf, H., Ruoppila, I., & Széman, Z. (2005). Use and acceptance of new technology by older people. Findings of the international mobilate survey: 'Enhancing mobility in later life.' Gerontechnology, 3(3), 126-137.
Techentin, C., Voyer, D., & Voyer, S. D. (2014). Spatial abilities and aging: A meta-analysis. Experimental Aging Research, 40(4), 395-425.
Toglia, J., Fitzgerald, K. A., O'Dell, M. W., Mastrogiovanni, A. R., & Lin, C. D. (2011). The Mini-Mental State Examination and montreal cognitive assessment in persons with mild subacute stroke: Relationship to functional outcome. Archives of Physical Medicine and Rehabilitation, 92(5), 792-798.
Vasunilashorn, S., Coppin, A. K., Patel, K. V., Lauretani, F., Ferrucci, L., Bandinelli, S., & Guralnik, J. M. (2009). Use of the Short Physical Performance Battery score to predict loss of ability to walk 400 meters: Analysis from the inchianti study. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 64(2), 223-229.
Veronese, N., Bolzetta, F., Toffanello, E. D., Zambon, S., De Rui, M., Perissinotto, E., . . . Manzato, E. (2014). Association between Short Physical Performance Battery and falls in older people: The progetto veneto anziani study. Rejuvenation Research, 17(3), 276-284.
Vogel, J., Haddadin, S., Jarosiewicz, B., Simeral, J. D., Bacher, D., Hochberg, L. R., . . . van der Smagt, P. (2015). An assistive decision-and-control architecture for force-sensitive hand–arm systems driven by human–machine interfaces. The International Journal of Robotics Research, 34(6), 763-780.
Werner, C., Ullrich, P., Geravand, M., Peer, A., Bauer, J. M., & Hauer, K. (2018). A systematic review of study results reported for the evaluation of robotic rollators from the perspective of users. Disability and Rehabilitation. Assistive Technology, 13(1), 31-39.
Wiener, J. M., Hanley, R. J., Clark, R., & Van Nostrand, J. F. (1990). Measuring the activities of daily living: Comparisons across national surveys. Journal of Gerontology, 45(6), S229-237.
Yanco, H. A., & Drury, J. (2004, 10-13 Oct. 2004). Classifying human-robot interaction: An updated taxonomy. Paper presented at the 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583).
Yang, Y., & Lee, L. C. (2010). Dynamics and heterogeneity in the process of human frailty and aging: Evidence from the U.S. older adult population. The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 65B(2), 246-255.
Yu, H., Spenko, M., & Dubowsky, S. (2003). An adaptive shared control system for an intelligent mobility aid for the elderly. Autonomous Robots, 15(1), 53-66.
Zafrani, O., & Nimrod, G. (2018). Towards a holistic approach to studying human–robot interaction in later life. The Gerontologist, 59(1), e26-e36.

Table 1. Participant characteristics

Variables	*n* = 25
Age, years	77.9 ± 7.9
Sex, females	20 (80.0)
Mini-Mental State Examination, score	25.6 ± 3.1
Barthel Index	85 [50-95]
Short Physical Performance Battery, score	6.1 ± 2.9
Recent history of falls	14 (56.0)
Geriatric Depression Scale, score	2 [0-11]
Falls Efficacy Scale-International, score	28.8 ± 10.0
Technology Acceptance, score[a]	
Attitudes towards technology (max. 20 pt.)	14.6 ± 5.0
Perceived usefulness (max. 30 pt.)	19.9 ± 8.4
Ease of use (max. 20 pt.)	10.8 ± 5.0
Gerontechnology self-efficacy (max. 20 pt.)	12.2 ± 5.2
Gerontechnology anxiety (max. 20 pt.)	12.5 ± 6.1
Facilitating conditions (max. 50 pt.)	30.3 ± 10.5
Living situation	
Community-dwelling	18 (72.0)
Institutionalized	7 (28.0)

Data presented as mean ± SD, n (%), and median [range]. [a]Higher scores indicates better attitudes towards technology, higher perceived usefulness, greater ease of use, higher gerontechnology self-efficacy, lower gerontechnology anxiety, and more facilitating conditions.

Table 2. Differences in the task effectiveness (coverage, step effectiveness) between the shared control and tele-manipulation modes

	n	Operation mode			Friedman ANOVA	Post-hoc comparisons between operation modes	
		Autonomous operation (1)	Shared control (2)	Tele-manipulation (3)	*p*-value	*p*-value[a]	*Effect size*[b]
Coverage [%]	21	100.0 ± 0.0 100.0 [100.0-100.0]	79.4 ± 18.2 83.3 [33.3-100.0]	64.4 ± 19.4 66.6 [33.3-100.0]	< 0.001	0.001 (1 vs. 2) < 0.001 (1 vs. 3) 0.009 (2 vs. 3)	0.74 (1 vs. 2) 0.84 (1 vs. 3) 0.57 (2 vs. 3)
Step effectiveness [%]	21	100.0 ± 0.0 100.0 [100.0-100.0]	51.6 ± 10.3 50.3 [28.3-75.0]	43.9 ± 8.6 42.9 [27.3-62.3]	< 0.001	< 0.001 (1 vs. 2) < 0.001 (1 vs. 3) 0.016 (2 vs. 3)	0.88 (1 vs. 2) 0.88 (1 vs. 3) 0.53 (2 vs. 3)

Data presented as mean ± SD and median [range]. [a]*P*-values for Wilcoxon signed-rank tests. Effect size given as $r = Z/\sqrt{N}$

Table 3. Differences in the user satisfaction between the different operation modes

	n	Operation mode			RM-ANOVA		Post-hoc comparisons between operation modes	
		Autonomous Operation (1)	Shared Control (2)	Tele-Manipulation (3)	*p*-value[a]	Effect size[b]	*p*-value[c]	Effect size[d]
ASQ	22	2.0 ± 1.0	2.5 ± 1.5	3.0 ± 1.4	0.037	0.16	0.071 (1 vs. 2) 0.003 (1 vs. 3) 0.337 (2 vs. 3)	0.50 (1 vs. 2) 0.70 (1 vs. 3) 0.23 (2 vs. 3)

Data presented as mean ± SD. [a]*P*-value for within-subject effect (operation mode). [b]Effect size given as η_p^2. [c]*P*-values for paired-samples *t*-tests. [d]Effect sizes given as Cohen's *d.* ASQ, After-Scenario Questionnaire.

Table 4. Interaction effects between subgroups of participants and different operation modes on the user satisfaction.

	n	Operation mode			Group × mode effect	
		Autonomous operation	Shared control	Tele-manipulation	*p*-value	Effect size[a]
Age						
< 80 years	12	2.0 ± 1.1	2.4 ± 1.4	3.1 ± 1.5	.621	.02
≥ 80 years	10	2.0 ± 0.9	2.7 ± 1.6	2.8 ± 1.2		
Cognitive Status						
NCI	10	2.3 ± 1.3	2.5 ± 1.0	3.2 ± 1.0	.709	.01
CI	12	1.8 ± 0.7	2.5 ± 1.8	2.8 ± 1.6		
Functional Status						
High	11	1.9 ± 0.9	2.3 ± 1.0	2.8 ± 1.5	.826	.01
Low	11	2.0 ± 1.1	2.8 ± 1.8	3.1 ± 1.3		
Physical performance						
High	8	2.1 ± 0.9	2.1 ± 0.9	2.9 ± 1.2	.491	.03
Low	14	1.9 ± 0.7	2.8 ± 1.7	3.0 ± 1.7		
Fall history						
Non-fallers	10	2.0 ± 1.1	2.5 ± 1.5	2.7 ± 1.3	.747	.01
Fallers	12	2.0 ± 1.0	2.6 ± 1.5	3.2 ± 1.4		
Fear of falling						
Low	7	2.2 ± 1.0	2.5 ± 1.2	2.9 ± 0.9	.734	.01
High	15	1.9 ± 1.0	2.5 ± 1.6	3.0 ± 1.5		
Technology acceptance						
High	11	2.2 ± 1.2	3.0 ± 1.3	3.2 ± 1.0	.647	.02
Low	11	1.8 ± 0.7	2.1 ± 1.5	2.7 ± 1.6		

Data presented as mean ± SD. Effect sizes given as η_p^2. NCI, not cognitively impaired; CI, cognitively impaired.

Figure legends

Figure 1. Installation of the I-SUPPORT bathing robot in a typical bathroom of a rehabiliation clinic at a geriatric hospital.

Figure 2. Robotic soft-arm providing water pouring on the upper back region.

Figure 3. Upper back region with the six target points for which the soft-arm provided water pouring. The dark gray outlined cross represents the starting and final position for all operation modes, the dotted arrows indicate the optimal 6-step path for the water pouring process on the upper back region.

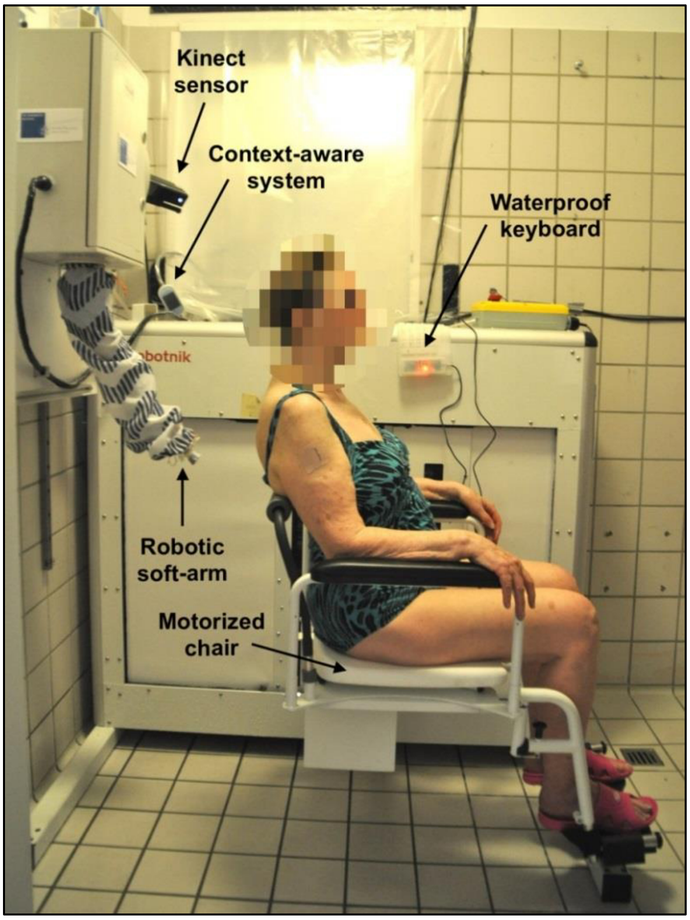

Figure 1. Installation of the I-SUPPORT bathing robot in a typical bathroom of a rehabiliation clinic at a geriatric hospital.

Figure 2. Robotic soft-arm providing water pouring on the upper back region.

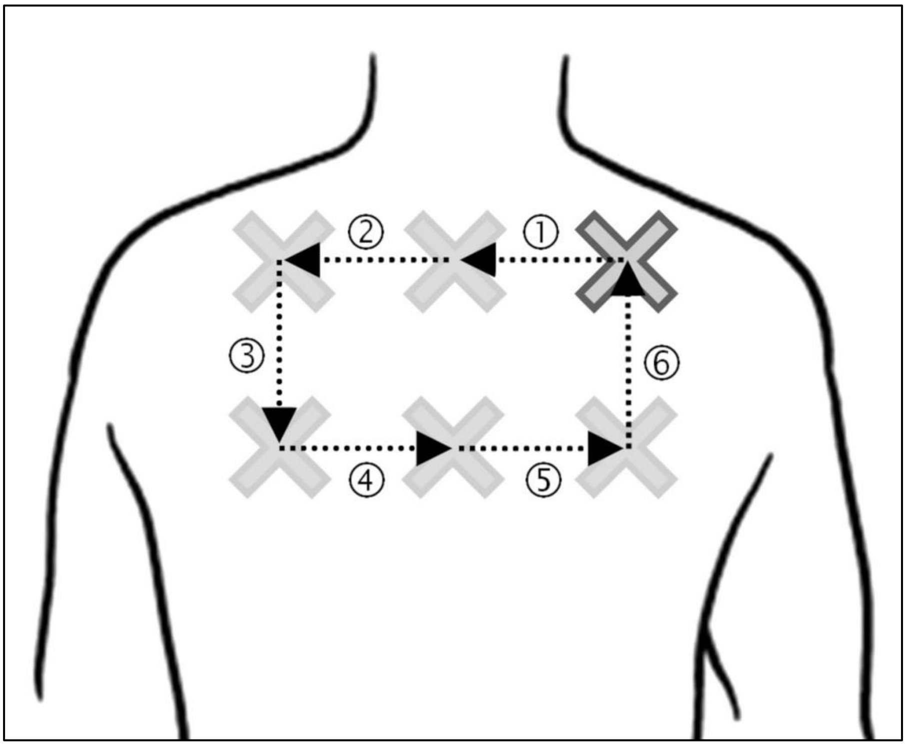

Figure 3. Upper back region with the six target points for which the soft-arm provided water pouring. The dark gray outlined cross represents the starting and final position for all operation modes, the dotted arrows indicate the optimal 6-step path for the water pouring process on the upper back region.

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Improving gesture-based interaction between an assistive bathing robot and older adults via user training on the gestural commands

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ABSTRACT

Background: Gesture-based human-robot interaction (HRI) depends on the technical performance of the robot-integrated gesture recognition system (GRS) and on the gestural performance of the robot user, which has been shown to be rather low in older adults. Training of gestural commands (GCs) might improve the quality of older users' input for gesture-based HRI, which in turn may lead to an overall improved HRI.
Objective: To evaluate the effects of a user training on gesture-based HRI between an assistive bathing robot and potential elderly robot users.
Methods: Twenty-five older adults with bathing disability participated in this quasi-experimental, single-group, pre-/post-test study and underwent a specific user training (10 − 15 min) on GCs for HRI with the assistive bathing robot. Outcomes measured before and after training included participants' gestural performance assessed by a scoring method of an established test of gesture production (TULIA) and sensor-based gestural performance (SGP) scores derived from the GRS-recorded data, and robot's command recognition rate (CRR).
Results: Gestural performance (TULIA = +57.1 ± 56.2 %, SGP scores = +41.1 ± 74.4 %) and CRR (+31.9 ± 51.2 %) significantly improved over training ($p < .001$). Improvements in gestural performance and CRR were highly associated with each other ($r = 0.80–0.81$, $p < .001$). Participants with lower initial gestural performance and higher gerontechnology anxiety benefited most from the training.
Conclusions: Our study highlights that training in gesture-based HRI with an assistive bathing robot is highly beneficial for the quality of older users' GCs, leading to higher CRRs of the robot-integrated GRS, and thus to an overall improved HRI.

1. Introduction

Bathing disability is one of the first limitations in activities of daily living (ADLs) to occur during aging process (Jagger, Arthur, Spiers, & Clarke, 2001; Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963) representing the strongest predictor of subsequent institutionalization in older adults (Fong, Mitchell, & Koh, 2015). Institutionalized and non-institutionalized older adults require personal assistance in bathing more frequently than for other ADLs (Wiener, Hanley, Clark, & Van Nostrand, 1990). The prevalence of bathing disability in community-living older adults increases with age, ranging from 4.6 to 8.6% in those aged ≥65 years (Wiener et al., 1990) to 20.1 % in those aged ≥85 years (Dawson, Hendershot, & Fulton, 1984). An even much higher prevalence has been documented in nursing homes and personal care

Abbreviations: ADLs, activities of daily living; BI, Barthel Index; CRR, command recognition rate; ES, effect size; FES-I, Falls Efficacy Scale-International; GC, gestural command; GDS-15, Geriatric Depression Scale, 15 items; GRS, gesture recognition system; HD, high definition; HRI, human-robot interaction; ICC, intraclass correlation coefficient; MMSE, Mini-Mental State Examination; OGP, observation-based gestural performance; RGB-D, red green blue-depth; SD, standard deviation; SGP, sensor-based gestural performance; SVM, support vector machine; SPPB, Short Physical Performance Battery; STAM, Senior Technology Acceptance Model, T1, pre-test; T2, post-test; TULIA, Test of Upper Limb Apraxia

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facilities, with ≥90 % of residents who require some assistance in bathing (Jones, Dawyer, Bercovitz, & Strahan, 2009; Wiener et al., 1990). As a consequence of the demographic change, the number of older adults in need for bathing assistance will increase, which in turn will contribute to an increase in the burden to both the formal health and social care system and the informal care system. Because bathing is highly sensitive and intimate, it is not unusual for older adults to be reserved against or avoid, as long as possible, personal bathing assistance from caregivers (Ahluwalia, Gill, Baker, & Fried, 2010). In this context, assistive bathing robots that collaboratively support older adults to take care of themselves in bathing can foster independent living, preserve dignity and privacy, and reduce the burden of caregivers.

Human-robot interaction can be defined as "information and action exchanges between human and robot to perform a task by means of a user interface" (International Organization for Standardization, 2012). To enable humans and robots to successfully perform tasks in a collaborative way, an adequate and efficient HRI interface needs to be implemented, making the interaction as natural, intuitive and easy as possible to use, preferably with a minimum of training. There are various ways to communicate and/or interact with a robot (e.g., speech, body posture, gestures, facial expressions, etc.) (Goodrich & Schultz, 2008). Previous studies suggest that older adults tend to appreciate communication methods that resemble natural interactions between humans (Begum, Wang, Huq, & Mihailidis, 2013; Fischinger et al., 2016). Being the most natural and simplest way in human communication, verbal communication is frequently used for HRI interfaces, enabling robots to identify voice commands of the user (Mavridis, 2015). In typical real-world scenarios, voice commands can, however, be disturbed by noise, reverberations, and other interfering sound sources (Alameda-Pineda & Horaud, 2015). Addressing this issue of speech-based HRI and given that gestures also play a central role in human communication (Goldin-Meadow & Alibali, 2013), gesture-based HRI has become a core element in the development of natural, intuitive and easy to use HRI interfaces (Hernandez-Belmonte & Ayala-Ramirez, 2016).

Gestures can be defined as a form of non-verbal communication in which visible bodily actions, typically of the hands and arms, communicate particular messages (Kendon, 2004; McNeill, 1992). For interacting with an assistive robot via gestures, several cognitive abilities are relevant such as attention control, working memory, information processing speed, executive function, and visuospatial abilities. However, most of these abilities show a pronounced decline across the life span into old age (Craik & Salthouse, 2008; Harada, Natelson Love, & Triebel, 2013). In addition, cognitive impairment is frequent among older adults with ADL limitations (Gure, Langa, Fisher, Piette, & Plassman, 2013; Hakkinen et al., 2007), representative of potential end users of assistive robots, which may considerably impede the interaction with such robots, as it has previously been reported also for interacting with other technologies (Schmidt & Wahl, 2019).

Research on gesture-based HRI often seems to focus on improving a robot's technical performance and robustness in recognizing and interpreting a user's input by integrating new hardware evolutions and/or developing new software algorithms (Guler et al., 2016; Liu & Wang, 2018; Wang, Kläser, Schmid, & Liu, 2011). However, successful HRI is not just a matter of the performance of the robot-integrated gesture recognition system (GRS), but also of the quality of a user's input and the characteristics of a user. Thus, to fully understand what makes interaction between humans and robots successful and how HRI can be improved in a broader context, a more in-depth understanding also of the human side of the HRI seems to be necessary. For example, a previous study on gesture-based HRI with assistive mobility robot reported rather poor HRI in frail older adults with some levels of cognitive impairment, with a command recognition rate (CRR) of the robot-integrated GRS of only 40 % (Efthimiou et al., 2016). The low gestural performance observed in a considerable portion of the sample (26 %) has been implicated as one major cause of the low HRI in this study, which therefore called for training approaches on HRI in older robot users to ensure successful HRI.

Training procedures used to teach naïve individuals how to interact with the robot provide a potential option to improve not only the performance of a user's input for HRI but also the user's attitudes and emotions toward the robot (Engelhardt & Edwards, 1992; Louie, McColl, & Nejat, 2014), which have been shown to improve over time of robot use (Stafford, MacDonald, Jayawardena, Wegner, & Broadbent, 2014; Wu et al., 2014) and to be predictive for the quality of HRI (Broadbent et al., 2010). User training on the HRI that takes into account the individual resources and limitations of the user might especially be of importance in older adults, who typically have less technology experience and express more negativity and anxiety toward robot assistance than younger people (Dyck & Smither, 1994; Scopelliti, Giuliani, D'Amico, & Fornara, 2004). The lack of training or advice on how to use new technologies can significantly affect older adults' acceptance of technology (Tacken, Marcellini, Mollenkopf, Ruoppila, & Széman, 2005). For example, the user's perception of his/her own insufficient user performance for HRI associated with a low efficiency in controlling the functionalities of the robot can potentially reduce the self-efficacy and reinforce the feeling of loss of control (Hauer, 2018).

The variability in physical, cognitive, sociological and psychological characteristics increases with age (Hunter, Pereira, & Keenan, 2016; Nelson & Dannefer, 1992; Yang & Lee, 2010). Older adults may thus be regarded as the most heterogeneous population of all. A recent systematic review suggests that previous studies most frequently failed, however, to consider the participant characteristics when studying the interaction of older adults with a robot and highlights the importance for future studies to better examine HRI in later life (Zafrani & Nimrod, 2018).

The primary aim of this study was to evaluate the effects of a specific user training on gesture-based HRI between an assistive bathing robot and potential robot users. We hypothesized that such a training would improve both the gestural performance of the participants and the performance of the robot-integrated GRS, leading to an overall improved HRI. Secondary aims were to explore participant characteristics associated with the initial gestural performance and the training response in the gestural performance, and to examine the relationship between the gestural performance and performance of the robot-integrated GRS. We expected lower cognitive abilities and more negative feelings toward technology to be significantly associated with lower gestural performance (i.e. user input for HRI). According to the rate-dependency phenomenon and general training principles which indicate that intervention response rates are highest in those individuals with the lowest baseline performance (Dews, 1977; Haskell, 1994; Snider, Quisenberry, & Bickel, 2016), we hypothesized that training response in the gestural performance would be significantly associated with the initial gestural performance before training. Moreover, as we assumed that the performance of the robot-integrated GRS in recognizing the user's gestural commands (GCs) would highly depend on the user's gestural performance, we expected better gestural performances to be significantly associated with better performance of the GRS.

2. Methods

2.1. I-SUPPORT bathing robot

The assistive bathing robot used in this study represented a first prototype developed in the I-SUPPORT project (ICT-Supported Bath Robots), which focused on the development of an innovative, modular, information and communication technology (ICT)-supported domestic service robotic system that safely assists frail older or disabled individuals in various bathing tasks (e.g., pouring water, soaping, scrubbing, drying), with the overall aim to promote their independence

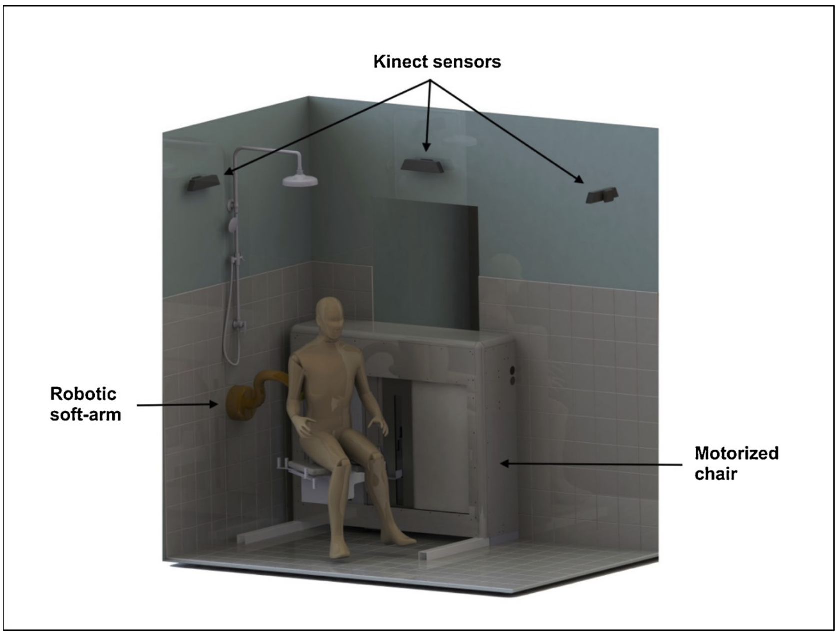

Fig. 1. Rendering of the I-SUPPORT bathing robot placed within the test environment (= typical bathroom of a rehabilitation clinic at a German geriatric hospital).

in this intimate ADL and to relieve the care burden of family caregivers or formal caregivers in medical centers and assisted living environments. More detailed and comprehensive information on the I-SUPPORT project can be found at the project website (http://www.i-support-project.eu/).

The I-SUPPORT bathing robot (Fig. 1) consists of the following main components: (1) a motorized chair for supporting stand-to-sit and sit-to-stand transfers and the transition into and out of the shower area; (2) a robotic soft-arm for the specific bathing tasks (e.g., pouring water, soaping, scrubbing, drying); (3) three Kinect V2 RGB-D sensors and eight condenser microphones for natural audio-gestural HRI (human and robot pose estimation, command and action recognition), and (4) a context-aware system for monitoring environmental (water flow and temperature, air temperature, humidity and illumination sensors) and user information (smartwatch for user identification and (in-)activity tracking) (not provided in Fig. 1). An overview of further technical details of the I-SUPPORT bathing robot will be published elsewhere.

2.2. I-SUPPORT user group

The intended users of the I-SUPPORT bathing robot are persons with (1) dependence in bathing activities and (2) no severe cognitive impairment (Werle & Hauer, 2016). The criteria for dependence in bathing activities was defined according to the bathing item of the Barthel Index (BI) (bathing item: 0 pt. = "patient can use a bath tub, a shower, or take a complete sponge bath only with assistance or supervision from another person") (Mahoney & Barthel, 1965). No severe cognitive impairment was defined as a score of > 17 points on the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975).

2.3. Gesture-based human-robot interaction

The I-SUPPORT bathing robot allows the interaction of the users with the robot through a predefined set of GCs for different bathing tasks (e.g., washing, scrubbing). The system architecture for gesture-based HRI consists of three Kinects V2 sensors installed at the walls of the bathroom. The Kinect V2 sensor is equipped with RGB-D and infrared sensors that enable to capture the video (Full HD RGB resolution) and depth information (time-of-flight principle) required for the human and robot pose reconstruction and the identification of the user's GCs. Kinect and other similar sensors are frequently employed for markerless motion tracking and visual recognition in robotics (El-laithy, Huang, & Yeh, 2012; Naeemabadi, Dinesen, Andersen, & Hansen, 2018). Two Kinect V2 sensors were placed inside the shower space for estimating the 3-dimensional pose of the human and robot, and one Kinect V2 sensor was placed outside the shower space for recognizing the GCs performed by the user. The processing methods of the visual information provided by the Kinect sensor for gesture recognition follow state-of-the-art computer vision and machine learning approaches for visual feature extraction and classification. In particular, "dense trajectories" are employed for feature extraction (Wang et al., 2011), an approach frequently used for action and gesture recognition (Baraldi, Paci, Serra, Benini, & Cucchiara, 2014; Yamada, Yoshida, Sumi, Habe, & Mitsugami, 2017) and various other visual recognition problems (Afshar & Salah, 2016; Huang, Zhang, & Li, 2016), especially in cases where the available data for training the algorithms is limited. In brief, this method consist in sampling salient points in the video (e.g., from hand edges, etc.) and tracking them through time, which produces a large number of trajectories. These trajectories are processed to extract the motion boundary histogram (MBH) descriptor in the standard bag-of-features framework (Dalal, Triggs, & Schmid, 2006; Zhang, Marszałek, Lazebnik, & Schmid, 2007), resulting in a high-dimensional numeric representation of the video. Finally, using this representation, each gesture is classified as one of the pre-defined GCs using non-linear support vector machines (SVMs) (Schuldt, Laptev, & Caputo, 2004; (Wang , Kläser , Schmid ,& Liu, 2011). More importantly, SVMs can also provide the probability of each video containing the recognized GC (see 2.9), enabling more in-depth analysis. More technical details on the GRS can be found elsewhere (Kardaris, Rodomagoulakis, Pitsikalis, Arvanitakis, & Maragos, 2016; Rodomagoulakis et al., 2016; Zlatintsi et al., 2018).

2.4. Study design

A quasi-experimental, single-group, pre-/post-test study design was used to analyze the effects of the user training on the gesture-based HRI between the participant and the I-SUPPORT bathing robot. The study was conducted between January 25 and February 8, 2018 with approval of the ethics committee of the Medical Faculty of the Heidelberg University (September 27, 2016; S-382/2016) and in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to study inclusion.

2.5. Study population

Participants were recruited from rehabilitation wards of a geriatric hospital, from nursing homes, and from a hospital-associated geriatric rehabilitation sports club. According to the predefined user group of the I-SUPPORT bathing robot, the following two main inclusion criteria were used to recruit participants: (1) dependence in bathing activities (BI, bathing item = 0 pt.) and (2) no severe cognitive impairment (MMSE score > 17 pt.). Further inclusion criteria were: no severe ADL impairment (BI ≥ 50 pt.); independence in bed-chair transfer (BI, transfer item = 15 pt.); no severe neurological, cardiovascular, metabolic, or psychiatric disorders; residence within 15 km of the study center, and written informed consent.

2.6. Test procedure

The I-SUPPORT bathing robot was installed in a typical bathroom of the rehabilitation clinic at a German geriatric hospital. Seven different GCs for the use case "back region shower process" had to be performed by the participants: (1) wash back; (2) higher temperature; (3) lower temperature; (4) scrub back; (5) repeat; (6) stop, and (7) halt. The correct GCs performed by an expert and used as reference standard can be found in online supplementary videos. During the whole testing procedure, the participants were seated on the motorized chair of the robot. Prior to the pre-test (T1), all participants received a brief introduction on the GCs. For each GC, a test administrator presented a large poster with images displaying the key movement elements of the specific GC and also demonstrated each GC once directly in front of the participant. After this brief introduction, the pre-test was performed with the participant. During the testing phase, the administrator subsequently presented the posters once more for each GC and asked the participant to perform the specific GC shown on the poster. After the participant performed a GC, a short brake was made to give the robot the opportunity to respond on the GC. In case of successful gesture recognition, the robot responded after about 3 s with an appropriate audio response (but did not actually perform the corresponding bathing task) and the next GC was tested. If the robot did not recognize the command correctly in this time interval, the test administrator asked the participant to repeat the GC once more. Independent of the robot response, the test procedure was continued with the next GC after such a second trial. This procedure was followed until all seven GCs were tested. After the pre-test was completed, a more extensive training phase on the GCs was performed by the administrator with the participant (see below). Following this training phase, the test procedure as described for the pre-test was repeated once more (T2 = post-test).

2.7. Intervention

Between the pre- and post-test, a training phase (10 − 15 min) on the specific GCs for the HRI with the I-SUPPORT bathing robot was performed with the participants. For this purpose, specific teaching methods and practice conditions, which have already been demonstrated to be effective for motor learning in older people with cognitive impairment (van Halteren-van Tilborg, Scherder, & Hulstijn, 2007; Werner et al., 2017), were used to facilitate learning of the GCs: mirror technique, combining movements with specific associations, haptic assistance, and high repetitions. The administrator sat directly in front of the participant and demonstrated the GC "like a mirror", that is, if the participants had to use their right hand for a GC, the administrator demonstrated this GC with the left hand. The participants were encouraged to immediately join the demonstration and to simply mirror the administrator's movements. During the demonstration, the administrator described the gestures by combining it with specific associations (e.g., "Like you would dip a sponge in a water bucket." [GC: wash my back]; "Like you would push someone away from you." [GC: stop]) to facilitate learning and memorizing of the GC. If necessary, also haptic assistance was provided by the administrator to ensure correct movement execution of the GC by the participant. Each GC was trained until the participant was able to perform it once correctly.

2.8. Descriptive measures

Sociodemographic and clinical characteristics including age, gender, living situation (community-dwelling vs. institutionalized), falls in the previous year, and ADL status (BI) were documented from patient charts or by standardized interviews. A trained interviewer assessed cognitive status (MMSE) and psychological status for depression (15-item Geriatric Depression Scale [GDS-15], Gauggel & Birkner, 1999; Sheikh & Yesavage, 1986), fear of falling (Falls Efficacy Scale-International [FES-I], Dias et al., 2006; Hauer et al., 2010), and technology acceptance (Senior Technology Acceptance Model [STAM], Chen & Chan, 2014): subscales for attitude towards technology, perceived usefulness, ease of use, gerontechnology self-efficacy, gerontechnology anxiety, and facilitating conditions). Physical performance was measured by the Short Physical Performance Battery (SPPB, Guralnik et al., 1994).

2.9. Outcome measures

The HRI was evaluated from both the human side, by assessing the participant's gestural performance, and the robot side, by assessing the performance of the GRS in recognizing the GCs.

Gestural performance was evaluated by (1) scores of a standardized clinical observation measure and (2) sensor-based performance scores derived from the GRS-recorded data.

The clinical observation measure was based on the scoring system of the Test of Upper Limb Apraxia (TULIA), which represents an established test for the comprehensive assessment of gesture production (Vanbellingen et al., 2010). Each GC was rated on a 6-point scale ranging from 0 to 5 points, with higher observation-based gestural performance (OGP) scores indicating better gestural performance. The scoring procedure followed a two-step assessment approach. In a first step, the achievement of the overall movement goal of the GC was evaluated, narrowing the range of the scores to either 0 or 1 points ('movement goal not achieved'), or 2–5 points ('movement goal achieved'). The movement goal of a GC was considered to be not achieved if errors occurred that seriously affected the trajectory of the gesture. Trajectories were defined as the spatial orientation of the movement including movement plane relative to the individual's body, joint coordination, and movement shape. If the movement goal of a GC was achieved, a more detailed error analysis was performed in a second step to yield the final score in the upper scale range (2–5 pt.). The detailed scoring method is presented in Table 1. The first step of this two-step assessment approach was directly performed during the test procedure and was used for deciding whether a second trial was given or not, while the more detailed error analysis was performed after the test procedure using the video recordings of the Kinect V2 sensor. The individual scores per GC were finally averaged over all seven GCs to yield a mean score for the overall observation-based gestural performance (OGP_{total}). Test procedure and scoring were consistently performed by the same person across all participants. Intra-rater reliability for scoring the video recordings of the GCs has been established in a pilot study with 8 participants randomly selected out of the total sample. Excellent intra-rater reliability was found with intraclass correlation coefficients (ICC(2,1), absolute agreement) ranging from 0.82 to 0.95.

A sensor-based gestural performance (SGP) score was calculated for each GC by applying Platt scaling (Platt, 2000) to the output of the SVM classifier of the GRS (see 2.3). This method is implemented by the software libraries used for the GRS (Chang & Lin, 2011) and has been

Table 1
Scoring guide for the observation-based assessment of the gestural performance.

Scores	Description of scoring
5 pt.	The movement goal of the gesture *was achieved*. The gesture was correct and identical to the demonstrated gesture.
4 pt.	The movement goal of the gesture *was achieved*, but errors occurred not affecting the trajectory of the gesture (normal movement plane and spatial location of the hand relative to the body, normal joint coordination and movement shape). Movement was too slow, hesitating, robot-like, and/or sloppy with minor spatial errors such as reduced or excessive amplitudes or unprecise location of the hand relative to the body.
3 pt.	The movement goal of the gesture *was achieved*, but errors occurred subtly affecting the trajectory of the gesture (imprecise movement plane relative to the body, inaccurate joint coordination and movement shape), which were corrected. Additions or omissions of movement components (mainly distal) were present. Brief content errors (substitutions, perseverations, pauses) occurred; however, corrections were made in the ongoing movement.
2 pt.	The movement goal of the gesture *was achieved*, but errors occurred subtly affecting the trajectory of the gesture (imprecise movement plane relative to the body, inaccurate joint coordination and movement shape), which were not corrected. Additions or omissions of (main) movement components (mainly distal) occurred without corrections.
1 pt.	The movement goal of the gesture *was not achieved*. Errors occurred seriously affecting the trajectory of the gesture. The final position was false, major errors in the movement plane, spatial position of the hand relative to the body, joint coordination and movement shape. Overshoot and additional movements (mainly proximal) were present or the gesture was performed with the wrong hand; however, the overall movement pattern of the gesture remained recognizable (1 point). Persisting substitutions (related or unrelated to the gesture) and perseverations occur.
0 pt.	The movement goal of the gesture *was not achieved*. No movement, gesture was totally incorrect or so incomplete that it was not recognizable. Seeking and amorphous movements. No temporal or spatial reference to the requested gesture.

thoroughly shown to provide reliable estimates of class membership probabilities (Caruana, Karampatziakis, & Yessenalina, 2008; Niculescu-Mizil & Caruana, 2005). Each SGP score ranged from 0 to 1 (with higher scores indicating better gestural performance) and quantifies the certainty or degree to which a performed gesture can be classified as the respective GC, according to the GRS. A mean score for the overall sensor-based gestural performance (SGP_{total}) was also calculated by averaging the individual SGP per GC over all seven GCs.

The performance of the robot-integrated GRS was evaluated by its command recognition rate (CRR), defined as the percentage of successfully recognized GCs relative to the seven GCs tested. The test administrator noted the (un-)successful recognition of each command directly during the test procedure.

2.10. Statistical analysis

Descriptive data were presented as frequencies and percentages for categorical variables, and median and interquartile ranges (IQR) and/or mean and standard deviations (SD) for continuous variables. If a participant performed two trials for a GC that both were not successfully recognized by the GRS, the trial with the highest observational-based assessment score was used for the statistical analysis of all outcome measures. In all other cases, the trial with the recognized GC was used. Differences in outcome measures between pre- (T1) and post-test (T2) were analyzed using Wilcoxon signed-rank tests. To quantify the magnitude of pre/post-test changes, effect sizes ($ES = Z/\sqrt{N}$) were calculated and interpreted as small (0.1 to < 0.3), moderate (0.3 to < 0.5), large (0.5 to < 0.7), or very large (≥0.7) (Cohen, 1988; Rosenthal, 1996). Associations between (1) participant characteristics (age, gender, cognitive status [MMSE], physical performance [SPPB], psychological status [GDS-15, FES-I, STAM]) and overall gestural performance (OGP_{total}, SGP_{total}) at T1; (2) system (CRR) and overall gestural performance (OGP_{total}, SGP_{total}); (3) participant characteristics (age, gender, MMSE, SPPB, GDS-15, FES-I, STAM, baseline gestural performance [OGP_{T1}, SGP_{T1}]) and relative changes in overall gestural performance (OGP_{total}, SGP_{total}) over the training phase (T1-T2), and (4) relative changes in the system (CRR) and overall gestural performance (OGP_{total}, SGP_{total}) over the training phase (T1-T2) were analyzed using Pearson's, Spearman rank or point-biserial correlation coefficients (*r*) as appropriate. Relative changes were calculated as: ((post-test score – pre-test score)/pre-test score) × 100). Correlation coefficients were interpreted as trivial (< 0.1), small (0.1 to < 0.3), moderate (0.3 to < 0.5), high (0.5 to < 0.7), very high (0.7 to < 0.9), extremely high (≥0.9) (Cohen, 1988; Hopkins, Marshall, Batterham, & Hanin, 2009). The sample size was calculated to be n = 25, based on an a priori power analysis for Wilcoxon signed rank tests comparing T1 vs. T2 gestural performance scores (Faul, Erdfelder, Lang, & Buchner, 2007), with a two-sided significance level (α) of 0.05, a statistical power (1-β) of 0.80, and a moderate effect size (Cohen's d_z = 0.6). The expected moderate effect size was derived from findings of previous studies that indicated gross motor skill learning in older adults after one session of semantic instruction and demonstration (Voelcker-Rehage and Willimczik, 2006; Cohen's d_z = 0.7–1.7) and in cognitively impaired older adults after a motor learning exercise program including the same teaching methods and practice conditions as used in the current study (Werner et al., 2017; Cohen's d_z = 0.5–1.1). A two-sided *p*-value of < 0.05 indicated statistical significance. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Participant characteristics

The study sample included 25 older people (77.9 ± 7.9 years) who all were dependent in bathing (BI, bathing item = 0 pt.). Thirteen (52 %) participants were recruited from the geriatric rehabilitation sports club, seven (28 %) from nursing homes, and five (20 %) from geriatric rehabilitation wards. The MMSE score averaged 25.6 ± 3.1 points, with about half of the participants (n = 13, 52 %) having some cognitive impairment (MMSE 17–26 pt.). The sample showed a slightly impaired ADL status, with a mean BI score of 81.6 ± 8.6 points (Brefka et al., 2019). The SPPB score averaged 6.1 ± 2.9 points, indicating low physical performance potentially associated with lower frailty status and increased fall risk (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995; Pritchard et al., 2017; Veronese et al., 2014). Most participants (88 %) had no clinically relevant depressive symptoms (GDS-15 > 5 pt.). More than the half reported one or more falls in the previous year (n = 14, 56 %). Fear of falling was low (FES-I = 16–19 pt.) in 4 (16 %), moderate (FES-I = 20–27 pt.) in 9 (36 %), and high (FES-I = 23 – 64 pt.) in 12 participants (48 %) (Delbaere et al., 2010). Almost three out of four participants (n = 18, 72 %) reported concerns about falling while taking a shower or bath (FES-I, bathing item > 1 pt.). Technology acceptance was moderate to high, with mean scores on the different STAM subscales in the upper half of the scoring range (see Table 2).

3.2. Training effects on human-robot interaction

Prior to the training phase, the overall gestural performance was low to moderate, with a median OGP_{total} score of 2.4 points (IQR 1.8–2.9) and a median SGP_{total} score of 0.60 points (IQR 0.47-0.67) (Table 3). Only three participants (12 %) performed at least one GC identical to the demonstrated ones without any movement errors (i.e.,

Table 2
Characteristics of 25 participants.

Variables	
Age, years	77.9 ± 7.9
Sex, females	20 (80.0)
Mini-Mental State Examination, score	25.6 ± 3.1
Geriatric Depression Scale, score	2 [1–3]
Falls Efficacy Scale-International, score	28.8 ± 10.0
Recent history of falls	14 (56.0)
Barthel Index	85.4 ± 11.4
Short Physical Performance Battery, score	6.1 ± 2.9
Technology Acceptance, score[a]	
Attitudes towards technology (max. 20 pt.)	14.6 ± 5.0
Perceived usefulness (max. 30 pt.)	19.9 ± 8.4
Ease of use (max. 20 pt.)	10.8 ± 5.0
Gerontechnology self-efficacy (max. 20 pt.)	12.2 ± 5.2
Gerontechnology anxiety (max. 20 pt.)	12.5 ± 6.1
Facilitating conditions (max. 50 pt.)	30.3 ± 10.5
Living situation	
Community-dwelling	18 (72.0)
Institutionalized	7 (28.0)

Data are presented as mean ± SD, n (%), and median [IQR].
[a] Higher scores indicates better attitudes towards technology, higher perceived usefulness, greater ease of use, higher gerontechnology self-efficacy, lower gerontechnology anxiety, and more facilitating conditions.

OGP score = 5 pt.). The performance of the GRS at pre-test was also only moderate, with a median CRR of 85.7 % (IQR 50.0–85.7).

3.3. Correlational results

Baseline gestural performance was significantly correlated with cognitive status (OGP_{total}: $r = .68$, $p < .001$; $SGP_{total:}$ $r = .68$, $p < .001$) and gerontechnology anxiety (OGP_{total}: $r = .59$, $p = .002$; $SGP_{total:}$ $r = .41$, $p = .041$), such that participants with a higher cognitive performance and less anxiety in gerontechnology showed a higher initial gestural performance at pre-test. High to very high correlation coefficients were observed for these significant correlations, expect for that between SGP_{total} and gerontechnology anxiety (moderate correlation). For all other participant characteristics, there were no significant correlations with the baseline gestural performance ($r = |.01\text{-}.33|$, $p = .144\text{-}.949$) (Table 4).

The pre-/post-test change in the OGP_{total} score was significantly and moderately correlated with gerontechnology anxiety ($r = -.41, p = .041$), such that those participants with the highest level of gerontechnology anxiety improved most in the overall gestural performance. The SGP_{total} score tend to confirm this association; however, it just missed the level of significance ($r = -.37$, $p = .069$). In addition, lower baseline gestural performance was significantly and highly correlated with training-induced improvements in the gestural performance (OGP_{total}, SGP_{total}: $r = 0.52\text{-}0.67$, $p < .001\text{-}.008$). For all other

Table 3
Training effects on the gestural performance of the participants and the performance of the robot-integrated gesture recognition system.

Variables	T1	T2	% change	*p*-value	Effect size
Gestural performance					
Observation-based performance scores [pt.]					
Wash back	2.3 ± 1.4	3.0 ± 1.7		.026	0.45
	2.0 [1.0–4.0]	4.0 [2.0–4.0]			
Higher temperature	2.2 ± 1.2	3.4 ± 1.2		.001	0.66
	2.0 [1.0–3.5]	4.0 [2.0–4.0]			
Lower temperature	2.9 ± 1.3	3.6 ± 1.3		.017	0.48
	4.0 [2.0–4.0]	4.0 [3.5–4.0]			
Scrub back	2.1 ± 1.9	3.6 ± 1.6		.002	0.63
	1.0 [0.5–4.0]	4.0 [2.5–5.0]			
Repeat	1.4 ± 1.0	2.3 ± 1.2		.001	0.64
	1.0 [1.0–2.0]	2.0 [2.0–3.0]			
Stop	2.2 ± 1.3	3.2 ± 1.2		.005	0.57
	2.0 [1.0–3.5]	4.0 [2.0–4.0]			
Halt	3.1 ± 1.4	4.2 ± 1.3		.001	0.69
	3.0 [2.0–4.0]	5.0 [4.0–5.0]			
Total performance	2.3 ± 0.8	3.3 ± 0.8	+57.1 ± 56.2	< .001	0.84
	2.4 [1.8–2.9]	3.6 [2.9–3.9]	38.1 [18.9–82.1]		
Sensor-based performance scores [pt.]					
Wash back	0.45 ± 0.33	0.54 ± 0.33		.069	0.36
	0.43 [0.06–0.76]	0.63 [0.21–0.84]			
Higher temperature	0.56 ± 0.33	0.77 ± 0.32		.003	0.59
	0.63 [0.18–0.88]	0.95 [0.72–0.98]			
Lower temperature	0.68 ± 0.36	0.80 ± 0.27		.034	0.42
	0.83 [0.32–0.98]	0.94 [0.60–0.98]			
Scrub back	0.35 ± 0.32	0.69 ± 0.30		< .001	0.79
	0.23 [0.04–0.66]	0.83 [0.58–0.90]			
Repeat	0.40 ± 0.40	0.68 ± 0.41		.022	0.53
	0.24 [0.02–0.91]	0.92 [0.24–0.98]			
Stop	0.66 ± 0.38	0.81 ± 0.31		.010	0.51
	0.86 [0.33–0.98]	0.98 [0.82–1.00]			
Halt	0.67 ± 0.33	0.79 ± 0.29		.211	0.25
	0.85 [0.39–0.96]	0.92 [0.78–0.96]			
Total performance	0.56 ± 0.21	0.73 ± 0.18	+51.1 ± 74.4	< .001	0.79
	0.60 [0.47–0.67]	0.80 [0.60–0.87]	27.6 [13.2–47.0]		
GRS performance					
CRR [%]	70.3 ± 24.0	84.6 ± 21.8	+31.9 ± 51.2	.003	0.59
	85.7 [50.0–85.7]	100 [71.4–100]	16.7 [0–40.0]		

Data are presented as mean ± SD and median [IQR]. *P*-values were given for Wilcoxon signed-rank tests. Effect sizes were calculated as Z/√N. GRS, gesture recognition system; CRR, command recognition rate.

Table 4
Correlations of participant characteristics with pre-test gestural performance (T1) and relative pre-post changes in gestural performance (T1-T2).

Participant characteristics	T1		T1-T2: % change	
	OGP_{total}	SGP_{total}	OGP_{total}	SGP_{total}
Age	.07	−.01	−.17	.01
Sex[a]	.21	.26	−.18	−.22
Mini-Mental State Examination	.68***	.68***	−.28	−.24
Geriatric Depression Scale	−.29	−.26	−.02	.05
Falls Efficacy Scale-International	−.06	−.04	−.02	−.01
Short Physical Performance Battery	−.17	−.33	.19	.33
Technology Acceptance				
Attitudes towards technology	.22	.15	.09	.08
Perceived usefulness	.28	.32	.04	.06
Ease of use	.07	.18	−.09	−.16
Gerontechnology self-efficacy	.16	.24	−.13	−.19
Gerontechnology anxiety	.59**	.41*	−.41*	-.37+
Facilitating conditions	.23	.35+	−.03	−.09
Baseline gestural performance				
OGP_{total}			−.67***	
SGP_{total}				−.52**

Correlations were given as Pearson's, Spearman rank or point-biserial correlation coefficients (r) as appropriate.
+ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

participant characteristics, there were no significant correlations with the changes in the overall gestural performance ($r = |<.01\text{-}.33|$, $p = .109\text{-}.987$).

Very high to extremely high significant correlations were obtained between the gestural performance and CRR at pre-test (OGP_{total}: $r = .94$, $p < .001$; SGP_{total}: $r = .83$, $p < .001$) and post-test (OGP_{total}, SGP_{total}: $r = 0.81$, $p < .001$) (Table 5). The improvement in the overall gestural performance of the participants was also significantly and highly correlated with the improvement in the CRR of the robot-integrated GRS (OGP_{total}, SGP_{total}: $r = 0.80\text{-}0.81$, $p < .001$).

4. Discussion

The present study aimed to provide a more in-depth understanding of the human side of the gesture-based HRI between an assistive bathing robot and potential end-users. Being representative of the potential user group of the bathing robot, we recruited older people with bathing disability and evaluated the effects on the HRI of a user training specifically designed and tailored to the needs and requirements of this population to improve their performance in interacting with the robot using GCs. In addition, we investigated whether the gestural performance and training response were associated with individual differences in participant characteristics and whether training-induced improvements in the gestural performance would lead to a better performance of the GRS in recognizing the participant's GCs.

Table 5
Correlations between the performance of the robot-integrated gesture recognition system and the gestural performance of the participants.

CRR	OGP_{total}			SGP_{total}		
	T1	T2	T1-T2: % change	T1	T2	T1-T2: % change
T1	.94***			.83***		
T2		.81***			.81***	
T1-T2: % change			.81***			.80***

Correlations were given as Pearson's or Spearman rank correlation coefficients (r) as appropriate.
*** $p < 0.001$. CRR, command recognition rate; OGP, observation-based gestural performance; SGP, sensor-based gestural performance.

Our results clearly indicate that the user training was highly beneficial for improving the gesture-based HRI between the assistive bathing robot and the participants. Lower cognitive performance and higher gerontechnology anxiety were identified to negatively affect the participants' initial gestural performance. However, lower cognitive performance did not influence their training response, and higher initial gerontechnology anxiety was associated with even greater benefits in the gestural performance over the training phase. The participants who benefited the most from the user training were those with the lowest initial gestural performance at baseline. For both testing sessions, as well as for the changes between pre- and post-test, the performance of the robot-integrated GRS was found to be closely related to the gestural performance of the participants.

4.1. Training effects on human-robot interaction

Due to the common lack of experience of older adults in interacting with a robot (Smarr et al., 2012, 2014), potential age-related limitations in cognitive abilities relevant for gesture-based HRI, and previous findings on gesture-based HRI for an assistive mobility robot in a similar population (Efthimiou et al., 2016), the initial gestural performance of the participants at pre-test was expected to be rather low. Our results confirmed this expectation, with only low to moderate gestural performance scores and a very small number of participants (3 out of 25) performing any GC without errors after the brief introduction before pre-test. This finding indicates that a single, brief introduction in gesture-based HRI with an assistive robot does not seem to be sufficient to ensure adequate quality of a user's input for such interaction in frail older adults with some levels of cognitive impairment. As the robot-integrated GRS depend on an adequate quality of the user's input, the low to moderate gestural performance was directly translated into an only moderate CRR, leading to an overall rather unsatisfying HRI at pre-test. To overcome these user-related issues of the HRI and to improve the gestural performance of the participants, a user training on HRI was implemented including teaching methods that have already been demonstrated to be effective for learning motor tasks in older people with cognitive impairment (van Halteren-van Tilborg et al., 2007; Werner et al., 2017). Significant improvements in almost all outcome measures – with predominantly large effect sizes – confirmed our primary study hypothesis that such training improves the participants' movement execution of the GCs, leading to an improved CRR of the robot-integrated GRS, and thus also to an overall improved HRI.

Improvements in the gestural performance were documented by different outcome measures. We developed and used a standardized clinical observation measure for which the scoring method was derived from an established and valid clinical test for gesture production (TULIA) (Vanbellingen et al., 2010), as well as sensor-based performance scores recorded by the robot-integrated GRS. The latter was chosen to substantiate the training effects documented by observation-based outcomes by technically measured, more objective outcomes. Further, this approach of using the already existing data flow of the robot-integrated sensing technique for assessment purposes has been recommended for the evaluation of HRI with assistive robots, allowing for highly specific assessments exactly tuned to the robot's functionality to be evaluated (Werner, Ullrich, Geravand, Peer, & Hauer, 2016).

4.2. Correlational results

Consistent with our hypothesis, lower initial gestural performance was significantly associated with lower cognitive status and more negative feelings toward technology, highlighting the relevance of the user's cognitive abilities for gesture-based HRI as well as the previously reported relationship between a user's emotions toward the robot and the quality of HRI (Broadbent et al., 2010). According to that, training programs to improve the quality of a user's input for HRI seem to be of particular importance in older adults with lower cognitive status and higher technology anxiety.

Higher gerontechnology anxiety was identified to be significantly associated with higher training gains in the gestural performance. This might be related to the fact that participants with a general higher anxiety towards technology may have been initially also more anxious toward the assistive bathing robot; however, as emotions toward a robot have been shown to improve with increasing user experience (Engelhardt & Edwards, 1992; Louie et al., 2014), the experience with the robot at pre-test may have reduced the anxiety in these participants, which in turn may have had a beneficial side effect on the gestural performance in participants with higher technology anxiety in addition to the specific training effect.

As hypothesized, the lower initial gestural performance was also a significant factor for higher training gains in the gestural performance, which is in accordance with the rate-dependency phenomenon and general training principles (Dews, 1977; Haskell, 1994; Snider et al., 2016). This suggests that the participants with the lowest initial gestural performance could also be successfully trained in the GCs and even represented those that benefitted most from the user training.

In contrast, improvements in the gestural performance over the training phase were not significantly associated with the participants' cognitive status in our study, suggesting that a positive training response can also be achieved in older adults with mild-to-moderate cognitive impairment. This might especially be explained by the fact that we applied specific teaching methods and practice conditions in the user training which have been shown to be effective for learning other motor tasks in older adults with cognitive impairment (van Halteren-van Tilborg et al., 2007; Werner et al., 2017).

Finally, higher gestural performances were closely related to higher CRRs at pre- and post-test, supporting our hypothesis and highlighting the high dependence of the robot-integrated GRS on the quality of a user's input for successful gesture recognition. The high extent by which improvements in the gestural performance parallel improvements in the CRR further emphasizes this dependence and suggest that improving the gestural performance of the users is directly translated into improvements in the CRR, leading to an overall improved HRI.

5. Limitations

This study has some limitations. First, the sample size was rather small, limiting the statistical power and generalizability of the results and the ability to perform multiple regression analyses. Second, training effects might not be generalizable to gesture-based HRI with another assistive robot. However, the predefined set of GCs for the assistive bathing robot included various GCs, suggesting that our training approach might be beneficial to improve the gestural performance of older users also for gesture-based HRI with other assistive robots. Third, as a quasi-experimental pretest-posttest study with no control was performed, training effects cannot unequivocally be attributed to the user training. Improvements in the CRR were, however, highly associated with those in the gestural performance, suggesting at least a causal relationship between improving the quality of a user's GCs and improving the CRR and overall HRI, respectively, which was the starting point of this study. Fourth, the study did not include a follow-up, and therefore the sustainability of training effects remains unclear. Future studies should investigate whether potential users are able to remember and correctly perform the GCs also after long periods of time or whether recurrent training sessions are necessary to ensure an adequate gestural performance for long-term successful HRI.

6. Conclusions

The present study reveals that providing a user training specifically tailored to the needs of potential robot users to improve their GCs is highly beneficial for gesture-based HRI with an assistive bathing robot. Our results demonstrated that improved gestural performance is directly translated into better technical performance of the robot-integrated GRS, leading to an overall improved gesture-based HRI. Training benefits can also be achieved in persons with mild-to-moderate cognitive impairment. Older users with low initial gestural performance and more negative feelings toward technology may even benefit the most from a tailored user training. Current findings highlight that for improving gesture-based HRI between assistive robots and older users, future developments and studies in this field should focus not only on refining technical aspects of the robot but also on improving the quality of a user's input by training. Training procedures may be particularly effective when considering the individual resources and limitations of potential users. The presented user training may represent a model for training older adults in gesture-based HRI with an assistive robot.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Christian Werner: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Nikos Kardaris:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Petros Koutras:** Software, Data curation, Writing - review & editing. **Athanasia Zlantintsi:** Software, Data curation, Writing - review & editing. **Petros Maragos:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Funding acquisition. **Jürgen M. Bauer:** Resources, Writing - review & editing. **Klaus Hauer:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.archger.2019.103996.

References

Afshar, S., & Salah, A. A. (2016). Facial expression recognition in the wild using improved dense trajectories and fisher vector encoding. *2016 IEEE conference on computer vision and pattern recognition workshops (CVPRW),* 1517–1525. https://doi.org/10.1109/CVPRW.2016.189.

Ahluwalia, S. C., Gill, T. M., Baker, D. I., & Fried, T. R. (2010). Perspectives of older persons on bathing and bathing disability: A qualitative study. *Journal of the American Geriatrics Society, 58*, 450–456 10.1111%2Fj.1532-5415.2010.02722.x.

Alameda-Pineda, X., & Horaud, R. (2015). Vision-guided robot hearing. *The International Journal of Robotics Research, 34*, 437–456 10.1177%2F0278364914548050.

Baraldi, L., Paci, F., Serra, G., Benini, L., & Cucchiara, R. (2014). Gesture recognition in egoentric videos using dense trajectories and hand segmentation. *2014 IEEE conference on computer vision and pattern recognition workshops,* 702–707. https://doi.org/10.1109/CVPRW.2014.107.

Begum, M., Wang, R., Huq, R., & Mihailidis, A. (2013). Performance of daily activities by older adults with dementia: The role of an assistive robot. *IEEE international conference on rehabilitation robotics 2013,* 6650405. https://doi.org/10.1109/ICORR.2013.6650405.

Brefka, S., Dallmeier, D., Muhlbauer, V., von Arnim, C. A. F., Bollig, C., Onder, G., et al. (2019). A proposal for the retrospective identification and categorization of older people with functional impairments in scientific studies-recommendations of the medication and quality of life in frail older persons (MedQol) research group. *Journal of the American Medical Directors Association, 20*, 138–146. https://doi.org/10.1016/j.jamda.2018.11.008.

Broadbent, E., Kuo, I. H., Lee, Y. I., Rabindran, J., Kerse, N., Stafford, R., et al. (2010). Attitudes and reactions to a healthcare robot. *Telemedicine Journal and e-Health, 16*, 608–613. https://doi.org/10.1089/tmj.2009.0171.

Caruana, R., Karampatziakis, N., & Yessenalina, A. (2008). An empirical evaluation of supervised learning in high dimensions. *Proceedings of the 25th international conference on machine learning* (pp. 96–103). . https://doi.org/10.1145/1390156.1390169.

Chang, C.-C., & Lin, C.-J. (2011). LIBSVM: A library for support vector machines. *ACM Transactions on Intelligent Systems and Technology, 2*, 1–27. https://doi.org/10.1145/1961189.1961199.

Chen, K., & Chan, A. H. (2014). Gerontechnology acceptance by elderly Hong Kong Chinese: A senior technology acceptance model (STAM). *Ergonomics, 57*, 635–652. https://doi.org/10.1080/00140139.2014.895855.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* New York: Routledge.

Craik, F. I. M., & Salthouse, T. A. (2008). *The handbook of aging and cognition* (3rd ed.). New York: Psychology Press.

Dalal, N., Triggs, B., & Schmid, C. (2006). *Human detection using oriented histograms of flow and appearance.* Berlin Heidelberg, Berlin, Heidelberg: Springer428–441. https://doi.org/10.1007/11744047_33.

Dawson, D., Hendershot, G., & Fulton, J. (1984). *Aging in the eighties. Functional limitations of individuals age 65 years and over. Advance data from vital and health statistics. Public health services; 1987. DHHS pub. No. 133*.

Delbaere, K., Close, J. C., Mikolaizak, A. S., Sachdev, P. S., Brodaty, H., & Lord, S. R. (2010). The falls efficacy scale international (FES-I). A comprehensive longitudinal validation study. *Age and Ageing, 39*, 210–216. https://doi.org/10.1093/ageing/afp225.

Dews, P. B. (1977). Rate-dependency hypothesis. *Science, 198*, 1182–1183. https://doi.org/10.1126/science.563103.

Dias, N., Kempen, G. I. J. M., Todd, C. J., Beyer, N., Freiberger, E., Piot-Ziegler, C., et al. (2006). Die Deutsche Version der Falls Efficacy Scale-International Version (FES-I). *Zeitschrift für Gerontologie und Geriatrie, 39*, 297–300. https://doi.org/10.1007/s00391-006-0400-8.

Dyck, J. L., & Smither, J. A.-A. (1994). Age differences in computer anxiety: The role of computer experience, gender and education. *Journal of Educational Computing Research, 10*, 239–248 10.2190%2FE79U-VCRC-EL4E-HRYV.

Efthimiou, E., Fotinea, S., Goulas, T., Koutsombogera, M., Karioris, P., Vacalopoulou, A., et al. (2016). The MOBOT rollator human-robot interaction model and user evaluation process. *2016 IEEE symposium series on computational intelligence (SSCI),* 1–8. https://doi.org/10.1109/SSCI.2016.7850061.

El-laithy, R. A., Huang, J., & Yeh, M. (2012). Study on the use of microsoft kinect for robotics applications. *Proceedings of the 2012 IEEE/ION position, location and navigation symposium,* 1280–1288. https://doi.org/10.1109/PLANS.2012.6236985.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175–191. https://doi.org/10.3758/BF03193146.

Engelhardt, K., & Edwards, R. (1992). Human-robot integration for service robots. In M. Rahimi, & W. Karwowski (Eds.). *Human-robot interaction*. London, UK: Taylor & Francis.

Fischinger, D., Einramhof, P., Papoutsakis, K., Wohlkinger, W., Mayer, P., Panek, P., et al. (2016). Hobbit, a care robot supporting independent living at home: First prototype and lessons learned. *Robotics and Autonomous Systems, 75*, 60–78. https://doi.org/10.1016/j.robot.2014.09.029.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*, 189–198.

Fong, J. H., Mitchell, O. S., & Koh, B. S. K. (2015). Disaggregating activities of daily living limitations for predicting nursing home admission. *Health Services Research, 50*, 560–578. https://doi.org/10.1111/1475-6773.12235.

Gauggel, S., & Birkner, B. (1999). Validität und Reliabilität einer deutschen Version der geriatrischen Depressionsskala (GDS). *Zeitschrift für Klinische Psychologie und Psychotherapie, 28*, 18–27. https://doi.org/10.1026//0084-5345.28.1.18.

Goldin-Meadow, S., & Alibali, M. W. (2013). Gesture's role in speaking, learning, and creating language. *Annual Review of Psychology, 64*, 257–283. https://doi.org/10.1146/annurev-psych-113011-143802.

Goodrich, M. A., & Schultz, A. C. (2008). Human–robot interaction: A survey. *Foundations and Trends® in Human–Computer Interaction, 1*, 203–275. https://doi.org/10.1561/1100000005.

Guler, A., Kardaris, N., Chandra, S., Pitsikalis, V., Werner, C., Hauer, K., et al. (2016). *Human joint angle estimation and gesture recognition for assistive robotic vision.* Cham: Springer International Publishing415–431. https://doi.org/10.1007/978-3-319-48881-3_29.

Guralnik, J. M., Ferrucci, L., Simonsick, E. M., Salive, M. E., & Wallace, R. B. (1995). Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. *The New England Journal of Medicine, 332*, 556–561. https://doi.org/10.1056/NEJM199503023320902.

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G., et al. (1994). A short physical performance battery assessing lower extremity function: Association with self-reported disability and prediction of mortality and nursing home admission. *Journal of Gerontology, 49*, M85–94. https://doi.org/10.1093/geronj/49.2.M85.

Gure, T. R., Langa, K. M., Fisher, G. G., Piette, J. D., & Plassman, B. L. (2013). Functional limitations in older adults who have cognitive impairment without dementia. *Journal of Geriatric Psychiatry and Neurology, 26*, 78–85. https://doi.org/10.1177/0891988713481264.

Hakkinen, A., Heinonen, M., Kautiainen, H., Huusko, T., Sulkava, R., & Karppi, P. (2007). Effect of cognitive impairment on basic activities of daily living in hip fracture patients: A 1-year follow-up. *Aging Clinical and Experimental Research, 19*, 139–144. https://doi.org/10.1007/BF03324680.

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine, 29*, 737–752. https://doi.org/10.1016/j.cger.2013.07.002.

Haskell, W. L. (1994). J.B. Wolffe memorial lecture. Health consequences of physical activity: Understanding and challenges regarding dose-response. *Medicine and Science in Sports and Exercise, 26*, 649–660. https://doi.org/10.1249/00005768-199406000-00001.

Hauer, K. (2018). Bewertung von AAL-Ambient-Assisted-Living-Systemen bei Personen mit kognitiver Schädigung: Match vs. Mismatch. In O. Bendel (Ed.). *Pflegeroboter* (pp. 89–111). Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-22698-5_5.

Hauer, K., Yardley, L., Beyer, N., Kempen, G., Dias, N., Campbell, M., et al. (2010). Validation of the falls efficacy scale and falls efficacy scale international in geriatric patients with and without cognitive impairment: Results of self-report and interview-based questionnaires. *Gerontology, 56*, 190–199. https://doi.org/10.1159/000236027.

Hernandez-Belmonte, U. H., & Ayala-Ramirez, V. (2016). Real-time hand posture recognition for human-robot interaction tasks. *Sensors (Basel, Switzerland), 16*, 36. https://doi.org/10.3390/s16010036.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*, 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278.

Huang, L., Zhang, X., & Li, W. (2016). Dense trajectories and dhog for classification of viewpoints from echocardiogram videos. *Computational and Mathematical Methods in Medicine, 2016*, 7. https://doi.org/10.1155/2016/9610192.

Hunter, S. K., Pereira, H. M., & Keenan, K. G. (2016). The aging neuromuscular system and motor performance. *Journal of Applied Physiology, 121*, 982–995. https://doi.org/10.1152/japplphysiol.00475.2016.

International Organization for Standardization (2012). *Robots and robotic devices - vocabulary (ISO 8373:2012(en)*. https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en.

Jagger, C., Arthur, A. J., Spiers, N. A., & Clarke, M. (2001). Patterns of onset of disability in activities of daily living with age. *Journal of the American Geriatrics Society, 49*, 404–409. https://doi.org/10.1046/j.1532-5415.2001.49083.x.

Jones, A., Dawyer, L., Bercovitz, A., & Strahan, G. (2009). The national nursing home survey: 2004 overview. National center for health statistics. *Vital and Health Statistics Series, 13*.

Kardaris, N., Rodomagoulakis, I., Pitsikalis, V., Arvanitakis, A., & Maragos, P. (2016). A platform for building new human-computer interface systems that support online automatic recognition of audio-gestural commands. *Proceedings of the 24th ACM international conference on Multimedia* (pp. 1169–1173). . https://doi.org/10.1145/2964284.2973794.

Katz, S., Ford, A. B., Moskowitz, R. W., Jackson, B. A., & Jaffe, M. W. (1963). Studies of illness in the aged. The index of ADL: A standardized measure of biological and psychosocial function. *Journal of the American Medical Association, 185*, 914–919. https://doi.org/10.1001/jama.1963.03060120024016.

Kendon, A. (2004). *Gesture: Visible action as utterance.* Cambridge: Cambridge University Press.

Liu, H., & Wang, L. (2018). Gesture recognition for human-robot collaboration: A review. *International Journal of Industrial Ergonomics, 68*, 355–367. https://doi.org/10.1016/j.ergon.2017.02.004.

Louie, W. Y., McColl, D., & Nejat, G. (2014). Acceptance and attitudes toward a human-like socially assistive robot by older adults. *Assistive Technology, 26*, 140–150. https://doi.org/10.1080/10400435.2013.869703.

Mahoney, F. I., & Barthel, D. W. (1965). Functional evaluation: The Barthel index. *Maryland State Medical Journal, 14*, 61–65.

Mavridis, N. (2015). A review of verbal and non-verbal human–robot interactive communication. *Robotics and Autonomous Systems, 63*, 22–35. https://doi.org/10.1016/j.robot.2014.09.031.

McNeill, D. (1992). *Hand in mind: Waht gestures reveal about thought.* Chicago, IL: University of Chicago Press.

Naeemabadi, M., Dinesen, B., Andersen, O. K., & Hansen, J. (2018). Investigating the impact of a motion capture system on Microsoft Kinect v2 recordings: A caution for using the technologies together. *PLoS One, 13*, e0204052. https://doi.org/10.1371/journal.pone.0204052.

Nelson, E. A., & Dannefer, D. (1992). Aged heterogeneity: Fact or fiction? The fate of diversity in gerontological research. *The Gerontologist, 32*, 17–23. https://doi.org/10.1093/geront/32.1.17.

Niculescu-Mizil, A., & Caruana, R. (2005). Predicting good probabilities with supervised learning. *Proceedings of the 22nd international conference on machine learning* (pp. 625–632). . https://doi.org/10.1145/1102351.1102430.

Platt, J. (2000). Probabilistic outputs for support vector machines and comparisons to regularized likelihood methods. In A. J. Smola, P. Bartlett, B. Schölkopf, & D. Schurrmans (Eds.). *Advances in large margin classifiers*. MIT Press.

Pritchard, J. M., Kennedy, C. C., Karampatos, S., Ioannidis, G., Misiaszek, B., Marr, S., et al. (2017). Measuring frailty in clinical practice: A comparison of physical frailty assessment methods in a geriatric out-patient clinic. *BMC Geriatrics, 17*, 264. https://doi.org/10.1186/s12877-017-0623-0.

Rodomagoulakis, I., Kardaris, N., Pitsikalis, V., Mavroudi, E., Katsamanis, A., Tsiami, A., et al. (2016). Multimodal human action recognition in assistive human-robot interaction. *2016 IEEE international conference on acoustics, speech and signal processing (ICASSP),* 2702–2706. https://doi.org/10.1109/ICASSP.2016.7472168.

Rosenthal, J. A. (1996). Qualitative descriptors of strength of association and effect size. *Journal of Social Service Research, 21*, 37–59. https://doi.org/10.1300/J079v21n04_02.

Schmidt, L. I., & Wahl, H. W. (2019). Predictors of performance in everyday technology tasks in older adults with and without mild cognitive impairment. *The Gerontologist, 59*, 90–100. https://doi.org/10.1093/geront/gny062.

Schuldt, C., Laptev, I., & Caputo, B. (2004). Recognizing human actions: A local SVM approach. *Proceedings of the 17th international conference on pattern recognition, 2004: Vol. 33*, (pp. 32–36). . https://doi.org/10.1109/ICPR.2004.1334462.

Scopelliti, M., Giuliani, M. V., D'Amico, A. M., & Fornara, F. (2004). If i had a robot at home… peoples' representation of domestic robots. In S. Keates, J. Clarkson, P. Langdon, & P. Robinson (Eds.). *Designing a more inclusive world* (pp. 257–266). London: Springer. https://doi.org/10.1007/978-0-85729-372-5_26.

Sheikh, J. I., & Yesavage, J. A. (1986). Geriatric depression scale (GDS): Recent evidence and development of a shorter version. In T. L. Brink (Ed.). *Clinical gerontology: A guide to assessment and intervention* (pp. 165–173). New York, NY: The Haworth Press.

Smarr, C.-A., Prakash, A., Beer, J. M., Mitzner, T. L., Kemp, C. C., & Rogers, W. A. (2012). *Older adults' preferences for and acceptance of robot assistance for everyday living tasks. Proceedings of the human factors and ergonomics society … annual meeting. human factors and ergonomics society. annual meeting, 56*, 153–157 10.1177%2F1071181312561009.

Smarr, C. A., Mitzner, T. L., Beer, J. M., Prakash, A., Chen, T. L., Kemp, C. C., et al. (2014). Domestic robots for older adults: Attitudes, preferences, and potential. *International Journal of Social Robotics, 6*, 229–247. https://doi.org/10.1007/s12369-013-0220-0.

Snider, S. E., Quisenberry, A. J., & Bickel, W. K. (2016). Order in the absence of an effect: Identifying rate-dependent relationships. In: *Behavioural Processes, 127*, 18–24. https://doi.org/10.1016/j.beproc.2016.03.012.

Stafford, R. Q., MacDonald, B. A., Jayawardena, C., Wegner, D. M., & Broadbent, E. (2014). Does the robot have a mind? Mind perception and attitudes towards robots predict use of an eldercare robot. *International Journal of Social Robotics, 6*, 17–32. https://doi.org/10.1007/s12369-013-0186-y.

Tacken, M., Marcellini, F., Mollenkopf, H., Ruoppila, I., & Széman, Z. (2005). Use and acceptance of new technology by older people. Findings of the international mobilate survey: 'Enhancing mobility in later life'. *Gerontechnology, 3*, 126–137. https://doi.org/10.4017/gt.2005.03.03.002.00.

van Halteren-van Tilborg, I. A., Scherder, E. J., & Hulstijn, W. (2007). Motor-skill learning in Alzheimer's disease: A review with an eye to the clinical practice. *Neuropsychology Review, 17*, 203–212. https://doi.org/10.1007/s11065-007-9030-1.

Vanbellingen, T., Kersten, B., Van Hemelrijk, B., Van de Winckel, A., Bertschi, M., Muri, R., et al. (2010). Comprehensive assessment of gesture production: A new test of upper limb apraxia (tulia). *European Journal of Neurology, 17*, 59–66. https://doi.org/10.1111/j.1468-1331.2009.02741.x.

Veronese, N., Bolzetta, F., Toffanello, E. D., Zambon, S., De Rui, M., Perissinotto, E., et al. (2014). Association between short physical performance battery and falls in older people: The Progetto Veneto Anziani study. *Rejuvenation Research, 17*, 276–284. https://doi.org/10.1089/rej.2013.1491.

Voelcker-Rehage, C., & Willimczik, K. (2006). Motor plasticity in a juggling task in older adults: A developmental study. *Age and Ageing, 35*, 422–427. https://doi.org/10.1093/ageing/afl025.

Wang, H., Kläser, A., Schmid, C., & Liu, C. (2011). Action recognition by dense trajectories. *CVPR,* 3169–3176. https://doi.org/10.1109/CVPR.2011.5995407.

Werle, J., & Hauer, K. (2016). Design of a bath robot system — User definition and user requirements based on international classification of functioning, disability and health (ICF). *2016 25th IEEE international symposium on robot and human interactive communication (RO-MAN),* 459–466. https://doi.org/10.1109/ROMAN.2016.7745159.

Werner, C., Ullrich, P., Geravand, M., Peer, A., & Hauer, K. (2016). Evaluation studies of robotic rollators by the user perspective: A systematic review. *Gerontology, 62*, 644–653. https://doi.org/10.1159/000444878.

Werner, C., Wiloth, S., Lemke, N. C., Kronbach, F., Jansen, C. P., Oster, P., et al. (2017). People with dementia can learn compensatory movement maneuvers for the sit-to-stand task: A randomized controlled trial. *Journal of Alzheimer's Disease, 60*, 107–120. https://doi.org/10.3233/JAD-170258.

Wiener, J. M., Hanley, R. J., Clark, R., & Van Nostrand, J. F. (1990). Measuring the activities of daily living: Comparisons across national surveys. *Journal of Gerontology, 45*, S229–237. https://doi.org/10.1093/geronj/45.6.S229.

Wu, Y. H., Wrobel, J., Cornuet, M., Kerherve, H., Damnee, S., & Rigaud, A. S. (2014). Acceptance of an assistive robot in older adults: A mixed-method study of human-robot interaction over a 1-month period in the living lab setting. *Clinical Interventions in Aging, 9*, 801–811. https://doi.org/10.2147/CIA.S56435.

Yamada, K., Yoshida, T., Sumi, K., Habe, H., & Mitsugami, I. (2017). Spatial and temporal segmented dense trajectories for gesture recognition. *SPIE*. https://doi.org/10.1117/12.2266859.

Yang, Y., & Lee, L. C. (2010). Dynamics and heterogeneity in the process of human frailty and aging: Evidence from the U.S. older adult population. *The Journals of Gerontology Series B, Psychological Sciences and Social Sciences, 65B*, 246–255. https://doi.org/10.1093/geronb/gbp102.

Zafrani, O., & Nimrod, G. (2018). Towards a holistic approach to studying human–robot interaction in later life. *The Gerontologist, 59*, e26–e36. https://doi.org/10.1093/geront/gny077.

Zhang, J., Marszałek, M., Lazebnik, S., & Schmid, C. (2007). Local features and kernels for classification of texture and object categories: A comprehensive study. *International Journal of Computer Vision, 73*, 213–238. https://doi.org/10.1007/s11263-006-9794-4.

Zlatintsi, A., Rodomagoulakis, I., Koutras, P., Dometios, A. C., Pitsikalis, V., Tzafestas, C. S., et al. (2018). Multimodal signal processing and learning aspects of human-robot interaction for an assistive bathing robot. *2018 IEEE international conference on acoustics, speech and signal processing (ICASSP),* 3171–3175.