Doctoral thesis submitted to
the Faculty of Behavioural and Cultural Studies
Heidelberg University
in partial fulfillment of the requirements of the degree of
Doctor of Philosophy (Dr. phil.)
in Sport Science

Title of the publication-based thesis

Investigating gait characteristics and dynamic stability during challenging walking

presented by
Forough Madehkhaksar

year of submission
2018

Dean: Prof. Dr. Dirk Hagemann
Advisor: Dr. Michael Schwenk
Prof. Dr. Clemens Becker

Dedication

To my parents

By the unconditional love and support.

Acknowledgments

I would like to thank Dr. Michael Schwenk who offered me this chance to complete my Ph.D. degree at Heidelberg University. I would also like to especially thank Prof. Becker and Dr. Karin Srulijes for their encouragement and support. I could never complete my thesis without access to their data and the lab.

I would like to especially thank Prof. Meusburger, whose memory is always alive in my heart, and all staff from Heidelberg University Graduate Academy for their valuable support during my hard times.

I would like to acknowledge members of the research group at the Department of Clinical Gerontology and Rehabilitation of Robert-Bosch hospital in Stuttgart, especially Dr. Jochen Klenk and Kim Sczuka for their feedback, data, collaboration, encouragement, and support. I would also like to thank Katharina Gordt, who was my best officemate ever, for her collaboration.

Last but not least, I would like to thank my family (my parents, Peyman, and Nadia) and my friends for their unconditional love and emotional support. I would also like to thank Dorothee, Malou, and Kreutzer family who never let me alone by their emotional support when I was far away from my family.

Table of Contents

Attachments: Manuscripts for the publication-based dissertation

Abstract

Fall is a leading cause of injuries in older adults, which mostly occurs during walking and under a challenging condition. Examples of challenging conditions are an unexpected perturbed walking, stair walking, or walking while positional transitions. A better understanding of postural control to maintain balance during similar tasks can help in reducing the risk of fall. For this aim, one approach is to examine the effects of the challenged walking on gait stability.

This dissertation consists of three studies focusing on postural responses under four different challenging circumstances including 1) walking while performing a manual and a cognitive secondary task, 2) stair walking at different inclinations (i.e. different levels of complexity), 3) sudden mechanically perturbed walking, and 4) gaze-shift walking. Firstly, the postural responses of healthy adults under the mentioned conditions were assessed. Secondly, different representative measures in order to quantify balance during perturbed walking were evaluated. Thirdly, the postural responses of young and old healthy adults during walking while gaze-shifting in terms of gait parameters and their variability were contrasted.

The first study examined how secondary cognitive and manual tasks interfere with stair gait when a person concurrently performed tasks at different levels of complexity. Gait kinematic data and secondary task performance measures were obtained from fifteen healthy young males while ascending and descending a four-step staircase at three inclinations (17.7°, 29.4°, and 41.5°) as well as level walking. They performed a cognitive task, ‘backward digit recall’, a manual task, ‘carrying a cup of water’ and a combination of the two tasks. Gait performance and dynamic stability were assessed by gait speed and whole body center of mass (CoM) range of motion in the medial-lateral direction, respectively. No significant effect of the gait task on the cognitive task performance was observed. In contrast, stair walking adversely affected the performance of the manual task compared to level walking. Overall, more difficult postural and secondary tasks resulted in a decrease in gait speed and variation in CoM displacement within a normal range. Results suggest that CoM displacement and gait alterations might be adopted to enhance the stability, and optimize the secondary task performance while walking under challenging circumstances. The findings of this study are useful for balance and gait evaluation, and for future falls prediction.

The second study examined changes in spatiotemporal gait and stability parameters in response to sudden mechanical perturbations in mediolateral (ML) and anterior-posterior (AP) direction during treadmill walking. Moreover, the most representative parameters to quantify postural recovery responses were evaluated. Ten healthy adults (mean=26.4, SD=4.1 years) walked on a treadmill that provided unexpected discrete ML and AP surface horizontal perturbations. Participants walked under no perturbation (normal walking), and under left, right, forward, and backward sudden mechanical perturbation conditions. Gait parameters were computed including stride length (SL), step width (SW), and cadence, as well as dynamic stability in AP- (MoS-AP) and ML- (MoS-ML) directions. Gait and stability parameters were quantified by means, variability, and extreme values. Overall, participants walked with a shorter stride length, a wider step width, and a higher cadence during perturbed walking, but despite this, the effect of perturbations on means of SW and MoS-ML was not statistically significant. These effects were found to be significantly greater when the perturbations were applied toward the ML-direction. Variabilities, as well as extremes of gait-related parameters, showed strong responses to the perturbations. The higher variability as a response to perturbations might be an indicator of instability and fall risk, on the same note, an adaptation strategy and beneficial to recover balance. Parameters identified in this study may represent useful indicators of locomotor adaptation to successfully compensate sudden mechanical perturbation during walking.

The third study was aimed to determine the gait characteristics of healthy young and older adults during gaze-shifting while treadmill-walking. Eleven young (age: 25 ± 4.5 years, 3 females) and 13 older (age: 72 ± 3.9 years, 6 females) adults performed normal treadmill-walking (no visual-triggers) and then treadmill-walking while rapidly gaze-shifting to randomly presented visual-triggers. A multilevel linear regression model was used to assess changes in a set of gait parameters between subject groups and walking conditions: normal walking, one gait cycle before (Pre-Cycle), and after (Post-Cycle) each triggering during gaze-shift walking. Comparing Pre-Cycle to normal walking, young adults showed no instability-related changes in their gait but older adults showed a more cautious gait with shorter step length (Est. = -1.59cm [95% CI: -2.2cm; -0.9cm]), reduced step width (Est. = -0.8cm [95% CI: -1.1cm; -0.6cm]), increased step frequency (Est. = 0.04 1/s [95% CI: 0.03 1/s; 0.05 1/s]), decreased maximum toe clearance (Est. = -0.3cm [95% CI: -0.4cm; -0.2cm]), and 30% higher minimum toe clearance variability. During Post-Cycle compared to Pre-Cycle, direct effects of gaze-shifts on gait parameters were significant but rather small. This experiment shows an influence of gaze-shifts on gait in both groups, although, the effect is larger in the older which might therefore need more compensation compared to the young adults. Present insights may facilitate the development of specific training paradigms to improve the oculomotor-locomotor interaction.

List of publications

This doctoral dissertation is based on the following original journal papers:

1) **Madehkhaksar, F.**, & Egges, A. (2016). Effect of dual task type on gait and dynamic stability during stair negotiation at different inclinations. *Gait & posture, 43*, 114-119.

2) **Madehkhaksar, F.**, Klenk, J., Sczuka, K., Gordt, K., Melzer, I., & Schwenk, M. (2018). The effects of unexpected mechanical perturbations during treadmill walking on spatiotemporal gait parameters, and the dynamic stability measures by which to quantify postural response. *PLoS One, 13*(4), e0195902.

3) **Madehkhaksar, F**., Klenk, J., Schwenk, M., Mack, D.J., L. Schwickert, Lindemann, U., Meyer, M., Srijana, K.C., Pomper, J.K., Synofzik, M., Ilg, U., Kerse, N., Maetzler, W., Becker, C., & Srulijes, K. (2018, submitted). Effect of gaze-shifting on gait characteristics during treadmill walking in healthy young and old adults. *Journal of Biomechanics.*

List of main abbreviations

AP: Anterior-posterior

BDR: Backward digit recall

BoS: Base of support

CCW: Carrying a cup of water

CI: Confidence interval

HGQ: high gait quality

LED: Light emitting diodes

LGQ: Low gait quality

Max-TC: Maximum toe clearance

Min-TC: Minimum toe clearance

ML: Mediolateral

MoCA: Montreal cognitive assessment

MoS: Margins of stability

P10: 10th percentile

P90: 90th Percentile

Post-Cycle: The gait cycle after visual triggering

Pre-Cycle: The gait cycle before visual triggering

SD: Standard deviation

SF: Step frequency

SL: Stride length

SW: Step width

X-CoM: Extrapolated center of mass

List of Figures

List of Equations

1. Introduction

1.1. General introduction

Fall is a leading cause of injuries in older adults, affecting approximately one-third of adults over the age of 65 years (Hausdorff, Rios, & Edelberg, 2001), which can result in morbidity, reduced the functional ability and even death (Prince, Corriveau, Hébert, & Winter, 1997). Most falls occur during walking (Berg, Alessio, Mills, & Tong, 1997) and following an unexpected perturbation such as slip or trip (Maki et al., 2008), during stair walking (Startzell, Owens, Mulfinger, & Cavanagh, 2000; Stel, Smit, Pluijm, & Lips, 2004), or during positional transitions, such as turning around or bending over (Cumming & Klineberg, 1994). Therefore, a better understanding of postural control to maintain balance and the effect of aging on these mechanisms during similar tasks is needed.

During gait, falls occur as a result of a complex interaction between numerous environmental hazards (e.g. uneven surface) and individual factors and sources (e.g., neuromuscular decline due to aging). Thus, the probability of falling depends not only on the individual's neuro-musculoskeletal capacity but also on external factors such as the type of challenge encountered in daily life.

One approach to obtaining a better understanding of postural responses under challenging circumstances is to examine the effects of the challenge on gait stability. There have been a variety of measures to quantify postural responses in these cases. Some studies investigated gait adaptation in terms of changes in spatiotemporal gait parameters and their variability to examine whether these responses could serve the purpose of decreasing the risk of fall (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005; Brach, Studenski, Perera, VanSwearingen, & Newman, 2008; Hak, Houdijk, Beek, & van Dieen, 2013; Hak et al., 2012; Maki, 1997). Also, several studies have investigated the effects of these changes on reducing fall risk by examining their effects on gait stability (Brady, Peters, & Bloomberg, 2009; J. Dingwell, Cusumano, Cavanagh, & Sternad, 2001; J. B. Dingwell, Robb, Troy, & Grabiner, 2008; England & Granata, 2007; Francis, Franz, O'Connor, & Thelen, 2015; Kao, Higginson, Seymour, Kamerdze, & Higginson, 2015; McAndrew, Dingwell, & Wilken, 2010; Süptitz, Catalá, Brüggemann, & Karamanidis, 2013). There are several methods to assess dynamic stability. In the literature, the margins of stability, which is a measure of stability based on the dynamical model of human movement, has been used to provide information on gait stability (Hak et al., 2013; A. Hof, Gazendam, & Sinke, 2005; A. L. Hof, 2008; Süptitz et al., 2013; Young, Wilken, & Dingwell, 2012).

This dissertation uses the most common measures to quantify postural responses including changes in spatiotemporal gait parameters and their variability, trunk movement, and margins of stability. Hence, a brief description of each method is presented. Then, a brief review of challenging walking conditions which were studied in this thesis are presented.

Gait parameters

Spatiotemporal gait parameters that can be measured with simple instrumentations provide valuable information for identifying individuals at a risk of falling. Figure 1 schematically illustrates spatiotemporal gait parameters. Spatial parameters are step length and step width, while temporal parameters include cadence, step frequency, stride time, swing, and double support time. Minimum toe clearance (Min-TC) is also a gait parameter which is a critical event in gait as the foot travels with maximum horizontal velocity around this instant. Figure 2 shows toe clearance during the swing phase of a gait cycle. A low Min-TC combined with high variability of Min-TC can potentially cause tripping during walking (Begg, Best, Dell'Oro, & Taylor, 2007).

Gait parameters have been extensively used to characterize gait between different subjects groups and during different walking conditions (Tay et al., 2016). Previous studies demonstrated adaptations of spatiotemporal gait parameters to challenged walking by taking faster, shorter, and wider steps (Hak et al., 2013; Hak et al., 2012; McAndrew et al., 2010; Stokes, Thompson, & Franz, 2017; Tay et al., 2016). Also, elevating MTC or reducing MTC variability is reported as an adaptation to reduce tripping risk (Begg et al., 2007).

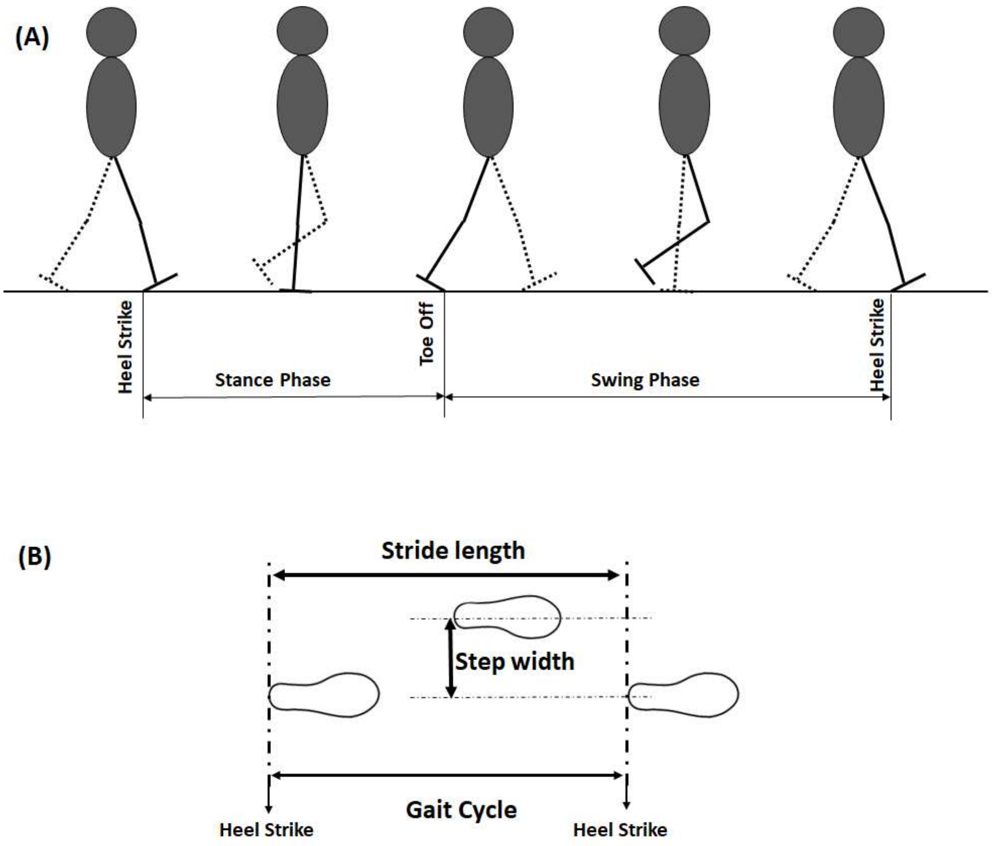

Figure 1. Schematic illustration of (A) temporal and (B) spatial gait parameters.

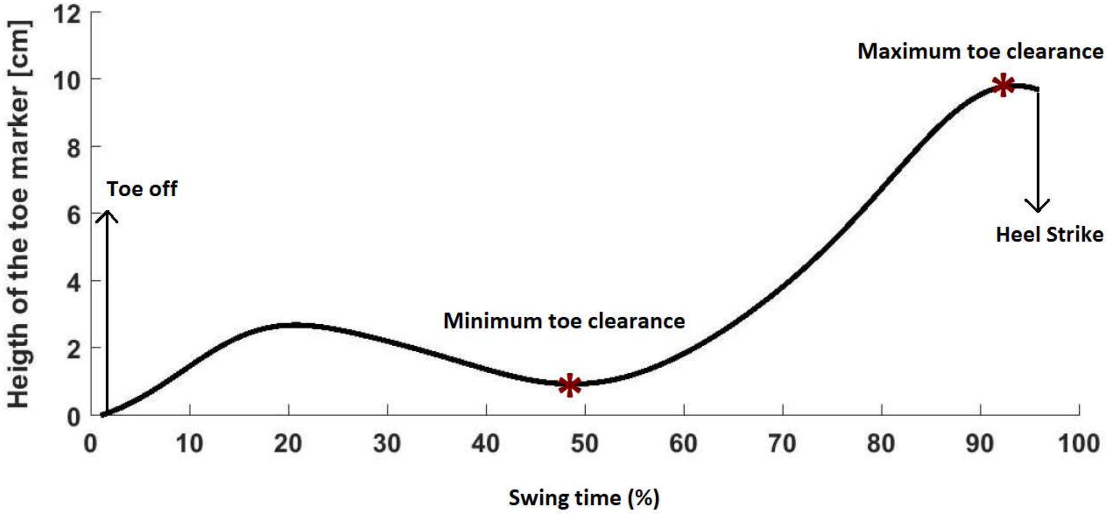

Figure 2. Toe clearance which is defined as the vertical position of toe during the swing phase of a gait cycle.

Gait variability

Variability, defined as the variance of a gait parameter around the mean, is an important indicator to quantify unstable gait patterns (Heiderscheit, 2000). In fact, gait variability is fluctuation in gait characteristics from one step to the next and a broad range of variability measures has been reported in the literature (Brach et al., 2005; J. Dingwell et al., 2001; Hausdorff, 2007; Hausdorff et al., 2001; Maki, 1997; Toebes, Hoozemans, Furrer, Dekker, & van Dieën, 2012). Generally, increased gait variability is associated with increased the risk of fall (Heiderscheit, 2000; Toebes et al., 2012), therefore, it has been used as an indicator of impaired mobility in older adults (Brach et al., 2008).

In this dissertation, variability is referred to the amount of variability of a specific parameter over gait cycles during walking. Variability of specific parameters includes variability of spatiotemporal gait parameters such as stride length, step width, and cadence.

Variability measures are often based on the standard deviation of a gait parameter. There are two major methods to calculate gait variability depending on the type of the gait parameter (i.e., discrete gait parameters or continuous gait parameters). For discrete gait parameters such as step width and cadence, the variability is usually calculated as the standard deviation over the entire data series of the values (Francis et al., 2015; McAndrew et al., 2010; Young et al., 2012). For continuous gait parameters such as acceleration time series, every stride is first time normalized (0-100%) (J. Dingwell et al., 2001; J. B. Dingwell et al., 2008; Toebes et al., 2012). The variability is then calculated as the standard deviation for each normalized time interval. The mean or sum of standard deviation over these 101 values is often used for further analyses. In this method, variability is usually calculated on velocity or acceleration time series, as it is important that data are stationary.

Trunk Movement

Maintaining the dynamic stability during gait relies on the ability to control CoM motion. Thus, measurement of CoM range of motion (RoM) is useful to provide a more accurate description of body movement in different planes and also provides insight into dynamic balance control mechanism during gait.

Particularly, increasing changes of CoM motions in mediolateral (ML) direction (i.e. ML-RoM) which is defined as the maximum minus minimum value achieved during the crossing stride has been used as an indicator for risk of fall. ML-RoM changes, which are thought to possibly be due to a reduced ability to confine the CoM within a more stable region, has been used to detect gait instability during stair negotiation (Mian, Narici, Minetti, & Baltzopoulos, 2007), obstacle crossing (Chou, Kaufman, Brey, & Draganich, 2001; Chou, Kaufman, Hahn, & Brey, 2003), and following impairments (Catena, Van Donkelaar, & Chou, 2007).

Margins of stability

Human standing is often biomechanically modeled using the inverted pendulum model as a simple mechanical system. In this model, stability is maintained as long as the projection of the center of mass (CoM) falls within the horizontal boundaries of the base of support (BoS). However, this simple model cannot be applied to walking, as walking is not static. Thus, this model needs to be extended to take the velocity of the CoM and BoS into account.

The margins of stability (MoS) proposed by Hof (A. Hof et al., 2005) is a stability measure that addresses this limitation and can appropriately be applied to dynamic tasks like walking.

The MoS is defined as the distance between the extrapolated center of mass (XCoM) and the border of the BoS at any instant in time. The XCoM which is a velocity adjusted position of the CoM extends the classical condition for static equilibrium for an inverted pendulum, in which the CoM must be positioned over the BoS by adding a linear function of the CoM to the CoM positions.

In order to calculate the MoS, first, the position of the whole body CoM and BoS need to be known. Then, XCoM is defined as:

$$\mathrm{XCoM} = \mathrm{CoM} + \left((V_{CoM})/\omega_0\right), \tag{1}$$

where CoM is the CoM location, V_{CoM} is the CoM velocity, and ω_0 is the inverted pendulum's eigenfrequency which is calculated as:

$$\omega_0 = \sqrt{{}^{g}/_{l}}\,, \tag{2}$$

where *g* is the acceleration of gravity and *l* is the pendulum length of the subject (i.e. leg length).

Finally, the MoS is defined as:

$$\text{MoS} = \text{BoS} - \text{XCoM}\ , \tag{3}$$

where BoS is the location of the boundary of the base of support. Figure 3 schematically illustrates MoS.

The concept of the MoS can be applied to both anteroposterior (AP) and mediolateral (ML) directions. If the XCoM is within the boundaries of the BoS (i.e. positive MoS), an individual is considered stable. This definition suggests that foot placement can be used to control MoS magnitude during walking (A. Hof et al., 2005; A. L. Hof, 2008). Thus, one potential goal of walking may be to maintain some minimum MoS. An individual can adjust the size of his BoS by making his steps wider or narrower, and longer or shorter depending on the motion of his CoM.

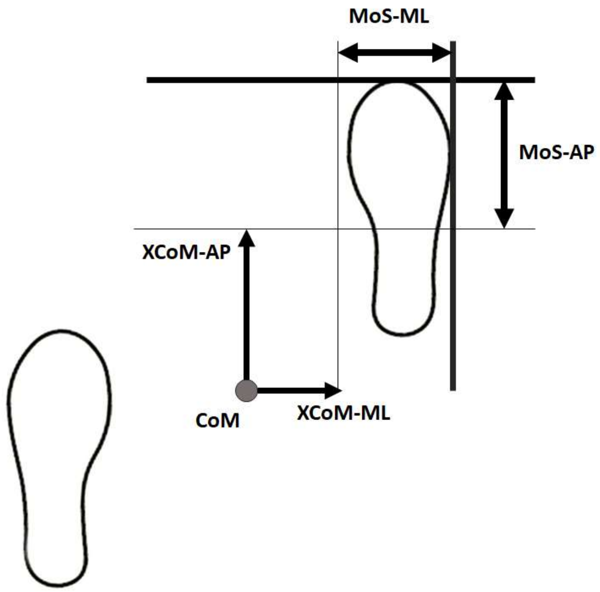

Figure 3. Schematic illustration of MoS in ML and AP directions which is defined as the distance between borders of the BoS and XCoM in corresponding directions.

Mean of MoS is often used to demonstrate stability in different experimental conditions. However, there are some studies that additionally examined the variability of MoS, suggesting that mean of MoS cannot reflect the effect of fluctuations in the protective foot stepping because it only quantifies an individual's overall, average stability over an entire series of steps (Young & Dingwell, 2012; Young et al., 2012).

1.2. Literature review

Balance control during walking involves a coordinated adjustment in posture by stabilization of the head and trunk, as well as foot placement from step to step. During walking, the control of trunk movement plays an important role in providing a stable platform for vision and head control (Winter, 1995). Particularly in unpredictable and challenging environmental conditions, these adjustments depend on the integration of reliable sensory feedback and the planning and execution of appropriate postural responses. In daily life, people frequently encounter challenging conditions that require proper postural responses in order to maintain balance. Accordingly, the number of studies that address mechanisms underlying balance control under challenging circumstances are increasing. Examples of these challenges are stair walking, dual task walking, mechanical and sensory perturbations during walking, as well as the execution of tasks which affect stabilization of the head such as gaze-shifting.

Results of previous studies suggest an alteration in gait parameters under challenging conditions. It has been suggested that there is a relation between changing gait characteristic and stability, and the aim of this changes is increasing stability and decreasing the probability of falling (Hak et al., 2013; Hak et al., 2012; Young & Dingwell, 2012).

In general, healthy adults adapt their stable gait by reducing walking speed, shortening step length, and increasing step width. Also, the variability of a number of parameters has been reported to increase during challenging conditions (Francis et al., 2015; Hak et al., 2012; Stokes et al., 2017). However, most of the previous studies resulted in inconsistent findings, suggesting that changes in gait parameters and their variabilities, as well as stability measures depend on the type of the challenge under which the walking is being performed.

In addition, the role of variability and different stability measures during different tasks and walking conditions seem contradictory and not yet well understood. High gait variability is suggested as a good predictor of the risk of fall (Toebes et al., 2012). However, under challenging circumstances such as responding to perturbations, increased variability might also result directly from the challenging condition such as perturbations. In this case, increased variability is a sign of adaptability as a proper response and does not necessarily imply destabilization of the system (Bruijn, Bregman, Meijer, Beek, & van Dieën, 2012; McAndrew et al., 2010). Therefore, there is a need to clearly understand how different specific challenging environments affect gait variability and stability to be able to contrast the proper with the improper response.

Moreover, increased age often brings reductions in the stability of the head (Cinelli, Patla, & Stuart, 2008; C. Paquette, Paquet, & Fung, 2006), sensory acuity (Li & Lindenberger, 2002), muscle strength (Goodpaster et al., 2006), and cognitive capacity (Li & Lindenberger, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008), as well as slowed neuromuscular function (Vandervoort, 2002) and diminished executive function (Yogev-Seligmann et al., 2008). Consequently, aging affects the ability to maintain balance and it is more profound under challenging conditions (C. Paquette et al., 2006). Older adults seem to adopt a more conservative walking pattern characterized by a slower walking velocity, shorter and wider steps, greater base of support, prolonged double support phase, and more variable gait step characteristics (Lord & Dayhew, 2001; Maki, 1997). It is generally assumed that these changes lead to an increased instability during walking and may predict the increased risk of falling (Lord & Dayhew, 2001; Maki, 1997). There is a critical need to conduct studies that address physiological changes associated with aging under challenging conditions in order to truly reduce the risk of falling. To this aim, normal healthy responses of young adults need to be examined. Then, the responses of older adults under the same condition should be examined and compared with normal responses in order to observe age-related differences in used adaptive responses.

The task-dependence of postural responses needs to be taken into account in order to obtain a better insight into proper postural responses. Investigating balance and postural responses under different challenging conditions that people may encounter frequently in daily life may be helpful in better understanding of mechanisms underlying postural responses and the risk of fall under specific conditions.

Walking while dual-tasking is a challenging condition that people experience in daily life. Previous studies suggest that the control of balance requires attentional resources, and challenging attention-splitting conditions (i.e. dual-tasking) strongly affect stability (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). Two different types of secondary tasks, a cognitive task and a manual task, have been used in dual-task studies (Asai, Misu, Doi, Yamada, & Ando, 2014; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). It has been reported that undertaking a secondary cognitive task adversely affects gait depending on the task complexity, the population studied and the instruction given regarding attention prioritization (Kelly, Janke, & Shumway-Cook, 2010; Patel, Lamar, & Bhatt, 2014; Simoni et al., 2013; Woollacott & Shumway-Cook, 2002). Performing a cognitive task affected gait patterns and trunk movements by reducing gait speed, increasing gait variability, and increasing fluctuation of trunk movements (Asai et al., 2014; Yogev-Seligmann et al., 2008). However, a manual task, like carrying an object, is used less often than a cognitive task in dual-task studies (Asai et al., 2014; de Lima, de Azevedo Neto, & Teixeira, 2010; Yogev-Seligmann et al., 2008). Some studies reported that a manual task, similarly to a cognitive task, adversely affects gait performance (Yogev-Seligmann et al., 2008). However, in another study, Asai et al. (Asai et al., 2014) showed that performing a cognitive task during walking increased lower trunk oscillations in ML direction, whereas, performing a manual task decreased trunk oscillations in the ML and AP directions. In this case, a secondary manual task may lead to extra stabilization rather than perturbation of posture (Asai et al., 2014; de Lima et al., 2010). Therefore, there is a need to investigate the effect of different types of secondary tasks on gait and stability, since the results of previous studies seem contradictory.

As another challenging walking condition, stair gait is among the most challenging and hazardous types of locomotion, and one of the leading cause of fall-related injuries for the aged population (Startzell et al., 2000; Stel et al., 2004). Stair walking involves greater peak joint moments for ankle and knee joints compared with level walking (Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008, 2009; Riener, Rabuffetti, & Frigo, 2002). Furthermore, previous studies showed that gait parameters vary based on stair inclination (Riener et al., 2002; Stacoff, Diezi, Luder, Stüssi, & Kramers-de Quervain, 2005) suggesting different levels of complexity of stair gait at different inclinations. These findings show a higher challenge during walking on a stair at steeper inclinations.

The risk of fall during stair walking further increases when people perform tasks like reasoning or carrying an object concurrently (Ojha, Kern, Lin, & Winstein, 2009; Vallabhajosula, Tan, Mukherjee, Davidson, & Stergiou, 2015). There is little information about dual-tasking during stair walking. Ojha et al. (Ojha et al., 2009) compared the attentional demands of ascending and descending a set of stairs in older and younger adults. They demonstrated that although both older and younger adults required similar attentional resources for the standing task, older adults required significantly more resources while performing stair gait concurrently with a verbal task. In another study, Vallabhajosula et al. (Vallabhajosula et al., 2015) showed that the impact of performing a cognitive or manual task during stair ascent varies based on the stair ascent phase and seem to have greater impact as one climbs higher. Also, they reported that the association between gait and secondary task performance becomes stronger as the level of complexity of the motor task increases. Their study did not include stair descent. However, stair descent is also important to be taken into account, since it has been reported as the most hazardous aspect of stair gait (Startzell et al., 2000). Although in daily life, people regularly encounter stairs at varying inclinations and concurrently perform additional tasks, there is a lack of study on the effect of different types of secondary tasks during such complex gait condition.

Mechanical and sensory perturbations during walking are another walking condition with high risk of fall that people frequently encounter in daily life. In the literature, there are several studies that investigated postural responses following different types of perturbations such as sudden mechanical perturbations (Süptitz et al., 2013), visual perturbations (Francis et al., 2015; O'Connor & Kuo, 2009; Stokes et al., 2017), continuous support surface perturbations (Brady et al., 2009; Hak et al., 2012), and combinations of visual and support surface perturbations (McAndrew et al., 2010). Their findings demonstrate that each of these perturbations affects gait and stability in different ways, depending not only on the individual characteristics of the subject group and the type of the perturbation but also on the direction of the perturbations (Brady et al., 2009; Kuo, 1999; McAndrew et al., 2010; O'Connor & Kuo, 2009). Studies on the effect of continuous support surface perturbation (McAndrew et al., 2010) and visual field perturbation (O'Connor & Kuo, 2009) in both AP and ML directions show anisotropic changes in gait variabilities. Despite that perturbations in the real world are multidirectional and always unexpected, there is a lack of information on the effects of sudden multidirectional mechanical perturbation on gait-related parameters and dynamic stability.

As another challenging walking condition, walking while gaze shifting is also a common activity in daily life. Gaze is the direction of sight within the world frame of reference. With a gaze shift the world object’s image coordinates on the retina change within the retinal frame of reference. Shifting gaze during walking in a natural environment is performed constantly (e.g. observing surrounding or to scan the pathway for obstacles) and may lead to alterations in gait and increased fall risk, especially in older adults (Cinelli et al., 2008). Previous studies examined adaptive strategies during performing tasks that are accompanied with destabilization of the head, such as, during a visually guided change in travel direction

(Hollands, Sorensen, & Patla, 2001), in stepping performance during removal of vision (Chapman & Hollands, 2006), or to avoid an obstacle (M. R. Paquette & Vallis, 2010). However, there are a limited number of studies on adaptive strategies during walking while gaze-shifting. Their findings suggest different strategies in coordinating body during this task between young and old adults. Old adults minimize the amount and the velocity of head and body rotation to minimize postural perturbations associated with this task (C. Paquette et al., 2006). Variability in the shoulder and hip rotation magnitudes are greater in older adults during gaze-shifting walking (Cinelli, Patla, & Stuart, 2007; Cinelli et al., 2008). However, these studies did not include the effect of gaze-shifting on gait characteristics. Despite the highly ecological validity of walking while gaze-shifting in daily life, there is a lack of information on adaptive responses in terms of changes in gait parameters and gait variability during this task.

2. Objectives

This dissertation consists of a collection of three studies which are already published or submitted. These studies focus on postural responses under four different challenging circumstances including 1) walking while performing a manual and a cognitive secondary task, 2) stair walking at different inclinations (i.e. different levels of complexity), 3) sudden mechanically perturbed walking, and 4) gaze-shift walking. Hence, the first aim was to assess the postural responses of healthy adults under mentioned conditions. The second aim was to evaluate different representative measures in order to quantify balance during perturbed walking. The third aim was to contrast the postural responses of young and old healthy adults during walking while gaze-shifting in terms of gait parameters and their variability.

Manuscript 1

Investigating the effect dual-task type and inclination of stair on gait and dual-task performance during stair walking.

This study examined how secondary cognitive and manual tasks interfere with stair gait at different inclinations when a person concurrently performed tasks at different levels of complexity.

Manuscript 2

Investigating the effect of unexpected multidirectional mechanical perturbations on gait characteristics and dynamic stability during treadmill walking in healthy young adults.

The first aim of this study was to examine the postural responses of healthy young adults to unexpected multidirectional mechanical perturbations during treadmill walking. The second aim was to evaluate the most affected parameters for measuring the effect of unexpected mechanical perturbations on postural adaptation.

Manuscript 3

Investigating the effect of gaze-shifting during treadmill walking on gait characteristics in healthy younger and older adults.

The aim of this study was to determine the gait characteristics and their variabilities as an adaptive strategy used by healthy young and old individuals during walking while gaze-shifting. In addition, the adaptive strategy used by young and old individuals was compared in order to examine the age-related changes in gait pattern corresponding to the task. To this aim, a part of the experiment which is given by Srulijes et al. (Srulijes et al., 2015) has been used in this study.

3. Overview of publications and findings

3.1. Manuscript 1

Effect of Dual Task Type on Gait and Dynamic Stability during Stair Negotiation at Different Inclinations

Madehkhaksar, F., & Egges, A. (2016). Effect of dual task type on gait and dynamic stability during stair negotiation at different inclinations. *Gait & posture, 43*, 114-119.

DOI: https://doi.org/10.1016/j.gaitpost.2015.09.009

Background and objectives

Stair gait is among the most challenging and hazardous types of locomotion, and one of the leading causes of fall-related injuries for the aged population. The risk of fall further increases when people perform tasks like reasoning or carrying an object concurrently with stair gait.

Previous studies have reported that undertaking a secondary cognitive task adversely affects gait depending on the task complexity, the population studied and the instruction given regarding attention prioritization (Kelly et al., 2010; Patel et al., 2014; Simoni et al., 2013). However, a manual task, like carrying an object, is used less often in dual-task studies and reported results are contradictory.

In addition, despite that people regularly encounter stairs at varying inclinations and concurrently perform additional tasks in daily life, little is understood about dual-tasking during stair gait. Previous studies showed gait and secondary task performance are more strongly associated if the gait task is more challenging (Vallabhajosula et al., 2015). On the other hand, gait parameters vary based on stair inclination suggesting different levels of complexity of stair gait at different inclinations (Riener et al., 2002; Stacoff et al., 2005). Therefore, there was a need to investigate the manual and cognitive dual-task performance during a complex gait task such as stair gait at different inclinations.

In this study, the interference of gait task and secondary cognitive and manual task during stair gait at different inclinations was investigated. The aim was to examine postural responses of healthy adults when they performed the gait task and the secondary tasks at different levels of complexity of both tasks.

Methods

Fifteen healthy males (age: 28.5 ± 3.7 years, height: 1.8 ± 0.07 m, mass: 74.6 ± 7.5 kg) participated in this study. Participants ascended and descended an adjustable four-step staircase at three different inclinations: flat, standard, and steep (17.7°, 29.4°, and 41.5°, respectively). They also performed level walking trials, in which they walked straight ahead covering the same distance as in the stair walking trials. They performed a cognitive task, 'backward digit recall' (BDR), a manual task, 'carrying a cup of water' (CCW) and a combination of the two tasks (BDR&CCW) concurrently with the gait task. In BDR, the experimenter read out a sequence of three digit random numbers, and the participants were required to repeat the numbers in reverse order in time to the beat. In CCW, participants were required to carry a cup of water in their dominant hand while trying to keep it vertical. Also, there was a baseline (single gait task) in which no secondary task was performed. Each participant performed three stair walks as well as level walking under each testing condition. Kinematic data was recorded using a 14-camera Vicon motion capturing system. A total of 35 reflective markers were placed at anatomical locations in accordance with the Plug-In-Gait marker set.

Gait performance and dynamic stability were assessed by gait speed and the whole body center of mass range of motion in the medial-lateral direction (ML-RoM), respectively. The performance of BDR was quantified by the ratio between the number of correct recalls and the total number of three-digit numbers presented in each trial. The performance of CCW was quantified by measuring the ratio of deviation of the cup in the vertical direction.

Main findings

1) The gait task had no effect on the cognitive task performance. In contrast, the manual task performance was affected by gait task complexity. This observation suggests that motor control tasks have a direct effect on a secondary manual task since the resources for the

postural control and the manual task performance are both within the motor control system. Performing a manual and cognitive task concurrently had no effect on the secondary task performance.

2) During stair gait, a significant gait speed decrease was observed compared to level walking. In addition, gait speed decreased with stair steepness. On the other hand, ML-RoM showed an increase during descent. Stair ascent was more challenging than stair descent and level walking, which was shown by slower gait speed and higher ML-RoM. However, ML-RoM was not significantly affected when ascending the steeper stair, which may represent a successful effort to avoid imbalance. Specifically, more caution was taken when stepping on a steeper stair.

3) The type and complexity of the secondary task altered gait performance and ML-RoM. Performing a cognitive task resulted in a slightly reduced gait speed. However, when the manual task was performed, gait speed reduction was more apparent compared to the cognitive task. A manual task shares the same resources as the postural control. Thus, performing a manual task had more effect on gait performance.

4) The manual task exhibited a potential in increased dynamic stability in ML direction compared to the cognitive task. During the manual task, subjects were required to consciously pay attention to postural control in order to hold the cup straight. This observation suggests that the constraint imposed by a more demanding manual component of the dual-task interplayed with the postural component, leading to improved body stability.

5) Performing a manual and cognitive task concurrently was the most difficult task and resulted in the most conservative gait (i.e. the slowest speed and the highest ML-RoM) in all gait tasks, demonstrating higher attentional demands of the secondary task and overlapping processing resources.

6) Overall, more difficult postural and secondary tasks resulted in a decrease in gait speed and variation in CoM displacement within a normal range. Results suggest that CoM displacement and gait alterations might be adopted to enhance the stability, and optimize the secondary task performance while walking under challenging circumstances.

Conclusion

Compromised ML-RoM and decreased gait speed are a compensation to improve dynamic stability and optimize the secondary task performance. The subjects in this study generally walked more slowly with alteration in ML-RoM when they were asked to walk and concurrently perform another task. The degree of reduction of gait speed and variation in ML-RoM changed by increasing gait and secondary task complexity. However, mean speeds and ML-RoM in all cases remained within normal limits. Variation in ML-RoM within the normal range does not necessarily indicate an increased risk of falling. This study suggests that the unconscious alteration in gait speed and CoM RoM might be key to avoiding hazards and preventing falls and reflects an increase in dynamic gait stability.

3.2. Manuscript 2

The effects of unexpected mechanical perturbations during treadmill walking on spatiotemporal gait parameters, and the dynamic stability measures by which to quantify postural response

Madehkhaksar, F., Klenk, J., Sczuka, K., Gordt, K., Melzer, I., & Schwenk, M. (2018). The effects of unexpected mechanical perturbations during treadmill walking on spatiotemporal gait parameters, and the dynamic stability measures by which to quantify postural response. *PLoS One, 13*(4), e0195902.

DOI: https://doi.org/10.1371/journal.pone.0195902

Background and objectives

Most falls occur after a loss of balance while walking, which is the most common activity in daily life, and following an unexpected perturbation such as a slip or trip. Previous studies showed alteration in gait parameters and dynamic stability during different types of perturbations such as continues mechanical and visual perturbations (Hak et al., 2012; Stokes et al., 2017; Süptitz et al., 2013). However, the majority of studies focused on mechanical perturbations included perturbations only in the anterior-posterior (AP) or in the mediolateral (ML) directions. However, each of these perturbations affects gait and stability in different ways, depending not only on the type but also on the direction of the perturbations. Therefore, there was a need to study the effect of perturbations on gait-related parameters and dynamic stability, which include sudden mechanical surface perturbation in both AP- and ML-directions.

In addition, the means of gait characteristic appeared resistant to the effect of challenging walking depending on the challenge (Francis et al., 2015). Alternatively, the response of variability to perturbations was stronger than the response of means during the continuous platform and visual perturbations (Young et al., 2012). However, studies on the response of variability of the gait parameters to perturbations provided contradictory results. Additionally, extremes of gait-related parameters may be a better representative estimate of the parameters in a challenging condition, such as perturbed walking compared with the mean values that traditionally being used in research (Rispens et al., 2015). However. There was a lack of studies which evaluate the response of extremes of gait-related parameters to quantify postural stability during perturbed walking.

The first aim of this study was to examine the postural responses of healthy young adults to unexpected mechanical perturbations in ML and AP directions during treadmill walking. The second aim was to evaluate more responsive parameters, in terms of mean, variability, and extremes of the parameters, to quantify balance in this context.

Methods

Ten healthy young adults (age: 26.4 ± 4.1 years, height: 1.7 ± 0.08 m, mass: 64.4 ± 12.5 kg, 7 females) were recruited to participate in this study. Participants walked on a perturbation treadmill and were subjected to unexpected surface perturbations in left, right, forward, and backward directions. First, the subjects completed 5 minutes of normal walking on the perturbation treadmill without perturbations to become familiar with treadmill walking. Afterward, 4 trials of 1 min perturbation treadmill walking were recorded. During each trial, participants were exposed to a single perturbation in a specific direction in order to become familiar with perturbed walking. Subsequently, 4 trials of 5 min perturbation treadmill walking including a series of 16 perturbations towards a specific direction were recorded. A total of 39 reflective markers were placed at specific anatomical locations. Kinematic data were recorded with an 8-camera Vicon motion capture system.

Postural responses were quantified by spatiotemporal gait parameters including stride length, step with, and cadence, as well as MoS in mediolateral and anteroposterior directions. Means, variability, and extremes of gait-related parameters were used to specify responses during perturbed treadmill walking.

Main findings

1) In general, participants took shorter, wider, and faster steps as an adaptive strategy in order to increase their MoS and thus to decrease the probability of falling in the presence of unexpected mechanical perturbations.

2) More noteworthy was the increase in variability of parameters relative to unperturbed walking, indicating that step irregularity is a specific characteristic of walking adaptability during perturbed walking. Therefore, gait variability may represent a useful measure in future studies estimating fall risk in fall-prone populations.

3) The higher variability (i.e., more fluctuations) during and immediately after recovery stepping may be referred to as unsteadiness, instability, and fall risk. However, not all variabilities are a mark of poor locomotor control. Indeed, the ability to adapt gait when negotiating unexpected hazards is crucial to maintain stability and avoid falling. In this study, the high variability may show the ability of the young subjects to adapt the gait pattern which may be a healthy behavior to respond to unexpected perturbations.

4) The results also showed the effect of direction of the perturbations on gait and stability parameters. The effects of perturbations were greater when the perturbations were applied in the ML-direction, suggesting that ML perturbations were more challenging than AP perturbations. Thus, the recovery response depends on the direction of the perturbation.

5) This study also suggests that frontal plane fluctuations (ML variability) are more variable compared with AP variability, reflecting the higher fluctuations in the placement of the protective stepping in frontal plane in order to enhance stability during the perturbation.

6) Presenting the ML perturbations affected stability in both ML- and AP-directions with a stronger effect in sideways direction than AP direction and AP perturbations resulted in a stronger effect in the direction of the presented perturbation.
7) In addition to variabilities, extremes of gait parameters related to “low gait quality” showed a strong response to perturbations. However, extremes related to “high gait quality” showed no sensitivity to perturbations. Therefore, measuring variabilities (i.e. the fluctuations over a series of steps) and extremes (i.e. local effects of the perturbations) of the parameters in addition to means can help to better understand balance control strategies.

Conclusion

The results show that the increase in cadence and step width, as well as the decrease in stride length, are strategies to increase MoS, and thus to decrease the probability of falling in the presence of perturbations. This study also suggests that frontal plane fluctuations (ML variability) are more variable compared with AP variability. Thus, the variability of responses depends not only on the status of the individuals but also depends on the type and direction of the perturbation. The participants were more sensitive to ML perturbations than to AP perturbations which shows the importance of including ML perturbations in assessment protocols. Variabilities, as well as extremes of gait-related parameters, showed strong responses for measuring the effects of perturbations. Therefore, measuring variabilities and extremes of the parameters in addition to means can help to better understand balance control strategies and may be used as a marker of unsteadiness, instability, and fall risk.

3.3. Manuscript 3

Effect of Gaze-Shifting on Gait Characteristics during Treadmill Walking in Healthy Young and Older adults

Madehkhaksar, F., Klenk, J., Schwenk, M., Mack, D.J., L. Schwickert, Lindemann, U., Meyer, M., Srijana, K.C., Pomper, J.K., Synofzik, M., Ilg, U., Kerse, N., Maetzler, W., Becker, C., & Srulijes, K. (2018, submitted). Effect of gaze-shifting on gait characteristics during treadmill walking in healthy young and old adults. *Journal of Biomechanics.*

Background and objectives

Shifting gaze during walking in a natural environment is performed constantly (e.g. observing surrounding or to scan the pathway for obstacles) and may lead to alterations in gait and increased fall risk, especially in older adults. Considering the frequent occurrence of gaze shifting while walking in daily life, it is important to understand the potential problems with gaze shifts on locomotion in the older as compared to the young individuals. These age-related differences may have significant implications for fall preventive exercise interventions in older persons.

In general, older adults adapt their stable gait by taking slower and shorter steps compared to young adults. Also, the variability of a number of gait parameters increases in older subjects, suggesting a higher risk of falls (Callisaya et al., 2011). However, there was a lack of studies which examine the direct effects on characteristics ("reaction") of the step immediately after gaze-shifting.

The aim of this study was to determine the influence of gaze shifts on a set of gait parameters and their variabilities in healthy young and older individuals in order to discuss potential adaptive strategies used for compensation. Therefore, individuals walked on a treadmill while shifting their gaze to fixate on visual targets.

Methods

Eleven healthy young (age: 25 ± 4.5 years, height: 175 ± 5.6 m, mass: 74 ± 11 kg, 3 females) and 13 healthy old participants (age: 72 ± 3.9 years, height: 170 ± 8.9 m, mass: 75 ± 16 kg, 6 females) participated in this study. All subjects walked on a treadmill, while seven light emitting diodes (LEDs) were arranged in front of them. One LED was positioned at 0° and the remaining were positioned at 30°, 45°, and 60° to the left and right side. Each subject wore 15 reflective markers. Kinematic data were collected using a 6-camera Vicon motion capture system. First, subjects walked on the treadmill without presenting any visual triggering (Normal walking). Then, they performed two blocks of walking on the treadmill while fixating visual triggers. During each gaze-shifting block, each LED triggering at 30°, 45°, and 60° on left and right sides was illuminated 5 times (5 triggering × 6 conditions).

Gait parameters including stride length (SL), step width (SW), step frequency (SF), minimum toe clearance (Min-TC), and maximum toe clearance (Max-TC) were calculated. The mean and variability of parameters were calculated for each participant for gait cycles during normal walking, as well as, during one gait cycle before the triggering (Pre-Cycles) and during one gait cycle after the triggering (Post-Cycles) during gaze-shift walking.

Main Findings

1) In general, individuals adapted their cautious gait pattern in response to gaze-shift walking by taking shorter, faster, and narrower steps. Older subjects walked with shorter steps during all walking conditions as compared to young subjects, whereas, SF and SW were not affected by age group. In this study, healthy elderly adopted the speed of their gait by taking shorter steps, and not by taking more frequent steps, compared to young subjects.
2) A reduction in SL and increase of SF was found in Pre-Cycle walking compared to normal walking in the older adults but not the young, whereas both groups reduced SL and increased SF during the Post-Cycle compared with the Pre-Cycle. Reduced SL seems primarily to be a compensation, as older adults but not the young showed a reduction in SL already in Pre-Cycle walking compared to normal walking. The reduced SL accompanied by increased SF in the younger during Post-Cycle could also reflect a protective adaptation or reaction effect of gait in response to a gaze shift in terms of a more cautious gait.
3) In the older adults, mean of SW increased a direct reaction to the gaze-shifting (i.e. by comparing Pre-Cycle and Post-Cycle). This observation might be a compensatory strategy by increasing walking stability in the mediolateral direction in older adults. However, young adults seem to have a more stable gait that does not need such a “reactive” strategy after perturbation. SW variability was increased in both groups during the challenging walking condition, suggesting a compensatory strategy to cope with gaze-shift perturbation.
4) Young adults decreased their mean of Min-TC, whereas older adults increased the mean and variability of Min-TC. However, the elderly exhibited greater variability of Min-TC than young individuals. An age-related increase in Min-TC variability, in the absence of an increase in Min-TC, increases the likelihood of tripping. Therefore, the older group might have increased their Min-TC during Post-Cycle to compensate for the higher Min-TC variability.

5) Young adults increased Max-TC during gaze-shift walking compared to normal-walking, whereas older adults decreased Max-TC. This difference could be explained by weaker dorsiflexor muscle of older adults compared to the young ones. Interestingly, when focusing on the direct reaction after the gaze-shifting, the young adults showed a decrease of Max-TC, which could reflect a perturbation effect on gait.

Conclusion

This experiment showed an influence of gaze-shifts on gait in both groups, although, the effect is larger in the older which might, therefore, need more compensation compared to the young adults. Comparing Pre-Cycle to normal walking, young adults showed no instability-related changes in their gait but older adults showed a more cautious gait with shorter step length, reduced step width, increased step frequency, decreased maximum toe clearance, and 30% higher minimum toe clearance variability. During Post-Cycle compared to Pre-Cycle, direct effects of gaze-shifts on gait parameters were significant but rather small. Age-related differences observed in this study might have resulted from a decline in motor, sensory, and cognitive functions which result in less ability in maintaining balance. However, age-related differences might be a successful adaptive strategy used by older adults in order to minimize the risk of fall.

4. General discussion and conclusions

The objective of this dissertation was to evaluate the postural responses in terms of gait parameters and their variability, as well as stability measures under challenging walking conditions including stair walking while dual-tasking, mechanically perturbed walking, and gaze-shift walking.

4.1. Task-dependent adaptive strategy

The findings of this dissertations suggest that the postural responses under challenging conditions are task-dependent, which shows the importance of studying each case of challenging condition with high risk of fall.

Manuscript 1 showed that when stair walking while dual tasking, healthy young adults showed variation in CoM displacement and reduced gait speed in order to enhance the stability and to optimize the secondary task performance. The level of alteration depended on the type of the secondary task (i.e. cognitive or manual task), as well as the complexity of the gait task (i.e. steeper steps). For instance, in contrast to the secondary cognitive task, performing the secondary manual task resulted in enhancing dynamic stability, suggesting the task-dependent effect of the secondary task. Concurrently performing two types of secondary task resulted in the most challenging walking condition. A previous study which investigated the effect of dual-tasking on trunk movement during walking has also reported a decrease in trunk movement when performing a manual task (carrying a ball in a try) during walking (Asai et al., 2014). However, the interference of different types of manual-task (i.e. cognitive and manual secondary tasks) with a complex gait task such as stair walking has been lacking. These new findings of this study can help to better evaluate the risk of challenges encounter in daily life, therefore to reduce the risk of fall.

Manuscript 2 also showed adaptive strategy of healthy young adults during sudden mechanically perturbed walking. Overall, participants walked with a shorter stride length, a wider step width, and a higher cadence during perturbed walking in order to enhance dynamic stability. In addition, the variability of parameters increased during perturbed walking. The effects of perturbations were found to be significantly greater when the perturbations were applied toward the ML-direction, which also supports the task-dependent effect of challenging walking. The direction-dependent effect of perturbations was also reported in previous studies using visual and continues perturbations (McAndrew et al., 2010; O'Connor & Kuo, 2009). The results of the manuscript 2 further supports the stronger effects of sudden discrete mechanical perturbations on postural stability during walking suggesting the importance of including ML perturbations in assessment protocols.

Manuscript 3 discussed the gait strategy of healthy young and older adults during gaze-shift walking. Similar to the mechanically perturbed walking (manuscript 2), participants walked with shorter step length and a higher frequency during gaze-shift walking. However, in contrast, participants took narrower steps (smaller step width) during gaze-shift walking. This difference also demonstrates the task-dependent strategy of healthy adults under a challenging circumstance. During mechanically perturbed walking, participants took wider steps to control lateral dynamic stability, since the MoS in ML direction is defined as the distance between the ML borders of the BoS and XCoM. Thus, increased step width resulted in an increase in MoS-ML. However, during gaze-shift walking, visual fixations might have had a stronger effect on gait than a gaze shift per se since participants were required to gaze at the central LED before and after performing gaze shifts. Thus, observed narrower base of support during gaze-shift walking could be interpreted as a correlate for an increase in dynamic stability via the mechanism of gaze stabilization. Although, there have been a handful of studies that investigate adaptive strategies during a visually guided change in travel direction (Hollands et al., 2001) or to avoid an obstacle (Lo, van Donkelaar, & Chou, 2015; M. R. Paquette & Vallis, 2010), the effect of gaze-shifting on gait parameters and their variabilities had been missing. Therefore, novel findings of this study can greatly help better understanding of adaptive strategies during gaze-shift walking as a basis for the development of specific training paradigms.

4.2. Measures to quantify postural responses

In this context, there are a variety of measures that should be considered according to the type of the task being performed. Common measures which were discussed in this dissertation include spatiotemporal gait parameters and gait variability, as well as dynamic stability measures such as trunk movement and margins of stability.

Moreover, different measures should be interpreted together, as each can reveal different aspects of strategies used by the subject groups. For example, when interpreting gait speed together with the trunk displacements (manuscripts 1), decreased gait speed and alterations in ML-RoM demonstrate a cautious strategy during walking under a more challenging condition (i.e. ascending steeper stair). As another case, increasing the variability of gait parameters may be an indicator of higher risk of fall (Brach et al., 2008; Maki, 1997). On the other hand, it may also reflect a successful recovery response when it is accompanied by increasing dynamic stability (see manuscript 2). Also, in the manuscript 3, older adults increased Min-TC during gaze-shift walking. It has been suggested that tripping risk can be reduced by elevating Min-TC (Begg et al., 2007). However, when counting the variability of Min-TC into account, the older adults might have increased their Min-TC to compensate for the higher Min-TC variability. Thus, in this case, elevated Min-TC does not simply indicate increased safety, but a compensatory strategy to reduce the risk of tripping due to the higher variability of Min-TC. Therefore, as a conclusion, one parameter alone is not sufficient to describe stability and postural responses.

Importantly, manuscript 2 showed that looking at the variability of parameters over a series of steps is a responsive measure of gait adaptations happening during perturbed walking. A previous study reported no difference between fallers and non-fallers ability to cope with perturbation when measuring mean of the parameters over every single step following the perturbation (Punt et al., 2017). In their study, the effect of the perturbations on gait variability over a series of steps (i.e. fluctuations) was not investigated, which might be helpful in providing additional information to discriminate between fallers and non-fallers. The interesting finding of the manuscript 2 suggests that capturing the variability of gait parameters may represent a useful measure in future studies estimating fall risk in fall-prone populations.

In addition, according to the type of the postural perturbation, especially when it appears at some specific instances during walking, it may be helpful to use measures of parameters which reflect the values around these instances (such as extremes of parameters) as compared to mean of values. Because mean of values is an average over all instances during walking and may cover the instantaneous effect of the perturbation (manuscript 2). Previous studies found a strong association between extremes relating to high gait quality and fall risk during daily life walking (Rispens et al., 2015). However, this measure had not been used previously to detect the effects of perturbations. As a novel finding, manuscript 2 showed the strong responsiveness of extreme of gait parameters to mechanical perturbations by capturing the local effects of perturbations within gait cycles.

4.3. Effects of age

Manuscript 3 showed that due to aging, a decline in motor and sensory functions results in a different gait strategy used in older adults, which was more profound under more challenging condition (i.e. Post-Cycle gaze-shift walking). Exploring differences in adaptive strategies used by younger and older adults may help better understanding of balance problems in older adults and may have great implications in reducing the risk of fall.

To this aim, similar to the procedure of the manuscript 3, it is essential to first investigate responses used by healthy young adults in order to explore the healthy normal response to a specific challenge. Then, the strategies used by the elderly under the same condition should be contrasted with that of healthy young individuals. There are some age-related observations which are independent of the effect of the specific experimental conditions. For instance, in the manuscript 3, older adults walked slower, with shorter SL, and lower Max-TC compared to young adults, whereas, SF and SW were not affected by age-group. These observations, which are in line with previous studies (Elble, Thomas, Higgins, & Colliver, 1991), were observed during all experimental conditions independent of the effects of gaze-shifting. On the other hand, there are some observations directly related to the effects of the experimental conditions. It should be noted that observed differences in elderly may be due to an inability in responding appropriately resulting in higher risk of fall. However, these differences may be a successful adaptive strategy to compensate for consequences of age-related declines in multiple systems. For example, older adults, but not young, reduced SL and increased SF during Pre-Cycle, which is in line with previous studies while walking on an irregular surface (Menz, Lord, & Fitzpatrick, 2003), as well as during walking when turning the head (Singh et al., 2017). This observation is possibly associated with a higher risk of falls since shorter SL results in less dynamic stability in the forward direction (Hak et al., 2012). However, older adults increased SW during Post-Cycle compared to Pre-Cycle as a direct reaction to the gaze-shifting which is also consistent with the literature (Vallis & Patla, 2004). This observation might be a compensatory strategy by increasing walking stability in the mediolateral direction in older adults (Hak et al., 2012), whereas, young adults seem to have a more stable gait that does not need such a “reactive” strategy after perturbation. Therefore, contrasting normal and impaired adaptive responses used by the elderly can help with assessment of balance recovery ability and thus may help to reduce the incidence of falls.

In general, healthy adults in all experimental conditions of this dissertation adapted their gait dependent on the task by alterations in gait speed, gait parameters, trunk movements, as well as the performance of additional tasks in order to improve their dynamic stability and to avoid falls. Observed alterations in their walking strategy demonstrate a successful healthy strategy to enhance balance under challenging circumstances.

There are some general limitations in the studies of this dissertation. First, findings came from a small sample of healthy adults. Thus, there is a need to investigate larger sample sizes and explore weaker and older individuals with impairments. Second, three specific types of challenging walking were addressed in this dissertation. Future studies are needed to examine postural responses under other challenging conditions.

The findings of this dissertation can impact the scientific and clinical communities. First, new knowledge is gained on the mechanisms underlying the postural responses. Second, the findings may aid advancements in the assessment of balance control in young and old adults. Finally, they can assist future clinical and basic research work on the development of more effective preventions, interventions, and training program in order to optimize balance control.

Bibliography

Asai, T., Misu, S., Doi, T., Yamada, M., & Ando, H. (2014). Effects of dual-tasking on control of trunk movement during gait: Respective effect of manual-and cognitive-task. *Gait & posture, 39*(1), 54-59.

Begg, R., Best, R., Dell'Oro, L., & Taylor, S. (2007). Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. *Gait & posture, 25*(2), 191-198.

Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and ageing, 26*(4), 261-268.

Brach, J. S., Berlin, J. E., VanSwearingen, J. M., Newman, A. B., & Studenski, S. A. (2005). Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. *Journal of neuroengineering and rehabilitation, 2*(1), 21.

Brach, J. S., Studenski, S., Perera, S., VanSwearingen, J. M., & Newman, A. B. (2008). Stance time and step width variability have unique contributing impairments in older persons. *Gait & posture, 27*(3), 431-439.

Brady, R. A., Peters, B. T., & Bloomberg, J. J. (2009). Strategies of healthy adults walking on a laterally oscillating treadmill. *Gait & posture, 29*(4), 645-649.

Bruijn, S. M., Bregman, D. J., Meijer, O. G., Beek, P. J., & van Dieën, J. H. (2012). Maximum Lyapunov exponents as predictors of global gait stability: a modelling approach. *Medical engineering & physics, 34*(4), 428-436.

Callisaya, M. L., Blizzard, L., Schmidt, M. D., Martin, K. L., McGinley, J. L., Sanders, L. M., & Srikanth, V. K. (2011). Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. *Age and ageing, 40*(4), 481-487.

Catena, R. D., Van Donkelaar, P., & Chou, L.-S. (2007). Cognitive task effects on gait stability following concussion. *Experimental brain research, 176*(1), 23.

Chapman, G., & Hollands, M. (2006). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental brain research, 174*(4), 613-621.

Chou, L.-S., Kaufman, K. R., Brey, R. H., & Draganich, L. F. (2001). Motion of the whole body's center of mass when stepping over obstacles of different heights. *Gait & posture, 13*(1), 17-26.

Chou, L.-S., Kaufman, K. R., Hahn, M. E., & Brey, R. H. (2003). Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait & posture, 18*(3), 125-133.

Cinelli, M., Patla, A., & Stuart, B. (2007). Involvement of the head and trunk during gaze reorientation during standing and treadmill walking. *Experimental brain research, 181*(1), 183-191.

Cinelli, M., Patla, A., & Stuart, B. (2008). Age-related differences during a gaze reorientation task while standing or walking on a treadmill. *Experimental brain research, 185*(1), 157-164.

Cumming, R. G., & Klineberg, R. J. (1994). Fall frequency and characteristics and the risk of hip fractures. *Journal of the American Geriatrics Society, 42*(7), 774-778.

de Lima, A. C., de Azevedo Neto, R. M., & Teixeira, L. A. (2010). On the functional integration between postural and supra-postural tasks on the basis of contextual cues and task constraint. *Gait & posture, 32*(4), 615-618.

Dingwell, J., Cusumano, J., Cavanagh, P., & Sternad, D. (2001). Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *Journal of biomechanical engineering, 123*(1), 27-32.

Dingwell, J. B., Robb, R. T., Troy, K. L., & Grabiner, M. D. (2008). Effects of an attention demanding task on dynamic stability during treadmill walking. *Journal of neuroengineering and rehabilitation, 5*(1), 12.

Elble, R., Thomas, S. S., Higgins, C., & Colliver, J. (1991). Stride-dependent changes in gait of older people. *Journal of neurology, 238*(1), 1-5.

England, S. A., & Granata, K. P. (2007). The influence of gait speed on local dynamic stability of walking. *Gait & posture, 25*(2), 172-178.

Francis, C. A., Franz, J. R., O'Connor, S. M., & Thelen, D. G. (2015). Gait variability in healthy old adults is more affected by a visual perturbation than by a cognitive or narrow step placement demand. *Gait & posture, 42*(3), 380-385.

Goodpaster, B. H., Park, S. W., Harris, T. B., Kritchevsky, S. B., Nevitt, M., Schwartz, A. V., . . . Newman, A. B. (2006). The loss of skeletal muscle strength, mass, and quality in older adults: the health, aging and body composition study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 61*(10), 1059-1064.

Hak, L., Houdijk, H., Beek, P. J., & van Dieen, J. H. (2013). Steps to take to enhance gait stability: the effect of stride frequency, stride length, and walking speed on local dynamic stability and margins of stability. *PLoS One, 8*(12), e82842.

Hak, L., Houdijk, H., Steenbrink, F., Mert, A., van der Wurff, P., Beek, P. J., & van Dieën, J. H. (2012). Speeding up or slowing down?: Gait adaptations to preserve gait stability in response to balance perturbations. *Gait & posture, 36*(2), 260-264.

Hausdorff, J. M. (2007). Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Human movement science, 26*(4), 555-589.

Hausdorff, J. M., Rios, D. A., & Edelberg, H. K. (2001). Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Archives of physical medicine and rehabilitation, 82*(8), 1050-1056.

Heiderscheit, B. C. (2000). Movement variability as a clinical measure for locomotion. *Journal of Applied Biomechanics, 16*(4), 419-427.

Hof, A., Gazendam, M., & Sinke, W. (2005). The condition for dynamic stability. *Journal of biomechanics, 38*(1), 1-8.

Hof, A. L. (2008). The 'extrapolated center of mass' concept suggests a simple control of balance in walking. *Human movement science, 27*(1), 112-125.

Hollands, M., Sorensen, K., & Patla, A. (2001). Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. *Experimental brain research, 140*(2), 223-233.

Kao, P.-C., Higginson, C. I., Seymour, K., Kamerdze, M., & Higginson, J. S. (2015). Walking stability during cell phone use in healthy adults. *Gait & posture, 41*(4), 947-953.

Kelly, V. E., Janke, A. A., & Shumway-Cook, A. (2010). Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. *Experimental brain research, 207*(1-2), 65-73.

Kuo, A. D. (1999). Stabilization of lateral motion in passive dynamic walking. *The International journal of robotics research, 18*(9), 917-930.

Li, K. Z., & Lindenberger, U. (2002). Relations between aging sensory/sensorimotor and cognitive functions. *Neuroscience & Biobehavioral Reviews, 26*(7), 777-783.

Lo, O.-Y., van Donkelaar, P., & Chou, L.-S. (2015). Distracting visuospatial attention while approaching an obstacle reduces the toe-obstacle clearance. *Experimental brain research, 233*(4), 1137-1144.

Lord, S. R., & Dayhew, J. (2001). Visual risk factors for falls in older people. *Journal of the American Geriatrics Society, 49*(5), 508-515.

Maki, B. E. (1997). Gait changes in older adults: predictors of falls or indicators of fear? *Journal of the American Geriatrics Society, 45*(3), 313-320.

Maki, B. E., Cheng, K. C.-C., Mansfield, A., Scovil, C. Y., Perry, S. D., Peters, A. L., . . . Corbeil, P. (2008). Preventing falls in older adults: new interventions to promote more effective change-in-support balance reactions. *Journal of electromyography and kinesiology, 18*(2), 243-254.

McAndrew, P. M., Dingwell, J. B., & Wilken, J. M. (2010). Walking variability during continuous pseudo-random oscillations of the support surface and visual field. *Journal of biomechanics, 43*(8), 1470-1475.

Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Acceleration patterns of the head and pelvis when walking are associated with risk of falling in community-dwelling older people. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 58*(5), M446-M452.

Mian, O. S., Narici, M. V., Minetti, A. E., & Baltzopoulos, V. (2007). Centre of mass motion during stair negotiation in young and older men. *Gait & posture, 26*(3), 463-469.

O'Connor, S. M., & Kuo, A. D. (2009). Direction-dependent control of balance during walking and standing. *Journal of neurophysiology, 102*(3), 1411-1419.

Ojha, H. A., Kern, R. W., Lin, C.-H. J., & Winstein, C. J. (2009). Age affects the attentional demands of stair ambulation: evidence from a dual-task approach. *Physical therapy, 89*(10), 1080-1088.

Paquette, C., Paquet, N., & Fung, J. (2006). Aging affects coordination of rapid head motions with trunk and pelvis movements during standing and walking. *Gait & posture, 24*(1), 62-69.

Paquette, M. R., & Vallis, L. A. (2010). Age-related kinematic changes in late visual-cueing during obstacle circumvention. *Experimental brain research, 203*(3), 563-574.

Patel, P., Lamar, M., & Bhatt, T. (2014). Effect of type of cognitive task and walking speed on cognitive-motor interference during dual-task walking. *Neuroscience, 260*, 140-148.

Prince, F., Corriveau, H., Hébert, R., & Winter, D. A. (1997). Gait in the elderly. *Gait & posture, 5*(2), 128-135.

Punt, M., Bruijn, S. M., Roeles, S., van de Port, I. G., Wittink, H., & van Dieën, J. H. (2017). Responses to gait perturbations in stroke survivors who prospectively experienced falls or no falls. *Journal of biomechanics, 55*, 56-63.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Maganaris, C. N. (2008). The demands of stair descent relative to maximum capacities in elderly and young adults. *Journal of electromyography and kinesiology, 18*(2), 218-227.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Maganaris, C. N. (2009). Older adults employ alternative strategies to operate within their maximum capabilities when ascending stairs. *Journal of electromyography and kinesiology, 19*(2), e57-e68.

Riener, R., Rabuffetti, M., & Frigo, C. (2002). Stair ascent and descent at different inclinations. *Gait & posture, 15*(1), 32-44.

Rispens, S. M., van Schooten, K. S., Pijnappels, M., Daffertshofer, A., Beek, P. J., & van Dieen, J. H. (2015). Identification of fall risk predictors in daily life measurements: gait characteristics' reliability and association with self-reported fall history. *Neurorehabilitation and neural repair, 29*(1), 54-61.

Simoni, D., Rubbieri, G., Baccini, M., Rinaldi, L., Becheri, D., Forconi, T., . . . Di Bari, M. (2013). Different motor tasks impact differently on cognitive performance of older persons during dual task tests. *Clinical biomechanics, 28*(6), 692-696.

Singh, H., Sanders, O., Waller, S. M., Bair, W.-N., Beamer, B., Creath, R. A., & Rogers, M. W. (2017). Relationship between head-turn gait speed and lateral balance function in community-dwelling older adults. *Archives of Physical Medicine and Rehabilitation*.

Srulijes, K., Mack, D. J., Klenk, J., Schwickert, L., Ihlen, E. A., Schwenk, M., . . . Hobert, M. A. (2015). Association between vestibulo-ocular reflex suppression, balance, gait, and fall risk in ageing and neurodegenerative disease: protocol of a one-year prospective follow-up study. *BMC neurology, 15*(1), 192.

Stacoff, A., Diezi, C., Luder, G., Stüssi, E., & Kramers-de Quervain, I. A. (2005). Ground reaction forces on stairs: effects of stair inclination and age. *Gait & posture, 21*(1), 24-38.

Startzell, J. K., Owens, D. A., Mulfinger, L. M., & Cavanagh, P. R. (2000). Stair negotiation in older people: a review. *Journal of the American Geriatrics Society, 48*(5), 567-580.

Stel, V. S., Smit, J. H., Pluijm, S. M., & Lips, P. (2004). Consequences of falling in older men and women and risk factors for health service use and functional decline. *Age and ageing, 33*(1), 58-65.

Stokes, H. E., Thompson, J. D., & Franz, J. R. (2017). The Neuromuscular Origins of Kinematic Variability during Perturbed Walking. *Scientific Reports, 7*.

Süptitz, F., Catalá, M. M., Brüggemann, G.-P., & Karamanidis, K. (2013). Dynamic stability control during perturbed walking can be assessed by a reduced kinematic model across the adult female lifespan. *Human movement science, 32*(6), 1404-1414.

Tay, C. S., Lee, J. K., Teo, Y. S., Foo, P. Q., Tan, P. M., & Kong, P. W. (2016). Using gait parameters to detect fatigue and responses to ice slurry during prolonged load carriage. *Gait & posture, 43*, 17-23.

Toebes, M. J., Hoozemans, M. J., Furrer, R., Dekker, J., & van Dieën, J. H. (2012). Local dynamic stability and variability of gait are associated with fall history in elderly subjects. *Gait & posture, 36*(3), 527-531.

Vallabhajosula, S., Tan, C. W., Mukherjee, M., Davidson, A. J., & Stergiou, N. (2015). Biomechanical analyses of stair-climbing while dual-tasking. *Journal of biomechanics, 48*(6), 921-929.

Vallis, L. A., & Patla, A. E. (2004). Expected and unexpected head yaw movements result in different modifications of gait and whole body coordination strategies. *Experimental brain research, 157*(1), 94-110.

Vandervoort, A. A. (2002). Aging of the human neuromuscular system. *Muscle & nerve, 25*(1), 17-25.

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & posture, 3*(4), 193-214.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & posture, 16*(1), 1-14.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement disorders, 23*(3), 329-342.

Young, P. M. M., & Dingwell, J. B. (2012). Voluntary changes in step width and step length during human walking affect dynamic margins of stability. *Gait & posture, 36*(2), 219-224.

Young, P. M. M., Wilken, J. M., & Dingwell, J. B. (2012). Dynamic margins of stability during human walking in destabilizing environments. *Journal of biomechanics, 45*(6), 1053-1059.

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.

Erklärung gemäß § 8 (1) d) der Promotionsordnung der Universität Heidelberg für die Fakultät für Verhaltens- und Empirische Kulturwissenschaften

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 Forough Madehkhaksar

Datum, Unterschrift

Date, Signature 18.07.2018

Gait & Posture 43 (2016) 114–119

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effect of dual task type on gait and dynamic stability during stair negotiation at different inclinations

Forough Madehkhaksar , Arjan Egges [*]

Virtual Human Technology Lab, Virtual Worlds Research Group, Information and Computing Science, Utrecht University, Utrecht P.O. Box 80.089, 3508 TB, the Netherlands

A R T I C L E I N F O

Article history:
Received 20 April 2015
Received in revised form 31 August 2015
Accepted 9 September 2015

Keywords:
Dual-task
Cognitive task
Manual task
Stair gait
Kinematics

A B S T R A C T

Stair gait is a common daily activity with great potential risk for falls. Stairs have varying inclinations and people may perform other tasks concurrently with stair gait. This study investigated dual-task interference in the context of complex gait tasks, such as stair gait at different inclinations, a topic about which little is understood. We examined how secondary cognitive and manual tasks interfere with stair gait when a person concurrently performed tasks at different levels of complexity. Gait kinematic data and secondary task performance measures were obtained from fifteen healthy young males while ascending and descending a four-step staircase at three inclinations (17.7°, 29.4°, and 41.5°) as well as level walking. They performed a cognitive task, 'backward digit recall', a manual task, 'carrying a cup of water' and a combination of the two tasks. Gait performance and dynamic stability were assessed by gait speed and whole body center of mass (COM) range of motion in the medial–lateral direction, respectively. No significant effect of the gait task on the cognitive task performance was observed. In contrast, stair walking adversely affected the performance of the manual task compared to level walking. Overall, more difficult postural and secondary tasks resulted in a decrease in gait speed and variation in COM displacement within normal range. Results suggest that COM displacement and gait alterations might be adopted to enhance the stability, and optimize the secondary task performance while walking under challenging circumstances. Our findings are useful for balance and gait evaluation, and for future falls prediction.

1. Introduction

Falls are a serious clinical problem and can result in severe injuries and even death among older adults [1]. Stair gait is among the most challenging and hazardous types of locomotion, and one of the leading causes of falls-related injuries for the aged population [2]. The risk of fall further increases when people perform tasks like reasoning or carrying an object concurrently with stair gait [3,4].

Two different types of secondary tasks – a cognitive task and a manual task – have been used in dual-task studies [5–7]. Previous studies have reported that undertaking a secondary cognitive task adversely affects gait depending on the task complexity, the population studied and the instruction given regarding to attention prioritisation [8–11]. A manual task, like carrying an object, is used less often in dual-task studies [5]. Some reports have demonstrated that a manual task, similarly to a cognitive task, adversely affects gait performance [5,12]. Contradictory results have been reported when the manual task requires increased postural stability in order to be correctly performed. In this case, a secondary manual task may lead to extra stabilization rather than perturbation of posture [13,14].

Little is understood about dual-tasking during stair gait. Ojha et al. [3] reported that older adults required more resources than younger adults while performing stair gait concurrently with a verbal task. Recently, Vallabhajosula et al. [4] showed that the impact of performing a cognitive or manual task during stair ascent varies based on the stair ascent phase. Also, they reported that gait and secondary task performance are more strongly associated if the gait task is more challenging. Stair descent is also important to be taken into account, since it has been reported as the most hazardous aspect of stair gait [2]. Finally, gait parameters vary based on stair inclination [15,16] suggesting different levels of complexity of stair gait at different inclinations. To our knowledge, no previous studies investigated manual and cognitive dual-task

---

[*] Corresponding author. Tel.: +31 302537588; fax: +31 302532804.
E-mail addresses: f.madehkhaksar@uu.nl (F. Madehkhaksar), j.egges@uu.nl (A. Egges).
URL: http://vhtlab.nl

http://dx.doi.org/10.1016/j.gaitpost.2015.09.009

performance during a complex gait task such as stair gait at different inclinations, even though in daily life, people regularly encounter stairs at varying inclinations and concurrently perform additional tasks.

In this study we examined how secondary cognitive and manual tasks interfere with stair gait at varying inclinations for healthy adults. We expected that increasing the complexity of the gait task as well as the type of secondary task would affect both gait and dual-task performance, such that performance of secondary tasks would decline as a compensation to maintain dynamic stability.

2. Methods

2.1. Subjects

Fifteen healthy males (age: 28.5 ± 3.7 years, height: 180.1 ± 7.5 cm, body mass: 74.6 ± 7.5 kg), participated in the experiment. All subjects reported to be free of any musculoskeletal or neurological dysfunction. Ethical approval was obtained from the ethical committee of the Faculty of Social and Behavioural Sciences of Utrecht University (Reference Number: FETC14-020). All subjects gave their informed consent.

2.2. Experimental setup and procedures

Stair gait was performed on an adjustable 4 step staircase at three different inclinations: flat, standard, and steep [15,16] (see Table 1). In the stair gait trials, the participants walked from a starting point about 2 meters away from the staircase on level ground, in order to start ascending the stair from a walk [17,18]. The participants then ascended to the top of the staircase in a step-over manner, turned around, descended the stair and walked back to the starting point. In the level walking trials, the participants walked straight ahead covering the same distance as in the stair walking trials. In all trials, the participants walked barefoot at their comfortable speed, in order to remove the influence of different shoe types.

They performed a cognitive task, backward digit recall (BDR), a manual task, ‘carrying a cup of water’ (CCW) and a combination of two tasks (BDR&CCW) concurrently with the gait task. In BDR, the experimenter read out a sequence of three-digit random numbers at a rate of 40 numbers per minute, and the participants were required to repeat the numbers in reverse order in time to the beat [19]. BDR commenced 10 s before the participants started walking and was performed continuously throughout each trial. In CCW, participants were required to carry a cup of water (0.63 kg) in their dominant hand while trying to keep it vertical. Also, there was a baseline (single gait task) in which no secondary task was performed. Therefore in total, there were four testing combinations for each gait task. Each participant performed three stair walks as well as level walking under each testing condition. The dual-task conditions were randomly presented to the participants. The participants were provided enough time to get familiar with the experimental procedure (see Fig. 1A for an outline).

Table 1
Stair dimensions of the present study.

Stair position	Riser height (cm)	Tread/run (cm)	Inclination (°)
Flat	12	37.5	17.7
Standard	15.5	27.5	29.4
Steep	15.5	17.5	41.5

The performance of BDR was quantified by the ratio between the number of correct recalls and the total number of three-digit numbers presented in each trial. In CCW, two markers were placed on the cup and participants were asked to hold the cup vertically. The task performance task was quantified by measuring the ratio of deviation of the cup in the vertical direction between the first five seconds (in which the subjects were asked not to walk) and the rest of trial.

2.3. Kinematics

Kinematic data was recorded at 100 Hz with a 14-camera three-dimensional motion capture system (Vicon Motion Systems, Oxford, UK). A total of 35 reflective markers were placed at specific anatomical locations in accordance with the Plug-In-Gait marker set (Bodybuilder, Plug in Gait model, Vicon Motion Systems, Oxford, UK). Additionally, one marker was placed on each step edge (see Fig. 1B). Motion data was analyzed using the Vicon Nexus software (version 1.8.5). Kinematic data of the lower limbs and whole body center of mass (COM) were collected using the Vicon Plug-In-Gait model [20].

The gait speed during a single gait cycle was used as a dependent measure to assess gait performance, since the effect of a concurrent cognitive task has shown to be most evident on this variable [9]. The gait speed was measured as the distance traveled by the ankle joint center during the gait cycle divided by the gait cycle time. During level walking, foot contact and toe off were determined according to the coordinate-based algorithm proposed by Zeni et al. [21] using corresponding toe and heel markers. During stair ascent and descent, the stair cycle under analysis was defined according to the literature [22]. During stair gait, foot contact was determined using the method by Grenholm et al. [23]. Event detection was performed with a custom MATLAB R2014a program (MathWorks Inc., Natic, USA).

Maintaining the dynamic stability during gait relies on the ability to control COM motion, thus changes in ML COM motion has been extensively used to detect gait instability [24–27]. Dynamic stability during gait was assessed by the whole body COM range of motion (RoM) in the medial–lateral (ML) direction, i.e. the maximum minus minimum value achieved during the crossing stride. Vertical and anterior–posterior RoM on stairs are constrained, respectively by the stair riser and tread dimensions and were therefore not investigated [26].

2.4. Analysis

Data was analyzed using SPSS for Windows, version 22. A two-factorial repeated measures ANOVA (seven gait task conditions × four secondary task conditions) including a post hoc Bonferroni test was used to analyze gait speed and ML-RoM as dependent measures. In addition, performance of each secondary task was analyzed using a two-factorial repeated measures ANOVA, separately: gait task (level walking vs. flat stair vs. standard stair vs. steep stair) and secondary task (single vs. BDR&CCW condition).

The data for cup inclination deviation was log-transformed to obtain a normal distribution and to decrease the influence of outliers. The level of significance was set at $p < 0.05$.

3. Results

3.1. Secondary task performance

Table 2 presents the secondary task performance measures. Results for CCW showed a main significant effect of gait task ($p < 0.001$). Cup deviation from the vertical direction during

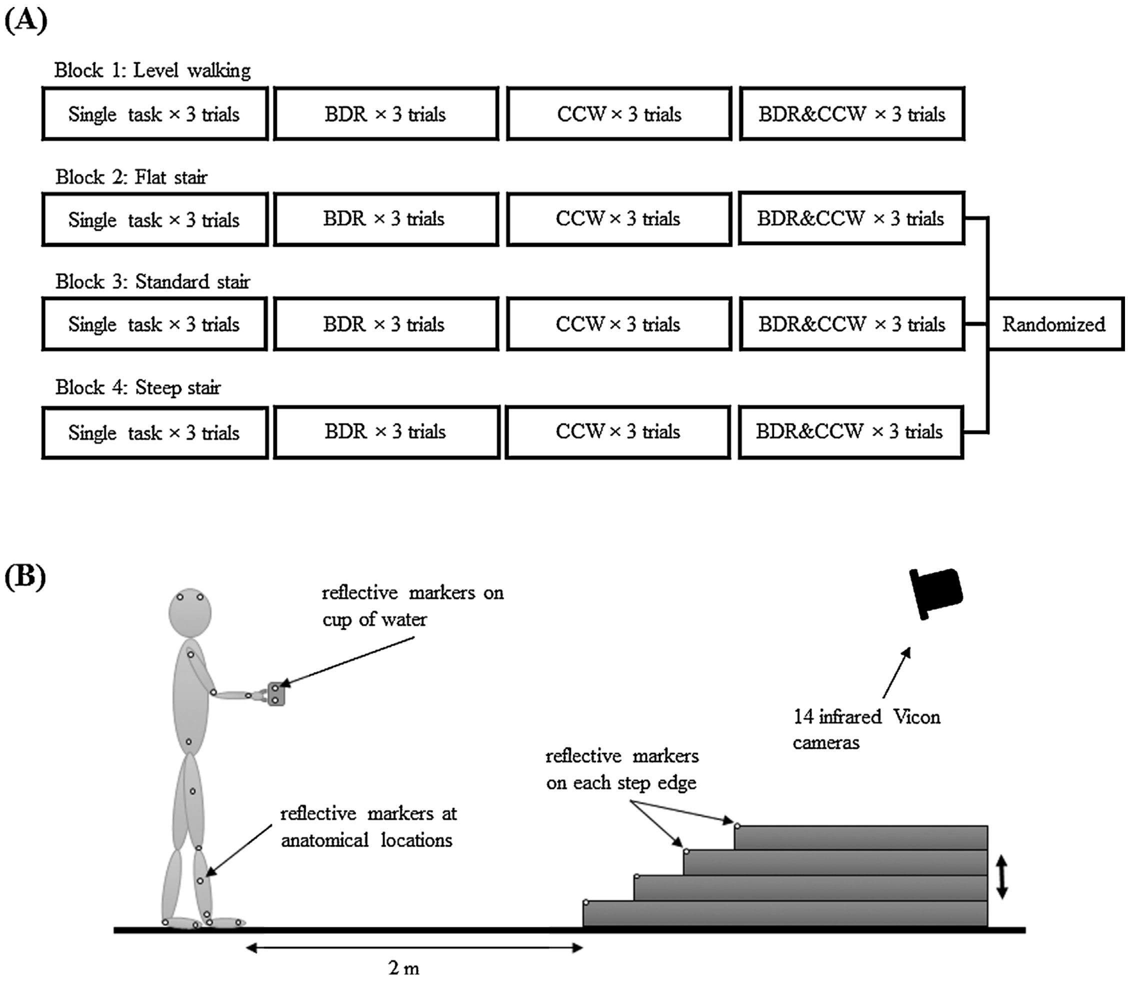

Fig. 1. (A) Block sequences. Trials within each block are randomized. Tasks in block 1 were performed before block 2, 3 and 4. Sequences of block 2, 3 and 4 were randomized. BDR, backward digit recall; CCW, carrying cup of water. (B) Schematic drawing of the staircase (without handrails) and experimental setup. The height of the staircase (riser and tread dimensions) can be adjusted so that the inclination can be varied. Reflective markers were placed at specific anatomical locations in accordance with the Plug-In-Gait marker set.

walking was significantly smaller than stair gait ($p < 0.05$ for all comparisons). In contrast, results for BDR performance showed no main significant effect of gait task. Also, subjects showed no significant difference in the performance of a single secondary task (either BDR or CCW) compared to concurrently performing two secondary tasks (BDR&CCW). A more complex gait task combined with concurrently performed secondary tasks had no effect on either BDR or CCW performance.

3.2. Gait speed

Fig. 2 shows the effects of gait tasks and secondary tasks on gait speed. Gait task significantly affected gait speed ($p < 0.001$) with a significantly slower speed during all stair ascent and descent compared to level walking ($p < 0.001$ for all comparisons). In all three stair inclinations, gait speed during ascent was significantly slower than descent ($p < 0.001$ for all inclinations). Steeper stairs resulted in a higher gait speed reduction.

The secondary task type showed a significant effect on gait speed ($p < 0.001$). Overall, performing a secondary task decreased gait speed compared to the single task condition. There was an interaction between the gait task by the secondary task effect on gait speed ($p < 0.001$). The effect of a secondary task on gait speed during level walking and stair descent were more obvious than during stair ascent. Gait speed was highest in the single task condition (walking only) and lowest during BDR&CCW compared to the other secondary task conditions. Regardless of the gait task complexity, the difference in gait speed between BDR and CCW was not significant, however participants walked slightly slower during CCW.

Table 2
BDR and CCW secondary task performance in each gait task and secondary task condition (single and concurrent secondary task).

	Single secondary task				BDR&CCW condition			
	Walking	Flat	Standard	Steep	Walking	Flat	Standard	Steep
BDR	0.908 (0.127)	0.956 (0.108)	0.958 (0.106)	0.939 (0.121)	0.924 (0.148)	0.977 (0.072)	0.967 (0.086)	0.951 (0.147)
CCW	0.539 (0.627)	0.607 (0.446)	0.705 (0.734)	0.516 (0.345)	0.529 (0.736)	0.693 (0.592)	0.764 (0.827)	0.639 (0.506)

Values are mean (standard deviation). BDR, backward digit recall; CCW, carrying cup of water. The BDR performance was quantified by the ratio between the number of correct recalls and the total number of three-digit numbers. The CCW performance was quantified by the ratio of deviation of the cup in the vertical direction.

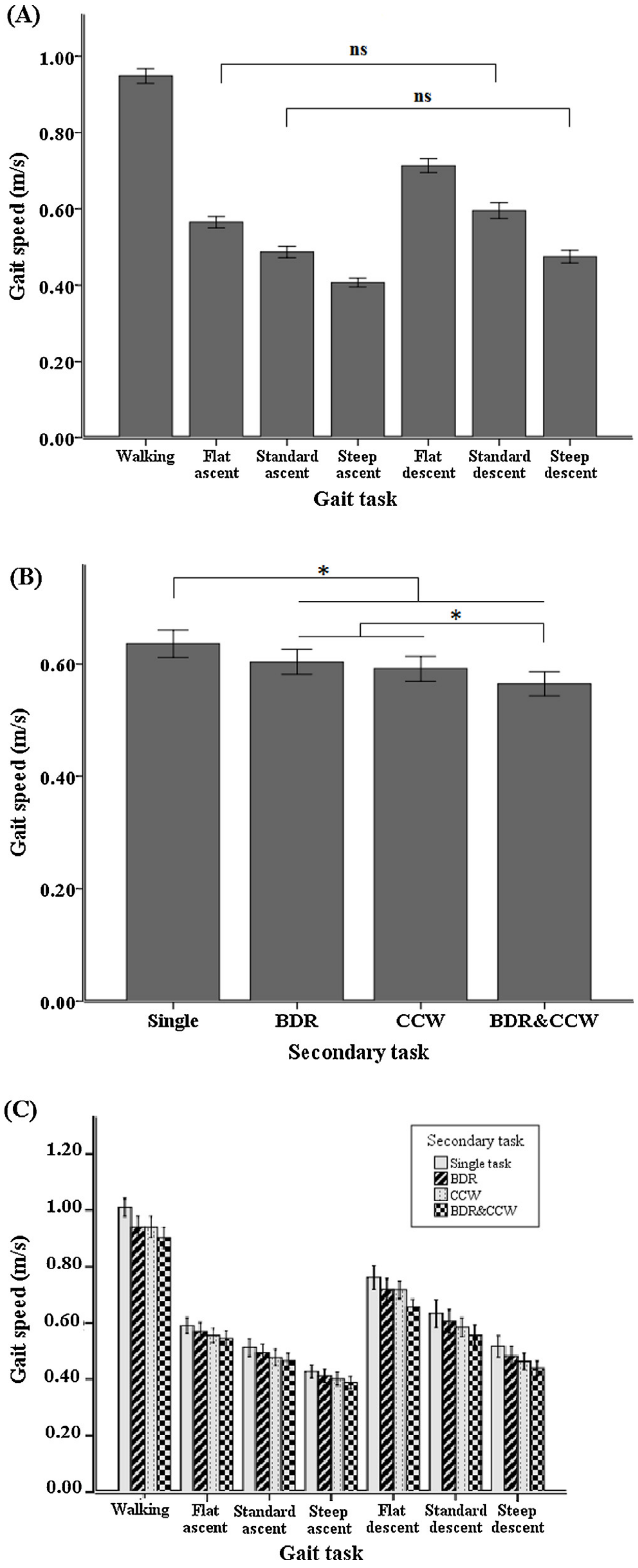

Fig. 2. Gait speed shown as a function of (A) gait task (level walking, flat, standard and steep stair ascent and descent), "ns" indicates non-significant differences ($p > 0.05$) between conditions, i.e. a significant difference is present between all other conditions (B) secondary task (single task, BDR, CCW and BDR&CCW), Significant differences ($p < 0.05$) between the conditions are indicated by *. (C) Gait speed shown a function of gait task and secondary task. BDR, backward digit recall; CCW, carrying cup of water. Error bars indicate standard error.

3.3. ML-RoM

Fig. 3 shows the effects of gait tasks and secondary tasks on ML-RoM. The secondary task type had a significant effect on ML-RoM ($p < 0.001$). Overall, performing a secondary task increased ML-RoM compared to the single task. However, the only significant difference appeared between the single task and BDR&CCW condition ($p < 0.05$). ML-RoM during CCW was slightly lower than BDR and BDR&CCW but still higher than the single task. BDR&CCW appeared with the highest ML-RoM compared to the other task conditions. There was a significant main effect of the gait task on ML-RoM ($p < 0.001$). However, differences did not appear systematically between the different gait conditions. No interaction effect of gait task by secondary task was observed for ML-RoM.

4. Discussion

This study explored the effect of complex gait tasks, notably stair gait at different inclinations, and different types of secondary tasks on gait and secondary task performance. As we expected, both gait performance and dynamic stability responded to gait task difficulty and secondary task performance. Compared to level walking (gait task baseline) and the single task condition (secondary task baseline), subjects showed an alteration in their gait speed and ML-RoM as a function of gait task complexity as well as type and complexity of the secondary task. The gait task had no effect on the cognitive task performance. In contrast, the manual task performance was affected by gait task complexity. Performing a manual and cognitive task concurrently had no effect on secondary task performance but strongly affected gait speed and ML-RoM.

Previous studies show that cognitive and motor performances decline to a variable extent, depending on the tests being used, when combined in a dual-task scenario. We confirmed this finding when our participants performed a manual task, suggesting that motor control tasks have a direct effect on a secondary manual task, since the resources for the postural control and the manual task performance are both within the motor control system [7]. Therefore, manual task performance declined under more challenging postural conditions in our study. Gait tasks had no effect on the cognitive task performance which is consistent with previous studies [8,10]. In the present work, the absence of any significant decline in cognitive performance during the dual-task test might indicate that no interference was present, as if two totally distinct neuronal control pathways processed the cognitive and motor tasks which is consistent with the literature [11]. This finding contrasts with other research showing that cognitive task performance declines with more difficult postural or walking tasks [28]. Because only one type of cognitive task was used in this study, characteristics of that specific task could contribute to the observed differences. Also, performing BDR and CCW concurrently had no effect on the performance of either task. The multiple resource model posits that processing may need a number of resources [7]. According to this theory, the cognitive and manual tasks in this study might not share common resources, which may explain our findings.

During stair gait, a significant gait speed decrease was observed compared to level walking. More complex gait tasks are more attentionally demanding. Thus, increasing the complexity of gait tasks resulted in decreased gait speed indicating increased motor cost for postural control. However, results for ML-RoM showed no systematic changes as a function of the gait task. ML-RoM was previously used to indicate gait instability [24,27,29]. ML-RoM changes are thought to possibly be due to a reduced ability to confine the COM within a more stable region. However, in our case, the mean values for ML-RoM appeared normal (ranging from

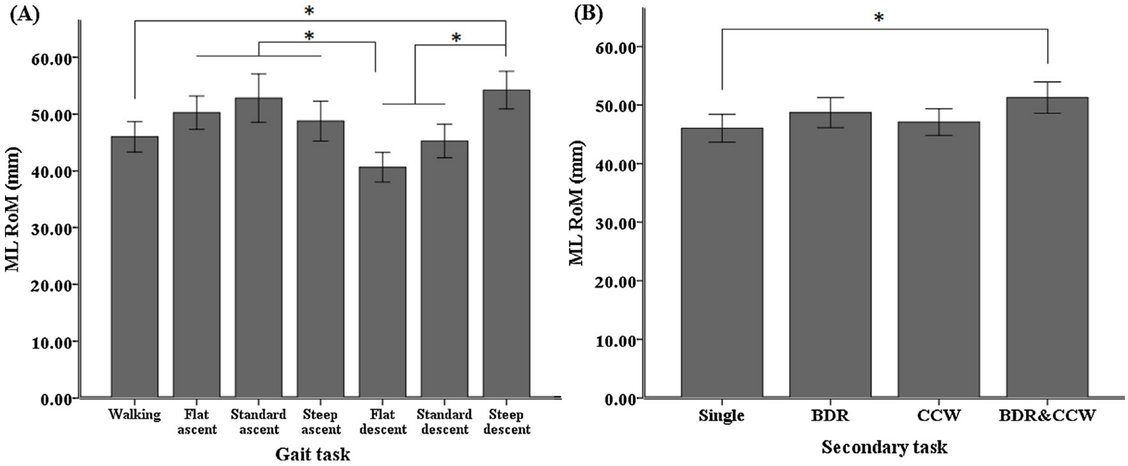

Fig. 3. ML-RoM shown as a function of (A) gait task (level walking, flat, standard and steep stair ascent and descent), (B) secondary task (single task, BDR, CCW and BDR&CCW). BDR, backward digit recall; CCW, carrying cup of water. Significant differences ($p < 0.05$) between the conditions are indicated by *. Error bars indicate standard error.

4.06 to 5.42 cm). Other studies reported an increased risk for falls only for larger displacements of ML COM (>6 cm) among community-dwelling older adults [24].

Gait speed decreased with stair steepness, which is also reported by others [16]. ML-RoM only showed an increase during descent. Consistent with other studies, our results show that stair ascent was more challenging than stair descent and level walking [22], which is shown by slower gait speed and higher ML-RoM. A possible explanation is that during ascent, system resources are directed towards *concentric* muscular action and energy generation, whereas during descent, resources are only directed towards *eccentric* muscle contraction, which is less demanding.

ML-RoM was not significantly affected when ascending steeper stairs—this may represent a successful effort to avoid imbalance. These observations are similar to those made during level walking and whilst stepping over an obstacle [24,25]: the average ML-RoM across all obstacle height conditions was significantly greater than during unobstructed walking but showed no significant increase as obstacle height increased. In our study, the largest ML-RoM may be indicative of cautious behaviour to reduce the risk of falling. Specifically, more caution is taken when stepping on a steeper stair.

In the current study, the type and complexity of the secondary task altered gait performance and ML-RoM. Performing a secondary task significantly decreased the gait speed indicating an interference of attentional demands between the secondary and the gait task. Previous studies have reported a similar alteration; motor and cognitive cost of dual-task walking heavily depends on the type and perceived complexity of the cognitive task being performed [9,12].

In each gait task, performing a cognitive task resulted in a slightly reduced gait speed indicating an attentionally demanding secondary task. In the cognitive task, the attentional resources were split and allocated arbitrarily to each task; the additional cognitive task draws attentional resources away from gait [5], thereby decreasing the gait speed and increasing ML-RoM compared to single task in this study. However, the increased ML-RoM in this study may also be due to an effort to produce a compensatory movement aimed at maintaining sideways stability which is consistent with previous research [24].

When the manual task was performed, gait speed reduction was more apparent compared to the cognitive task. A manual task shares the same resources as postural control. Thus, performing a manual task had more effect on gait performance. In contrast to these findings, another study reported that participants walked slower while performing a cognitive task as opposed to a manual task [12]. A possible explanation could be the fact that this study used cognitively impaired older people as opposed to younger adults.

The manual task exhibited a potential in increased dynamic stability in ML direction compared to the cognitive task, however, the effect was not significant in this study. In the present work, during the manual task, subjects were required to consciously pay attention to postural control in order to hold the cup straight. Further study of different types of manual tasks may support the idea that the constraint imposed by a more demanding manual component of the dual-task interplayed with the postural component, leading to improved body stability [13,14]. Also the cross-talk theory supports our findings, suggesting that performing two tasks which share the same resources may cause less interference in the performance of either tasks [30].

Conceptually and experimentally, BDR&CCW is the most difficult task and resulted in the most conservative gait in all gait tasks in this study. Attentional resources are limited in capacity; Result for dynamic stability and gait speed during BDR&CCW in all gait tasks demonstrated higher attentional demands of the secondary task and overlapping processing resources.

A limitation in the current study is that our results only show the effects of one particular type of manual task during gait. Investigating the kinetics of lower-extremities may provide a deeper understanding of the stair gait mechanisms under the secondary task condition. Also, a further application to the elderly population or patients with balance problems may enhance our understanding of the mechanisms underlying the increase of falls in the elderly. Finally, findings of this study, in particular the strategy chosen to avoid falls in challenging circumstances, can be used to evaluate balance and gait, and predict future falls.

5. Conclusion

Compromised ML-RoM and decreased gait speed are a compensation to improve dynamic stability and optimize the secondary task performance. The subjects in this study generally walked more slowly with alteration in ML-RoM when they were asked to walk and concurrently perform another task. The degree of reduction of gait speed and variation in ML-RoM changed by increasing gait and secondary task complexity. However, mean speeds and ML-RoM in all cases remained within normal limits. Variation in ML-RoM within the normal range does not necessarily indicate an increased risk of falling. This study suggests that the unconscious alteration in gait speed and COM RoM might be key to avoiding hazards and preventing falls and reflects an increase in dynamic gait stability.

Acknowledgments

This work is supported by the Dutch research project COMMIT—Virtual Worlds for Well-Being. The authors would like to thank Nicolas Pronost for his involvement in setting up the experiment, Ali A. Sangari for his help with analysing the results, and Yasaman Ganji and Mohammed N. Ashtiani for proofreading the manuscript.

Conflict of interest

There are no conflicts of interest.

References

[1] Stel VS, Smit JH, Pluijm SM, Lips P. Consequences of falling in older men and women and risk factors for health service use and functional decline. Age Ageing 2004;33:58–65.
[2] Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR. Stair negotiation in older people: a review. J Am Geriatr Soc 2000;48:567–80.
[3] Ojha HA, Kern RW, Lin C-HJ, Winstein CJ. Age affects the attentional demands of stair ambulation: evidence from a dual-task approach. Phys Ther 2009;89:1080–8.
[4] Vallabhajosula S, Tan CW, Mukherjee M, Davidson AJ, Stergiou N. Biomechanical analyses of stair-climbing while dual-tasking. J Biomech 2015;48:921–9.
[5] Asai T, Misu S, Doi T, Yamada M, Ando H. Effects of dual-tasking on control of trunk movement during gait: respective effect of manual-and cognitive-task. Gait Posture 2014;39:54–9.
[6] Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 2002;16:1–14.
[7] Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. Movement Disord 2008;23:329–42.
[8] Kelly VE, Janke AA, Shumway-Cook A. Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. Exp Brain Res 2010;207:65–73.
[9] Patel P, Lamar M, Bhatt T. Effect of type of cognitive task and walking speed on cognitive-motor interference during dual-task walking. Neuroscience 2014;260:140–8.
[10] Schaefer S, Jagenow D, Verrel J, Lindenberger U. The influence of cognitive load and walking speed on gait regularity in children and young adults. Gait Posture 2015;41:258–62.
[11] Simoni D, Rubbieri G, Baccini M, Rinaldi L, Becheri D, Forconi T, et al. Different motor tasks impact differently on cognitive performance of older persons during dual task tests. Clin Biomech 2013;28:692–6.
[12] Taylor ME, Delbaere K, Mikolaizak AS, Lord SR, Close JC. Gait parameter risk factors for falls under simple and dual task conditions in cognitively impaired older people. Gait Posture 2013;37:126–30.
[13] Morioka S, Hiyamizu M, Yagi F. The effects of an attentional demand tasks on standing posture control. J Physiol Anthropol Appl Hum Sci 2005;24:215–9.
[14] de Lima AC, de Azevedo Neto RM, Teixeira LA. On the functional integration between postural and supra-postural tasks on the basis of contextual cues and task constraint. Gait Posture 2010;32:615–8.
[15] Riener R, Rabuffetti M, Frigo C. Stair ascent and descent at different inclinations. Gait Posture 2002;15:32–44.
[16] Stacoff A, Diezi C, Luder G, Stüssi E, Kramers-de-Quervain IA. Ground reaction forces on stairs: effects of stair inclination and age. Gait Posture 2005;21:24–38.
[17] Vallabhajosula S, Yentes JM, Momcilovic M, Blanke DJ, Stergiou N. Do lower-extremity joint dynamics change when stair negotiation is initiated with a self-selected comfortable gait speed? Gait Posture 2012;35:203–8.
[18] Vallabhajosula S, Yentes JM, Stergiou N. Frontal joint dynamics when initiating stair ascent from a walk versus a stand. J Biomech 2012;45:609–13.
[19] Maylor EA, Wing AM. Age differences in postural stability are increased by additional cognitive demands. J Gerontol Ser B: Psychol Sci Soc Sci 1996;51:P54–143.
[20] Kadaba MP, Ramakrishnan H, Wootten M. Measurement of lower extremity kinematics during level walking. J Orthopaed Res 1990;8:383–92.
[21] Zeni Jr J, Richards J, Higginson J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait Posture 2008;27:710–4.
[22] Protopapadaki A, Drechsler WI, Cramp MC, Coutts FJ, Scott OM. Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. Clin Biomech 2007;22:203–10.
[23] Grenholm A, Stensdotter A-K, Häger-Ross C. Kinematic analyses during stair descent in young women with patellofemoral pain. Clin Biomech 2009;24:88–94.
[24] Chou L-S, Kaufman KR, Hahn ME, Brey RH. Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait Posture 2003;18:125–33.
[25] Chou L-S, Kaufman KR, Brey RH, Draganich LF. Motion of the whole body's center of mass when stepping over obstacles of different heights. Gait Posture 2001;13:17–26.
[26] Mian OS, Narici MV, Minetti AE, Baltzopoulos V. Centre of mass motion during stair negotiation in young and older men. Gait Posture 2007;26:463–9.
[27] Catena RD, van Donkelaar P, Chou L-S. Cognitive task effects on gait stability following concussion. Exp Brain Res 2007;176:23–31.
[28] Shumway-Cook A, Woollacott M. Attentional demands and postural control: the effect of sensory context. J Gerontol-Biol Sci Med Sci 2000;55:M10.
[29] Silsupadol P, Siu K-C, Shumway-Cook A, Woollacott MH. Training of balance under single-and dual-task conditions in older adults with balance impairment. Phys Ther 2006;86:269–81.
[30] Schmidt RA, Lee T. Motor Control Learning: Human Kinetics 1988.

RESEARCH ARTICLE

The effects of unexpected mechanical perturbations during treadmill walking on spatiotemporal gait parameters, and the dynamic stability measures by which to quantify postural response

Forough Madehkhaksar[1,2]*, Jochen Klenk[2,3], Kim Sczuka[2], Katharina Gordt[2,4], Itshak Melzer[5], Michael Schwenk[2,4]

1 Department of Sports Sciences, Heidelberg University, Heidelberg, Germany, **2** Department of Clinical Gerontology and Rehabilitation, Robert-Bosch-Hospital, Stuttgart, Germany, **3** Insitute of Epidemiology and Medical Biometry, Ulm University, Ulm, Germany, **4** Network Aging Research (NAR), Heidelberg University, Heidelberg, Germany, **5** Department of Physical Therapy, Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

* madehkhaksar@stud.uni-heidelberg.de

Abstract

Most falls occur after a loss of balance following an unexpected perturbation such as a slip or a trip. Greater understanding of how humans control and maintain stability during perturbed walking may help to develop appropriate fall prevention programs. The aim of this study was to examine changes in spatiotemporal gait and stability parameters in response to sudden mechanical perturbations in medio-lateral (ML) and anterior-posterior (AP) direction during treadmill walking. Moreover, we aimed to evaluate which parameters are most representative to quantify postural recovery responses. Ten healthy adults (mean = 26.4, SD = 4.1 years) walked on a treadmill that provided unexpected discrete ML and AP surface horizontal perturbations. Participants walked under no perturbation (normal walking), and under left, right, forward, and backward sudden mechanical perturbation conditions. Gait parameters were computed including stride length (SL), step width (SW), and cadence, as well as dynamic stability in AP- (MoS-AP) and ML- (MoS-ML) directions. Gait and stability parameters were quantified by means, variability, and extreme values. Overall, participants walked with a shorter stride length, a wider step width, and a higher cadence during perturbed walking, but despite this, the effect of perturbations on means of SW and MoS-ML was not statistically significant. These effects were found to be significantly greater when the perturbations were applied toward the ML-direction. Variabilities, as well as extremes of gait-related parameters, showed strong responses to the perturbations. The higher variability as a response to perturbations might be an indicator of instability and fall risk, on the same note, an adaptation strategy and beneficial to recover balance. Parameters identified in this study may represent useful indicators of locomotor adaptation to successfully compensate sudden mechanical perturbation during

Citation: Madehkhaksar F, Klenk J, Sczuka K, Gordt K, Melzer I, Schwenk M (2018) The effects of unexpected mechanical perturbations during treadmill walking on spatiotemporal gait parameters, and the dynamic stability measures by which to quantify postural response. PLoS ONE 13(4): e0195902. https://doi.org/10.1371/journal.pone.0195902

Editor: Jeffrey M Haddad, Purdue University, UNITED STATES

Received: November 4, 2017

Accepted: April 2, 2018

Published: April 19, 2018

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: Forough Madehkhaksar was supported by Network Aging Research (NAR) during working on this project. We acknowledge financial support by Deutsche Forschungsmemeintschaft within the funding programme Open Access Publishing, by the Baden-Württemberg Ministry of Science, Research and the Arts and by Ruprecht-Karls-Universität Heidelberg.

Competing interests: The authors have declared that no competing interests exist.

walking. The potential association of the extracted parameters with fall risk needs to be determined in fall-prone populations.

Introduction

Falls are a serious clinical problem and often lead to injuries, the decline in mobility, and self-imposed limitations on daily activities, especially in older adults. Fall-related injuries increase costs for health care and rehabilitation and diminish the quality of life [1–3]. Most falls occur after a loss of balance while walking, which is the most common activity in daily life, and following an unexpected perturbation such as a slip or trip [4]. Therefore, understanding of how humans control balance and maintain stability during unexpected perturbed walking can help with assessment of balance recovery ability and thus may help to reduce the incidence of falls.

In order to enhance understanding of falls caused by perturbations, recent studies have examined changes in spatiotemporal gait parameters and dynamic stability (i.e., the margins of stability [5,6]) following perturbations. Evidence has demonstrated adaptations of spatiotemporal gait parameters to challenged walking by taking faster, shorter, and wider steps [7–11]. Consequently, an alteration in gait parameters led to increased margins of stability (MoS) and to enhanced stability during challenging walking [8,9]. While these alterations in spatiotemporal gait parameters and dynamic stability occurred during different types of perturbations, such as continuous mechanical and visual perturbations [9–14], it remains inconclusive whether these observable adaptations also occur during sudden mechanical surface perturbations in different directions.

The majority of perturbation studies has included perturbations only in the anterior-posterior (AP) [7,15–17] or in the medio-lateral (ML) direction [9,11,13,14,18,19]. However, each of these perturbations affects gait and stability in different ways, depending not only on the type but also on the direction of the perturbations. Exposure to the continuous support surface [10,12] and visual field [10,20,21] in both AP- and ML-directions produced anisotropic changes in gait variabilities. The effects of perturbations were also found to be significantly greater when perturbations were applied in the ML-direction [10,12,21]. Also, the unidirectionality (AP or ML) of the perturbation may help the subjects in developing a volitional plan for a stepping response thus lack's the ecological validity since falls in the real world are multidirectional and always unexpected [22,23]. Therefore, further studies on the effect of perturbations on gait-related parameters and dynamic stability, which include sudden mechanical surface perturbation in both AP- and ML-directions may reveal valuable information.

The means of gait characteristic appeared resistant to the effect of challenging walking depending on the challenge [18,24]. Alternatively, the response of variability to perturbations was stronger than the response of means during the continuous platform and visual perturbations [12]. This indicated an increased challenge in stability that was not captured by means but by the variability of parameters [12]. Thus, gait variability, which is defined as fluctuation in gait parameters from one step to the next, might be an important indicator of gait stability [25,26], and more responsive than the mean differences of the gait parameters.

Prior studies have used gait variability to characterize balance during walking [10,11,18,21,27]. However, studies on the response of variability of the gait parameters to perturbations provided contradictory results. Continuous support surface perturbations during walking in a static visual environment induced increased step width variability [14]. On the other hand, Francis et al. reported no significant increase in gait variability in young adults in response to visual ML perturbation [18]. These differences might appear due to different types of perturbations applied in these studies. In a recent work, Punt et al. explored the effects of multidirectional sudden mechanical perturbations in stroke survivors who prospectively experienced falls or no falls [28]. By comparing the gait characteristics and dynamic stability in both fallers and non-fallers group over every step after the perturbation, they observed no difference in individual's ability to cope with the perturbations. Although their study provided interesting insight into the response strategy in stroke survivors, the variability of the parameters which might reveal helpful information in discriminations between fallers and non-fallers was not included. There is a need for studies which examine the effect of sudden multidirectional unexpected mechanical perturbations on the variability of gait-related parameters.

Additionally, extremes of gait-related parameters may be a better representative estimate of the parameters in a challenging condition, such as perturbed walking compared with the mean values that traditionally being used in research [29]. Rispens et al. found a strong association between extremes relating to high gait quality and fall risk during daily life walking. During perturbed treadmill walking, extremes may better capture pronounced postural responses after perturbations, and in turn may be more sensitive indicators of gait stability [29]. To the best of our knowledge, there have been no studies to evaluate the response of extremes of gait-related parameters to quantify postural stability during perturbed walking.

The first aim of this study was to examine the changes in a candidate set of spatiotemporal gait and stability parameters in response to sudden unexpected multidirectional mechanical perturbations. Secondly, we aimed to evaluate the most affected parameters of this set for measuring the effect of perturbations on postural recovery responses. Means, variability, and extremes of gait-related parameters were used to specify responses during perturbed treadmill walking. We hypothesized that participants would exhibit: (1) alterations in spatiotemporal gait parameters to enhance dynamic stability and (2) a greater effect of perturbations on extremes and variability of measures, as compared to means.

Methods

Participants and experimental protocol

Ten healthy young adults (age: 26.4 ± 4.1 years, height: 1.7 ± 0.08 m, mass: 64.4 ± 12.5 kg, 7 females) participated in this study. All participants provided written informed consent and the study was approved by the ethical committee of the Medical Faculty, Tübingen University. Recruited subjects had no experience of walking on the perturbation treadmill.

Participants walked on a perturbation treadmill (Balance Tutor, MediTouch, Netanya, Israel) at the fixed speed of 1.11 ms^{-1} and were subjected to unexpected surface perturbations in left, right, forward, and backward directions (Fig 1). The system has been described in detail previously [30]. The treadmill platform is mounted on linear slides, which allow to translate it in the lateral direction. Left and right perturbations were induced by automatically moving the treadmill surface in ML-direction (12.8 cm and 1.5 ms^{-2}). Forward and backward perturbations were induced by acceleration and deceleration of the belt. To present the forward perturbation, the belt speed accelerated toward 2.5 ms^{-1} and subsequently decelerated toward 1.1 ms^{-1}. The backward perturbation was presented by deceleration of the belt speed toward 0 ms^{-1} and subsequent acceleration toward 1.1 ms^{-1}. First, the subjects completed 5 minutes (min) of normal walking on the perturbation treadmill without perturbations to become familiar with treadmill walking. The last min of the treadmill walking trial was used for data analysis (Normal) in order to measure the subject's normal walking pattern. Afterwards, 4 trials of 1 min perturbation treadmill walking were recorded. During each trial, participants were exposed to a single perturbation in a specific direction in order to become familiar with perturbed

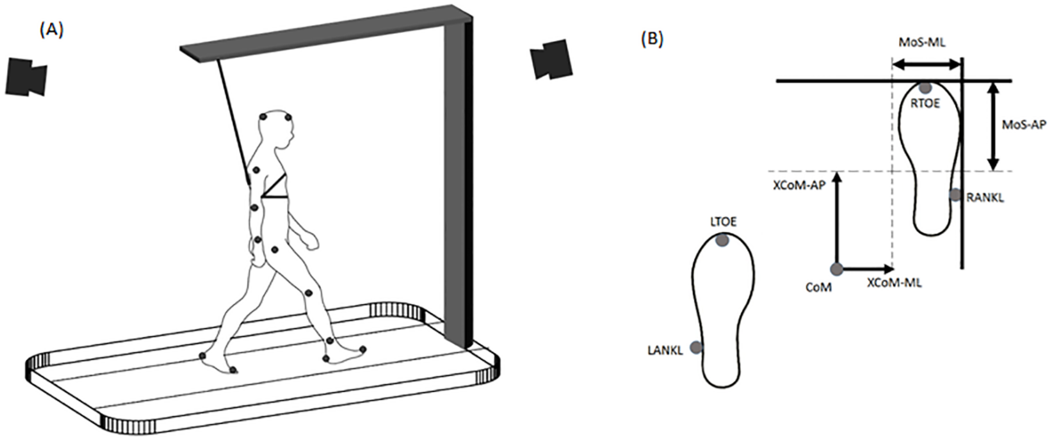

Fig 1. (A) A schematic drawing of the experimental setup. Forward and backward perturbations were induced by acceleration and deceleration of the treadmill's belt. Left and right perturbations were induced by moving the treadmill surface in the ML-direction. Reflective markers were placed at specific anatomical locations in accordance with the plug-in-gait marker set. (B) MoS-AP was defined as the AP distance between the XCoM-AP and the anterior boundary of the BoS, defined by the leading toe marker (either RTOE or LTOE for the right and the left foot, respectively). MoS-ML was defined as the ML distance between the XCoM-ML and the lateral boundary of the BoS, defined by the ankle marker (RANKL and LANKL for the right and the left foot, respectively).

https://doi.org/10.1371/journal.pone.0195902.g001

walking. Subsequently, 4 trials of 5 min perturbation treadmill walking including a series of 16 perturbations towards a specific direction were recorded. The moment of all perturbations was unpredictable. The time interval between perturbations ranged from 15–25 sec. All participants walked in their comfortable sport shoes. Subjects always wore a loss safety harness to prevent falls that prevented falls but did not restrict their gait.

Measurements and data analysis

Kinematic data were recorded at 200 Hz with an eight cameras motion capture system (Vicon Motion System, Oxford, UK). A total of 39 reflective markers were placed at specific anatomical locations in accordance with the Plug-In-Gait marker set (Bodybuilder, Plug in Gait model, Vicon Motion Systems, Oxford, UK). Motion data was analyzed using the Vicon Nexus software (Version 2.5). The time frame of interest was 15 sec including 5 sec before and 10 sec after the perturbation.

Spatiotemporal gait parameters including step length, step width, and cadence were measured at the instant of the heel strike. Heel strike was identified as the local maxima of the position of the heel markers in the AP-direction [31]. Stride length was defined as the AP-distance between heel markers at the instant of heel strike plus the treadmill translation during the stride. Step width was measured as the ML-distance between ankle markers at the moment of heel strike. Cadence was calculated as the number of steps per minute.

Dynamic margins of stability were adapted from Hof et al. [5]. In this study, the extrapolated center of mass (XCoM) was calculated as the position of the center of mass (CoM), plus its velocity multiplied by the factor $\sqrt{lg^{-1}}$, where g was the acceleration of gravity and l was the distance from the ankle marker of the trailing foot to the CoM at the instant of heel strike. The margins of stability in the anterior-posterior direction (MoS-AP) were calculated as the AP distance between the XCoM and the toe marker of the leading foot. The margins of stability in the ML-direction (MoS-ML) were calculated as the lateral distance between the XCoM and the ankle marker of the leading foot (Fig 1). MoS was calculated at heel strike for every step during each time frame (~ 24 steps per each 15 sec time frame). All processing and analyses were performed with custom MATLAB R2015a programs (Mathworks, Inc., Natic, USA). Measured values were visually checked regarding plausibility and wrong values resulted from an error in the calculations due to the disturbed trajectory of markers were removed for further analyzing.

For each time frame of 15 sec treadmill walking, the mean from all steps performed was calculated for each spatiotemporal gait parameter and MoS. Additionally, variability characterized as the standard deviation was calculated for each spatiotemporal gait parameter and MoS. Thus, gait characteristics were measured as the mean (mn) and standard deviation (sd) of the spatiotemporal gait parameters including stride length (SL_{mn} and SL_{sd}), step width (SW_{mn} and SW_{sd}), and cadence ($cadence_{mn}$ and $cadence_{sd}$). Dynamic stability was calculated as the mean and standard deviation of MoS in AP- ($MoS\text{-}AP_{mn}$ and $MoS\text{-}AP_{sd}$) and ML- ($MoS\text{-}ML_{mn}$ and $MoS\text{-}ML_{sd}$) directions.

In addition, extremes were estimated as the 10th and 90th percentiles of the stride length (SL_{P10} and SL_{P90}), step width (SW_{P10} and SW_{P90}), and cadence ($cadence_{P10}$ and $cadence_{P90}$), as well as MoS in AP- ($MoS\text{-}AP_{P10}$ and $MoS\text{-}AP_{P90}$) and ML- ($MoS\text{-}ML_{P10}$ and $MoS\text{-}ML_{P90}$) directions.

Statistical analysis

Multiple measures of variable including the mean, variability, and extremes of the spatiotemporal gait parameters as well as MoS in ML- and AP-directions were reduced to the mean values for each walking condition. Paired t-test and corresponding confidence interval (CI) was used to examine differences between normal walking and perturbed walking conditions. In addition, the effect size of responses was calculated using Cohen's *d* statistic (*d*) to describe the strength of the effect of perturbation conditions on each measurement. Cohen's *d* statistic was defined as the mean difference between normal and perturbed walking conditions divided by the standard deviation of changes between conditions.

All statistical analyses were performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA) with a confidence interval of 95% for all comparisons.

Results

All subjects completed the experiment with no fall into the harness system during the perturbation trials. In total, 116 left, 130 right, 141 forward, and 144 backward perturbations were analyzed. The results for means, variabilities, and extremes of normal walking, as well as perturbed walking, are presented in Table 1. Also, results of statistical analyses including mean differences of perturbed walking conditions relative to normal walking, as well as the associated CI and effect sizes (i.e., Cohen's *d* statistic) are presented in Figs 2 and 3.

Means of gait parameters and dynamic stability

Overall, compared with unperturbed treadmill walking, participants walked with shorter stride length, wider step width, and higher cadence during ML perturbations. However, the effect of perturbations on SW_{mn} was not statistically significant (Fig 2A, 2B and 2C). Exposure to the right perturbation resulted in a significantly shorter stride length (Est. = -3.478, 95% CI [-5.302, -1.652], d = -1.363). In left perturbation, participants tended to decrease their stride length (Est. = -2.448, 95% CI [-5.101, 0.206], d = -0.66). However, there were no significant differences in SL_{mn}, SW_{mn}, and $Cadence_{mn}$ during forward and backward perturbations compared with unperturbed walking (Fig 2A, 2B and 2C).

Table 1. Results for spatiotemporal gait parameters and margins of stability during different walking conditions (mean and SD; n = 10).

	Condition				
	Normal	**Left**	**Right**	**Backward**	**Forward**
Stride length [cm]					
Mean	128.83 ± 8.68	126.38 ± 7.56	125.35 ± 7.98	129.59 ± 7.54	127.61 ± 7.56
Variability	2.08 ± 0.48	6.43 ± 1.75	7.86 ± 1.98	4.03 ± 0.78	5.41 ± 1.09
P10	126.32 ± 8.55	121.65 ± 6.61	121.52 ± 7.53	125.82 ± 7.25	122.62 ± 7.76
P90	131.54 ± 8.78	131.34 ± 8.00	130.53 ± 8.40	133.08 ± 8.09	132.18 ± 8.14
Step width [cm]					
Mean	20.97 ± 2.92	21.71 ± 3.30	21.69 ± 3.51	21.74 ± 3.22	21.14 ± 3.32
Variability	1.57 ± 0.39	3.18 ± 0.53	2.87 ± 0.38	2.02 ± 0.60	2.06 ± 0.72
P10	19.06 ± 2.86	18.56 ± 3.29	18.62 ± 3.70	19.29 ± 3.42	18.53 ± 3.46
P90	22.96 ± 3.03	25.19 ± 3.29	24.87 ± 3.34	24.49 ± 3.46	23.78 ± 3.52
Cadence [steps/min]					
Mean	103.96 ± 5.49	106.26 ± 6.26	107.14 ± 6.67	103.70 ± 5.72	105.08 ± 5.94
Variability	1.45 ± 0.40	4.83 ± 2.28	5.81 ± 1.76	2.50 ± 0.44	4.87 ± 1.35
P10	102.14 ± 6.63	102.81 ± 6.27	103.28 ± 6.33	101.06 ± 5.73	101.64 ± 5.89
P90	105.85 ± 6.64	110.96 ± 6.87	112.19 ± 7.09	106.25 ± 5.62	108.39 ± 5.81
MoS-ML [cm]					
Mean	8.89 ± 1.24	9.17 ± 1.41	9.07 ± 1.48	9.19 ± 1.38	8.92 ± 1.51
Variability	0.67 ± 0.16	1.43 ± 0.27	1.42 ± 0.18	0.97 ± 0.24	1.03 ± 0.20
P10	8.01 ± 1.30	7.73 ± 1.25	7.75 ± 1.58	8.05 ± 1.38	7.83 ± 1.39
P90	9.76 ± 1.26	10.62 ± 1.61	10.48 ± 1.46	10.42 ± 1.53	10.13 ± 1.62
MoS-AP [cm]					
Mean	9.38 ± 2.86	8.11 ± 2.39	7.61 ± 2.35	9.67 ± 2.64	8.81 ± 2.66
Variability	0.96 ± 0.25	3.37 ± 1.01	2.89 ± 0.55	1.62 ± 0.51	3.94 ± 0.48
P10	8.17 ± 3.00	4.78 ± 2.55	3.67 ± 2.57	7.78 ± 2.99	6.41 ± 2.41
P90	10.62 ± 2.69	11.01 ± 2.34	10.07 ± 2.17	11.32 ± 2.46	11.33 ± 2.74

https://doi.org/10.1371/journal.pone.0195902.t001

Similar to SL_{mn}, exposure to right perturbation resulted in significantly shorter MoS-AP_{mn} compared with unperturbed walking (Est. = -1.776, 95% CI [-2.665, -0.887], d = -1.429, Fig 3A). Also, MoS-AP_{mn} tended to decrease during left perturbation, however, the effect did not reach to the significant level (Est. = -1.269, 95% CI [-3.093, 0.555], d = -0.498). The perturbations had no significant effect on MoS-ML_{mn} (Fig 3B).

Variability of gait parameters and dynamic stability

During all perturbation conditions, the variability of stride length, step width, and cadence was significantly higher than during unperturbed walking (Fig 2D, 2E and 2F). Lateral perturbations resulted in an increase in the variability of stride length and step width than forward and backward perturbations. However, the strength of the effect on stride length variability appeared high during all perturbation conditions (Left: Est. = 4.352, 95% CI [3.091, 5.613], d = 2.468; Right: Est. = 5.784, 95% CI [4.271, 7.298], d = 2.733; Backward: Est. = 1.955, 95% CI [1.278, 2.632], d = 2.066; Forward: Est. = 3.331, 95% CI [2.488, 4.175], d = 2.826, Fig 2D). On the other hand, the results of SW_{sd} exhibited stronger effect of lateral perturbations than forward and backward perturbations (Left: Est. = 1.609, 95% CI [1.261, 1.958], d = 3.307; Right: Est. = 1.299, 95% CI [1.073, 1.526], d = 4.109; Backward: Est. = 0.448, 95% CI [0.142, 0.754], d = 1.048; Forward: Est. = 0.495, 95% CI [0.053, 0.937], d = 0.801, Fig 2E).

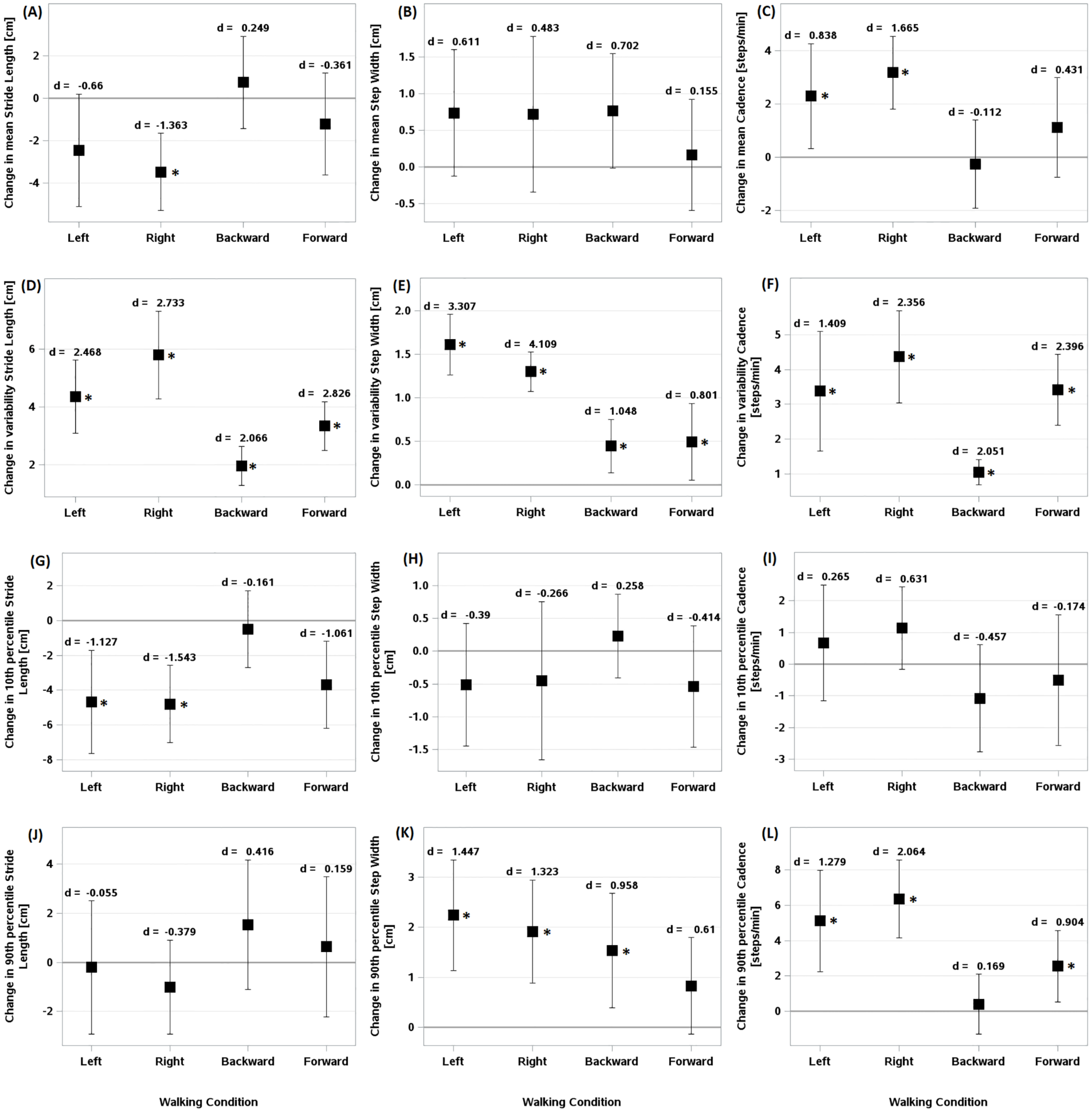

Fig 2. Difference of means, variability, and extremes of spatiotemporal gait parameters during perturbed walking conditions relative to normal walking. Difference of means of (A) stride length, (B) step width, and (C) cadence. Difference of variability of (D) stride length, (E) step width, and (F) cadence. Difference of 10th percentile of (G) stride length, (H) step width, and (I) cadence. Difference of 90th percentile of (J) stride length, (K) step width, and (L) cadence. *d* indicates Cohen's *d* statistic effect size. Error bars indicate confidence intervals. (*) indicates statistically significant differences from Normal walking.

https://doi.org/10.1371/journal.pone.0195902.g002

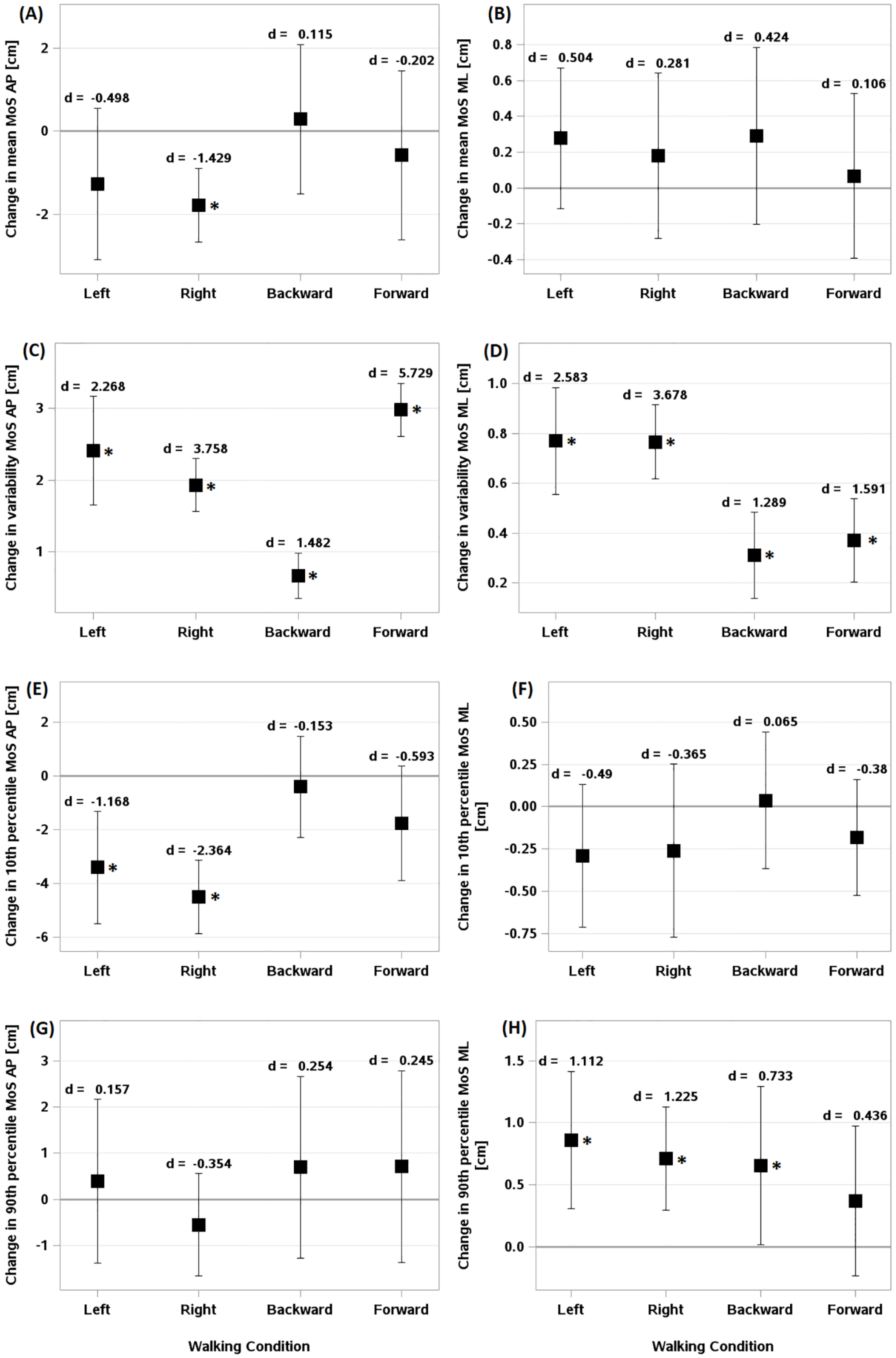

Fig 3. Difference of means, variability, and extremes of dynamic stability during perturbed walking conditions relative to normal walking. Difference of means of (A) MoS-AP and (B) MoS-ML. difference of variability of (C) MoS-AP and (D) MoS-ML. difference of 10th percentile of (E) MoS-AP and (F) MoS-ML. difference of 90th percentile of (G) MoS-AP and (H) MoS-ML. *d* indicates Cohen's *d* statistic effect size. Error bars indicate confidence intervals. (*) indicates statistically significant differences from Normal walking.

https://doi.org/10.1371/journal.pone.0195902.g003

Similar to the results of gait parameters, the dynamic stability exhibited significantly greater variability during all perturbation conditions relative to unperturbed treadmill walking (Fig 3C and 3D). However, forward perturbation had greater effect on MoS-AP$_{sd}$ than on MoS-ML$_{sd}$ (Est. = 2.979, 95% CI [2.607, 3.351], d = 5.729 and Est. = 0.371, 95% CI [0.204, 0.537], d = 1.591, respectively).

Extreme values

The results for extremes of spatiotemporal gait parameters showed no significant differences between SL$_{P90}$, SW$_{P10}$, and Cadence$_{P10}$ during perturbation walking conditions compared with unperturbed treadmill walking (Fig 2J, 2H and 2I). SL$_{P10}$ during lateral and forward perturbations was significantly shorter than during unperturbed walking (Left: Est. = -4.663, 95% CI [-7.624, -1.702], d = -1.127; Right: Est. = -4.794, 95% CI [-7.017, -2.572], d = -1.543; Forward: Est. = -3.699, 95% CI [-6.192, -1.205], d = -1.061, Fig 2G). Also, SW$_{P90}$ significantly increased during lateral and backward perturbations (Left: Est. = 2.239, 95% CI [1.132, 3.347], d = 1.447; Right: Est. = 1.913, 95% CI [0.879, 2.948], d = 1.323; Backward: Est. = 1.534, 95% CI [0.389, 2.679], d = 0.958, Fig 2K). In addition, cadence$_{P90}$ during sideway and forward perturbations was significantly greater than during unperturbed walking, however the effect of lateral perturbations was stronger compared with backward perturbation (Left: Est. = 5.11, 95% CI [2.253, 7.968], d = 1.279; Right: Est. = 6.349, 95% CI [4.148, 8.549], d = 2.064; Forward: Est. = 2.549, 95% CI [0.531, 4.568], d = 0.904, Fig 2L).

Similar to the results of step width, MoS-ML$_{P90}$ during lateral and backward perturbations was significantly larger than during unperturbed walking (Left: Est. = 0.861, 95% CI [0.307, 1.414], d = 1.112; Right: Est. = 0.714, 95% CI [0.297, 1.131], d = 1.225; Backward: Est. = 0.656, 95% CI [0.016, 1.297], d = 0.733, Fig 3H). However, the results of MoS-ML$_{P10}$ showed no significant change between perturbed and unperturbed gait (Fig 3F). Also, MoS-AP$_{P90}$ was not significantly different between perturbed and unperturbed treadmill walking (Fig 3G), whereas MoS-AP$_{P10}$ during ML perturbation was significantly greater than during unperturbed walking (Left: Est. = -3.401, 95% CI [-5.484, -1.318], d = -1.168; Right: Est. = -4.505, 95% CI [-5.868, -3.142], d = -2.364, Fig 3E).

Discussion

In this study, we found that spatiotemporal gait parameters, as well as MoS, were affected during exposure to AP- and ML- perturbations depending on the direction of the perturbations. Participants took shorter, wider, and faster steps in order to increase their dynamic stability in balance recovery during walking. More noteworthy was the increase in variability of these parameters relative to unperturbed walking. These effects were also found to be significantly greater when the perturbations were applied in the ML-direction.

Interestingly and as one might have expected by theory, the response of stride length (i.e. AP response of spatial gait parameters) and MoS-AP (i.e. AP response of dynamic stability) exhibited the same pattern of response to perturbations. Similarly, the response pattern of step width (i.e. ML response of spatial gait parameters) and MoS-ML (i.e. ML response of dynamic stability) appeared comparable. In addition, the response pattern of cadence (i.e., temporal gait parameter) was reversely the same as that for stride length. Based on the theoretical models, in which the human body during walking is modeled as a simple inverted pendulum, cadence, stride length, and walking speed cannot be adapted independently from each other [5,6,8,32]. In the present study, subjects walked on the treadmill with a fixed walking speed, therefore cadence was adapted according to the stride length.

Previous studies showed decreases in stride length, increases in step width and cadence with increasing perturbation intensity [9–11,33]. In this study, subjects exhibited shorter, larger, and faster steps during ML than AP perturbations, suggesting that ML perturbations were more challenging than AP perturbations, which is consistent with McIntosh et al. who used ML and AP overground platform perturbations during walking [34]. However, they quantified responses by CoM displacement and velocity, thus it remained unknown to what extent the stability of gait was affected by perturbations.

In line with previous studies, MoS-AP significantly decreased in response to ML perturbations [12]. MoS-AP is defined as the distance between the AP boundaries of the base of support (BoS) and XCoM. Shorter and faster steps, which bring the CoM closer to the moving BoS, improved stability in AP-direction [7,9,32,33]. Conversely, MoS-ML slightly increased in response to applied perturbations implies a decrease in risk of falling [9,12]. Similar to the previous studies, our results show that lateral dynamic stability was controlled by taking slightly wider steps to maintain stable walking during the perturbed walking [6,9,12]. The MoS in ML direction is defined as the distance between the ML borders of the BoS and XCoM. Thus, increased step width resulted in an increase in MoS-ML [9,20].

Perturbations had a strong effect on variabilities, indicating that step irregularity is a specific characteristic of walking adaptability during perturbed walking [10,11,13,21]. Our results suggest that looking at the variability of parameters over a series of steps is a responsive measure of gait adaptations happening during perturbed walking. Importantly, it should be noted that in this method, the effect of the perturbations on the mean of the parameters could be smeared out, since it was measured over a series of steps and not over every single step after the perturbation. Despite limited responsiveness for measuring the effects on means, the presented approach of capturing the variability may represent a useful measure in future studies estimating fall risk in fall-prone populations. For instance, in a recent study, Punt et al. reported no difference between fallers and non-fallers ability to cope with perturbation when measuring mean of the parameters over every single step following the perturbation [28]. In their study, the effect of the perturbations on gait variability over series of steps (i.e. fluctuations) was not investigated, which might be helpful in providing additional information to discriminate between fallers and non-fallers. Our findings of high responsiveness of variability parameters are in agreement with Terry et al. who reported variabilities of CoM position and step width as the most sensitive parameters in response to continuous visual and mechanical perturbations toward ML-direction [13]. Also, in a recent study, Stokes et al. reported a more profound effect of continuous visual ML perturbations on variabilities of step width, step length, and trunk sway [11].

Significantly greater variability in response to ML perturbations indicates that to maintain stability, participants needed to exert greater control in response to ML perturbations [10,21,35]. The variability of SL was strongly affected by both ML and AP perturbations, whereas the effect of ML perturbations on the variability of SW was much greater than the effect of AP perturbations. MoS variability increased during all perturbed walking conditions. However, similar to variabilities of gait parameters, the variability of MoS was also greater for ML perturbations, as reported previously [12], reflecting the increased fluctuations in the placement of protective stepping after the onset of the perturbation in order to enhance stability [27]. Additionally, the variability of MoS-AP during the forward perturbation increased which was also reported by Young et al., demonstrating higher fluctuations of MoS-AP in the forward direction [12]. In the present study, gait instability was analyzed using an approach similar to that used by Lipsitz et al. [36] measuring heart rate variability and by Hausdorff et al. [37] measuring gait variability. The higher variability (i.e., more fluctuations) during and immediately after recovery stepping may be referred to as unsteadiness. In this sense, the variability of gait and stability parameters may be used as a marker of unsteadiness, instability, and fall risk. This should be further explored by applying this method in older adults and impaired population since not all variability is a mark of poor locomotor control. As in heart rate variability, some variability may reflect adaptability and be beneficial especially after an unexpected loss of balance. Indeed, the ability to adapt gait when negotiating unexpected hazards is crucial to maintain stability and avoid falling [38]. In the present study, the healthy young participants experienced no difficulty and no fall during perturbed walking. Thus, the high variability may show the ability of the young subjects to adapt the gait pattern which may be a healthy behavior to respond to unexpected perturbation. This initial work suggests that just as there is much to be gained by investigating gait and heart rate dynamics, above and beyond the study of the average heart rate and gait dynamics, similar investigations of step dynamics after an unexpected loss of balance may provide insight into postural stability and may also have clinical applications.

ML perturbations resulted in a deviation from the straight walking trajectory. Consequently, a lateral step or a crossing step was necessary to prevent sideward fall. Probably, increasing the step width causing increased MoS-ML which results in decreasing the risk of a sideward fall was prioritized above the stability in AP-direction. Therefore, participants in this study increased the variability of AP responses as well as ML responses to compensate for the higher risk of fall following the ML perturbations by taking wider and shorter steps. But AP perturbations resulted in an interruption of the forward progression. In this case, the risk of fall in backward and forward direction could decrease, respectively, by taking a backward or a fast and short forward step which resulted in the higher effect on the variability of AP responses than on ML responses. This observation suggests that presenting the ML perturbations affected stability in both ML- and AP-directions with a stronger effect in sideway fall than AP falls, and AP perturbations resulted in a stronger effect in the direction of the presented perturbation.

Backward perturbation reduced the distance between the anterior border of the BoS and the XCoM thus increased MoS-AP. It should be noted that increase in MoS-AP simultaneously might have the disadvantage increasing the risk of a backward loss of balance. Consequently, subjects took wider steps to recover stability. The increased step width during backward perturbation resulted in a greater MoS in ML-direction. However, the results of backward perturbation in this study should be interpreted with some cautions. Backward perturbations were presented by deceleration of the treadmill belt, which was accompanied by a sudden stop in the belt movement. Thus, gait cycles included in the backward perturbation consisted of gait cycles before and after the belt stop, and motion's frames related to the stop of the belt were excluded from the analysis.

Extremes related to 'high gait quality' (HGQ) contain information about the best possible performance in the high-risk situation, whereas extremes related to 'low gait quality' (LGQ) contain information about responding to the risk which is related to the more demanding situations [29]. Therefore, together with the findings of this study, HGQ parameters are related to responses which show larger stride length (SL_{P90}), shorter step width (SW_{P10}), lower cadence ($cadence_{P10}$), higher MoS-AP ($MoS\text{-}AP_{P90}$), and lower MoS-ML ($MoS\text{-}ML_{P10}$). While, LGQ parameters are expected to represent subject's responses in the high-risk situations (i.e. during perturbations) which show shorter stride length (SL_{P10}), larger step width (SW_{P90}), higher cadence ($cadence_{P90}$), lower MoS-AP ($MoS\text{-}AP_{P10}$), and higher MoS-ML ($MoS\text{-}ML_{P90}$).

HGQ parameters during perturbed walking exhibited no difference with that of normal walking. Thus, they showed no sensitivity to perturbations. As suggested by Rispens et al., perhaps the HGQ extremes are an accurate estimation of the individual's capacities and do not capture the effect of perturbations [29]. Therefore, they showed the capacity and the best performance of young healthy adults in response to perturbations which exhibited no difference with normal walking.

Interestingly, the results of LGQ for all parameters were similar with the results of means and showed the same response pattern. However, the effect of LGQ of parameters was somewhat more significant and stronger compared to means. Thus, it seems that LGQ were more responsive and might be representative of the effect of unexpected perturbations.

There are some limitations in this study. First, due to technical limitations of the treadmill, all expected numbers of perturbations were not presented. Second, trials were not presented in a randomized order, therefore, the results of each condition could be influenced by learning of the previous condition. However, this fact does not interfere with the findings of this study since the main goal of this exploratory experiment was to find the effect of perturbations on spatiotemporal gait and dynamic stability parameters in order to evaluate the most sensitive measures which can better represent the effect of perturbations. Third, the data came from a fairly small sample of relatively healthy young adults. Thus there is a need to investigate larger sample sizes and explore older and "weaker" populations. Forth, there was no reflective markers attached to the treadmill. Consequently, the exact frame in which the perturbation was presented was undetectable. To address this limitation, all parameters were measured over a series of recovery steps and not over every single step after the perturbation. In this study, the extreme of the parameters may have captured the immediate effect of the perturbations on the parameters. Therefore, the present approach may potentially capture both the local effects (extremes) and the fluctuations over a series of steps (variability), although this needs to be validated in future studies. The detected information on extremes and variability of the parameters should be clinically validated as a fall risk assessment by applying this method on fall-prone populations. We acknowledge that the method of measurement over series of steps from a perturbation trial arose some limitations such as missing the subtleties that happen around the single steps following the perturbation. While the approach of analyzing a series of steps provided interesting information about the variability, it may smear out the effects of means. Therefore, the effect of the perturbations on the immediate steps after the perturbations should be investigated in future studies. In addition, the moment of the perturbation was adjusted to mid-stance of the left foot. However, there was a delay in triggering of the perturbations due to limitations in the setup of the treadmill device and since we could not detect the frame in which the perturbation was presented, the exact moment of the perturbations could not be determined. Thus, some cautions in interpreting the results should be taken into account, considering that depending on the moment of the perturbation within the gait cycle the response is different.

Conclusions

The results show that the increase in cadence and step width, as well as the decrease in stride length, are strategies to increase MoS, and thus to decrease the probability of falling in the presence of perturbations. The present study also suggests that frontal plane fluctuations (ML variability) are more variable compared with AP variability. Thus, the variability of responses depends not only on the status of the individuals but also depends on the type and direction of the perturbation. The participants were more sensitive to ML perturbations than to AP perturbations which shows the importance of including ML perturbations in assessment protocols. Variabilities, as well as extremes of gait-related parameters, showed strong responses for measuring the effects of perturbations. Therefore, measuring variabilities and extremes of the parameters in addition to means can help to better understand balance control strategies and may be used as a marker of unsteadiness, instability, and fall risk. Further studies need to evaluate whether similar postural responses exist in older adults with different balance control abilities, such as between fallers and non-fallers. In this context, this study can be useful for designing advanced stability and gait evaluation and for introducing novel assessment protocols for estimating fall risk.

Supporting information

S1 Data. Data of the gait characteristics and dynamic stability. Parameters including SL, SW, cadence, MoS-ML, and MoS-AP were measured over each gait cycle during the time frames of interest in each walking condition.
(XLSX)

Acknowledgments

Forough Madehkhaksar was supported by Network Aging Research (NAR) during working on this project. Authors would like to thank Jonathan Griffiths for the English language editing, and Anja Sander from the Institute of Medical Biometry and Informatics in Heidelberg for statistical consultation.

Author Contributions

Conceptualization: Forough Madehkhaksar, Jochen Klenk, Kim Sczuka, Katharina Gordt, Michael Schwenk.

Data curation: Kim Sczuka, Katharina Gordt.

Formal analysis: Forough Madehkhaksar.

Funding acquisition: Michael Schwenk.

Investigation: Jochen Klenk.

Methodology: Forough Madehkhaksar, Kim Sczuka.

Resources: Michael Schwenk.

Software: Forough Madehkhaksar.

Supervision: Michael Schwenk.

Visualization: Forough Madehkhaksar.

Writing – original draft: Forough Madehkhaksar.

Writing – review & editing: Jochen Klenk, Kim Sczuka, Katharina Gordt, Itshak Melzer, Michael Schwenk.

References

1. Deandrea S, Lucenteforte E, Bravi F, Foschi R, La Vecchia C, et al. (2010) Review Article: Risk Factors for Falls in Community-dwelling Older People: "A Systematic Review and Meta-analysis". Epidemiology: 658–668. https://doi.org/10.1097/EDE.0b013e3181e89905 PMID: 20585256
2. King MB, Tinetti ME (1995) Falls in Community-Dwelling Older Persons. Journal of the American Geriatrics Society 43: 1146–1154. PMID: 7560708
3. Schwenk M, Lauenroth A, Stock C, Moreno RR, Oster P, et al. (2012) Definitions and methods of measuring and reporting on injurious falls in randomised controlled fall prevention trials: a systematic review. BMC medical research methodology 12: 50. https://doi.org/10.1186/1471-2288-12-50 PMID: 22510239

4. Maki BE, Cheng KC-C, Mansfield A, Scovil CY, Perry SD, et al. (2008) Preventing falls in older adults: new interventions to promote more effective change-in-support balance reactions. Journal of electromyography and kinesiology 18: 243–254. https://doi.org/10.1016/j.jelekin.2007.06.005 PMID: 17766146
5. Hof A, Gazendam M, Sinke W (2005) The condition for dynamic stability. Journal of biomechanics 38: 1–8. https://doi.org/10.1016/j.jbiomech.2004.03.025 PMID: 15519333
6. Hof AL (2008) The 'extrapolated center of mass' concept suggests a simple control of balance in walking. Human movement science 27: 112–125. https://doi.org/10.1016/j.humov.2007.08.003 PMID: 17935808
7. Espy DD, Yang F, Bhatt T, Pai Y-C (2010) Independent influence of gait speed and step length on stability and fall risk. Gait & posture 32: 378–382.
8. Hak L, Houdijk H, Beek PJ, van Dieen JH (2013) Steps to take to enhance gait stability: the effect of stride frequency, stride length, and walking speed on local dynamic stability and margins of stability. PLoS One 8: e82842. https://doi.org/10.1371/journal.pone.0082842 PMID: 24349379
9. Hak L, Houdijk H, Steenbrink F, Mert A, van der Wurff P, et al. (2012) Speeding up or slowing down?: Gait adaptations to preserve gait stability in response to balance perturbations. Gait & posture 36: 260–264.
10. McAndrew PM, Dingwell JB, Wilken JM (2010) Walking variability during continuous pseudo-random oscillations of the support surface and visual field. Journal of biomechanics 43: 1470–1475. https://doi.org/10.1016/j.jbiomech.2010.02.003 PMID: 20346453
11. Stokes HE, Thompson JD, Franz JR (2017) The Neuromuscular Origins of Kinematic Variability during Perturbed Walking. Scientific Reports 7.
12. Young PMM, Wilken JM, Dingwell JB (2012) Dynamic margins of stability during human walking in destabilizing environments. Journal of biomechanics 45: 1053–1059. https://doi.org/10.1016/j.jbiomech.2011.12.027 PMID: 22326059
13. Terry K, Sinitski EH, Dingwell JB, Wilken JM (2012) Amplitude effects of medio-lateral mechanical and visual perturbations on gait. Journal of biomechanics 45: 1979–1986. https://doi.org/10.1016/j.jbiomech.2012.05.006 PMID: 22648147
14. Brady RA, Peters BT, Bloomberg JJ (2009) Strategies of healthy adults walking on a laterally oscillating treadmill. Gait & posture 29: 645–649.
15. Süptitz F, Catalá MM, Brüggemann G-P, Karamanidis K (2013) Dynamic stability control during perturbed walking can be assessed by a reduced kinematic model across the adult female lifespan. Human movement science 32: 1404–1414. https://doi.org/10.1016/j.humov.2013.07.008 PMID: 24071548
16. McCrum C, Eysel-Gosepath K, Epro G, Meijer K, Savelberg HH, et al. (2014) Deficient recovery response and adaptive feedback potential in dynamic gait stability in unilateral peripheral vestibular disorder patients. Physiological reports 2: e12222. https://doi.org/10.14814/phy2.12222 PMID: 25501424
17. Süptitz F, Karamanidis K, Catalá MM, Brüggemann G-P (2012) Symmetry and reproducibility of the components of dynamic stability in young adults at different walking velocities on the treadmill. Journal of electromyography and kinesiology 22: 301–307. https://doi.org/10.1016/j.jelekin.2011.12.007 PMID: 22240093
18. Francis CA, Franz JR, O'Connor SM, Thelen DG (2015) Gait variability in healthy old adults is more affected by a visual perturbation than by a cognitive or narrow step placement demand. Gait & posture 42: 380–385.
19. Hof A, Vermerris S, Gjaltema W (2010) Balance responses to lateral perturbations in human treadmill walking. Journal of Experimental Biology 213: 2655–2664. https://doi.org/10.1242/jeb.042572 PMID: 20639427
20. Hof AL, van Bockel RM, Schoppen T, Postema K (2007) Control of lateral balance in walking: experimental findings in normal subjects and above-knee amputees. Gait & posture 25: 250–258.
21. O'Connor SM, Kuo AD (2009) Direction-dependent control of balance during walking and standing. Journal of neurophysiology 102: 1411–1419. https://doi.org/10.1152/jn.00131.2009 PMID: 19553493
22. Schonnop R, Yang Y, Feldman F, Robinson E, Loughin M, et al. (2013) Prevalence of and factors associated with head impact during falls in older adults in long-term care. Canadian Medical Association Journal 185: E803–E810. https://doi.org/10.1503/cmaj.130498 PMID: 24101612
23. Yang Y, Mackey D, Liu-Ambrose T, Feldman F, Robinovitch S (2016) Risk factors for hip impact during real-life falls captured on video in long-term care. Osteoporosis international 27: 537–547. https://doi.org/10.1007/s00198-015-3268-x PMID: 26252977
24. Tay CS, Lee JK, Teo YS, Foo PQ, Tan PM, et al. (2016) Using gait parameters to detect fatigue and responses to ice slurry during prolonged load carriage. Gait & posture 43: 17–23.
25. Brach JS, Studenski S, Perera S, VanSwearingen JM, Newman AB (2008) Stance time and step width variability have unique contributing impairments in older persons. Gait & posture 27: 431–439.

26. Maki BE (1997) Gait changes in older adults: predictors of falls or indicators of fear? Journal of the American geriatrics society 45: 313–320. PMID: 9063277

27. Yang F, Pai Y-C (2014) Can stability really predict an impending slip-related fall among older adults? Journal of biomechanics 47: 3876–3881. https://doi.org/10.1016/j.jbiomech.2014.10.006 PMID: 25458148

28. Punt M, Bruijn SM, Roeles S, van de Port IG, Wittink H, et al. (2017) Responses to gait perturbations in stroke survivors who prospectively experienced falls or no falls. Journal of biomechanics 55: 56–63. https://doi.org/10.1016/j.jbiomech.2017.02.010 PMID: 28267989

29. Rispens SM, van Schooten KS, Pijnappels M, Daffertshofer A, Beek PJ, et al. (2015) Do extreme values of daily-life gait characteristics provide more information about fall risk than median values? JMIR research protocols 4: e4. https://doi.org/10.2196/resprot.3931 PMID: 25560937

30. Shapiro A, Melzer I (2010) Balance perturbation system to improve balance compensatory responses during walking in old persons. Journal of neuroengineering and rehabilitation 7: 32. https://doi.org/10.1186/1743-0003-7-32 PMID: 20630113

31. Zeni J, Richards J, Higginson J (2008) Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait & posture 27: 710–714.

32. Pai Y-C, Patton J (1997) Center of mass velocity-position predictions for balance control. Journal of biomechanics 30: 347–354. PMID: 9075002

33. Hak L, Houdijk H, Steenbrink F, Mert A, van der Wurff P, et al. (2013) Stepping strategies for regulating gait adaptability and stability. Journal of biomechanics 46: 905–911. https://doi.org/10.1016/j.jbiomech.2012.12.017 PMID: 23332822

34. McIntosh EI, Zettel JL, Vallis LA (2016) Stepping Responses in Young and Older Adults Following a Perturbation to the Support Surface During Gait. Journal of Motor Behavior: 1–11.

35. Kuo AD (1999) Stabilization of lateral motion in passive dynamic walking. The International journal of robotics research 18: 917–930.

36. Lipsitz LA, Mietus J, Moody GB, Goldberger AL (1990) Spectral characteristics of heart rate variability before and during postural tilt. Relations to aging and risk of syncope. Circulation 81: 1803–1810. PMID: 2344676

37. Hausdorff JM, Forman DE, Ladin Z, Goldberger AL, Rigney DR, et al. (1994) Increased walking variability in elderly persons with congestive heart failure. Journal of the American Geriatrics Society 42: 1056–1061. PMID: 7930329

38. Caetano MJD, Menant JC, Schoene D, Pelicioni PHS, Sturnieks DL, et al. (2016) Sensorimotor and cognitive predictors of impaired gait adaptability in older people. Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences 72: 1257–1263.

Effect of Gaze-Shifting on Gait Characteristics during Treadmill Walking in Healthy Young and Older adults

Madehkhaksar, F., Klenk, J., Schwenk, M., Mack, D.J., L. Schwickert, Lindemann, U., Meyer, M., Srijana, K.C., Pomper, J.K., Synofzik, M., Ilg, U., Kerse, N., Maetzler, W., Becker, C., & Srulijes, K.

Note: This manuscript has been submitted in the journal of Biomechanics.

Abstract

Walking in a natural environment requires constant gaze-shifting (e.g. scanning obstacles). It may lead to gait alterations and increased fall-risk, especially in elderly. Our purpose was to determine the gait characteristics of healthy young and older adults during gaze-shifting while treadmill-walking. Eleven young (age: 25 ± 4.5 years, 3 females) and 13 older (age: 72 ± 3.9 years, 6 females) adults performed normal treadmill-walking (no visual-triggers) and then treadmill-walking while rapidly gaze-shifting to randomly presented visual-triggers. A multilevel linear regression model was used to assess changes in a set of gait parameters between subject groups and walking conditions: normal walking, one gait cycle before (Pre-Cycle), and after (Post-Cycle) each triggering during gaze-shift walking. Comparing Pre-Cycle to normal walking, young adults showed no instability-related changes in their gait but older adults showed a more cautious gait with shorter step length (Est. = -1.59cm [95% CI: -2.2cm; -0.9cm]), reduced step width (Est. = -0.8cm [95% CI: -1.1cm; -0.6cm]), increased step frequency (Est. = 0.04 1/s [95% CI: 0.03 1/s; 0.05 1/s]), decreased maximum toe clearance (Est. = -0.3cm [95% CI: -0.4cm; -0.2cm]), and 30% higher minimum toe clearance variability. During Post-Cycle compared to Pre-Cycle, direct effects of gaze-shifts on gait parameters were significant but rather small. This experiment shows an influence of gaze-shifts on gait in both groups, although, the effect is larger in the older which might therefore need more compensation compared to the young adults. Present insights may facilitate the development of specific training paradigms to improve the oculomotor-locomotor interaction.

Keywords: gaze-shifting; treadmill walking; perturbation; age; gait parameters.

1. Introduction

Gaze is the direction of sight within the world frame of reference. With a gaze shift the world object's image coordinates on the retina change within the retinal frame of reference. Shifting gaze during walking in a natural environment is performed constantly (e.g. observing surrounding or to scan the pathway for obstacles) and may lead to alterations in gait and increased fall risk, especially in older adults. A stable reference frame which is provided by integrating sensory information is an important contribution to stable locomotion (Cinelli, Patla, & Stuart, 2008; M. A. Hollands & Marple-Horvat, 2001; C. Paquette, Paquet, & Fung, 2006). Due to age-related deteriorations in motor and sensory systems, gaze reorienting may result in less stable locomotion leading to falls (Berard, Fung, McFadyen, & Lamontagne, 2009; Cinelli et al., 2008; M. R. Paquette & Vallis, 2010). Considering the frequent occurrence of gaze shifting while walking in daily life, it is important to understand the potential problems with gaze shifts on locomotion in the older as compared to the young individuals. These age-related differences may have significant implications for fall preventive exercise interventions in older persons.

Gait parameters have been extensively used to assess adaptive strategies under challenging circumstances (Francis, Franz, O'Connor, & Thelen, 2015; Grabiner, Biswas, & Grabiner, 2001; Hak et al., 2012; Latt, Menz, Fung, & Lord, 2008; M. R. Paquette & Vallis, 2010; Richardson, Thies, DeMott, & Ashton-Miller, 2004). In general, older adults adapt their stable gait by taking slower and shorter steps compared to young adults. Also, the variability of a number of gait parameters increases in older subjects, suggesting a higher risk of falls (Callisaya et al., 2011; Maki, 1997; Owings & Grabiner, 2004). Minimum toe clearance (Min-TC) and increased variability of Min-TC seems particularly important during a trip or fall (Barrett, Mills, & Begg, 2010; Winter, 1992) and a low Min-TC combined with a high Min-TC variability can potentially cause tripping (Begg, Best, Dell'Oro, & Taylor, 2007).

Previous studies that investigated adaptive strategies during a visually guided change in travel direction (M. Hollands, Sorensen, & Patla, 2001) or to avoid an obstacle (Lo, van Donkelaar, & Chou, 2015; M. R. Paquette & Vallis, 2010) have also suggested different strategies between the young and the old individuals. Recent work showed changes in various gait parameters in response to head turn walking in older adults with lower versus greater lateral balance (Singh et al., 2017) but neither analysis of age effect nor variability of gait parameters was performed.

Further, to our knowledge, there has been no study to examine the direct effects on characteristics ("reaction") of the step immediately after gaze-shifting.

The purpose of this study was to describe the influence of gaze shifts on a set of gait parameters and their variabilities in healthy young and older individuals in order to discuss potential adaptive strategies used for compensation. Therefore, individuals walked on a treadmill while shifting their gaze to fixate on visual targets. We hypothesized that gait characteristics would show more deficit in older adults in response to gaze-shifting than young, and changes would be more obvious during one gait cycle after visual triggering.

2. Methods

Subjects and design

The present study is a part of a large cross-sectional experiment (Srulijes et al., 2015). Eleven healthy young (age: 25 ± 4.5 years, height: 175 ± 5.6 cm, mass: 74 ± 11 kg, 3 females) and 13 healthy older adults (age: 72 ± 3.9 years, height: 170 ± 8.9 cm, mass: 75 ± 16 kg, 6 females) were recruited with the support of the office of Sport and Exercise, city of Stuttgart, Germany and the Bosch BKK health insurance. Included were individuals with a global cognitive test (Montreal Cognitive Assessment [MoCA] score ≥ 26. Exclusion criteria were neurological or psychiatric disorders, drug abuse, ophthalmologic disorders, extremity prosthesis, arthritis or musculoskeletal injuries in the past 3 months, and visual correction by glasses stronger than ±3 dpt. The study was approved by the local ethics committee (University of Tuebingen, 602/2012BO1) and was in agreement with the Declaration of Helsinki. All subjects gave written informed consent.

Experimental set-up

All subjects first went through clinical assessment including clinical data like sex, age, body mass index, assessment of global cognition using the *Montreal Cognitive Assessment (MoCA)* (Nasreddine et al., 2005), assessment of habitual overground walking speed and an sensor-based assessment of the timed up and go test (iTUG 3m) using a wearable sensors system (APDM Inc, Portland).

All subjects then walked on a treadmill (h/p/cosmos venus, sport medical GmbH, Germany) after a familiarization time for treadmill walking.

Figure 4.1 shows a schematic view of the experimental set-up. Seven light emitting diodes (LEDs) were arranged at fixed positions at the center (0°) together with left and right side (30°,45°, and 60°) at a distance of 120 cm with an adjustable height of the LEDs to the level of each participant's eyes. The LEDs were controlled using a programmable microcontroller. Stimulus presentation time was 500ms to provoke rapid gaze shifts.

A 6-camera motion capture system (Vicon Motion System, Oxford, UK) was used to collect kinematic data at 200 Hz. Each subject wore 15 reflective markers (head front-/top-/back; first metatarsal head and the heel on each foot, one reference marker on the fifth metatarsal head of the right foot; trunk at jugulum, 7th cervical vertebra, and 5th lumbar vertebra; two on each wrist (Figure 1B).

Experimental protocol

First, subjects walked without any visual triggering (Normal-walking) at their comfortable speed for 30 to 40 seconds. Then, subjects performed two blocks of gaze-shift walking at the same gait speed. Each block consisted of the presentation of 30 unpredictable LED illuminations at the given positions [5 triggering × 6 conditions] with varying inter-stimulus intervals of 2-6s. Participants were asked to always fixate the central LED (0°) during walking unless asked to move their gaze towards the eccentric LEDs "as fast as possible" whenever they appeared. All subjects wore a safety harness to prevent injury due to falls.

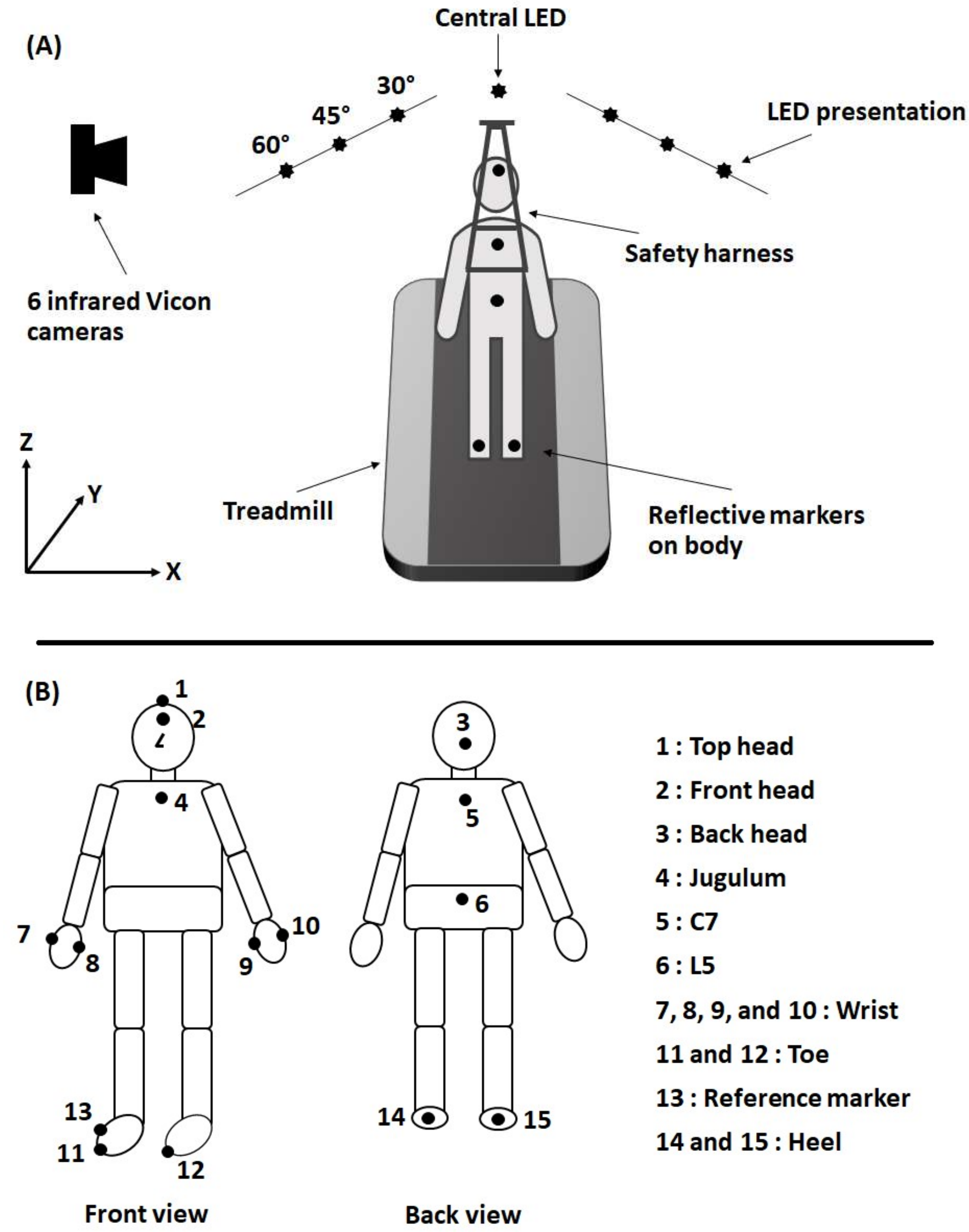

Figure 1. (A) Schematic presentation of the experimental setup. Subjects walked on a treadmill while seven LEDs were arranged in front of the participants. One LED was positioned at 0° and the remaining were positioned at 30°, 45°, and 60°. Subjects were asked to fixate the central LED (0°) during walking. Whenever peripheral LEDs appear, subjects were asked to fixate the LEDs "as fast as possible" and after each fixation to re-fixate the central LED. Each participant has presented a total of 60 LED triggerings (30 triggerings for each triggering block). A 6-

camera Vicon motion capture system was used to collect kinematic data. (B) Placement of 15 reflective markers on the body.

Measurements and data analysis

Motion data were analyzed using the Vicon Nexus software (Version 1.5.2). Marker's data were low-pass filtered using a 4th order Butterworth filter and a cut-off frequency of 10 Hz.

With the aim of using data during steady-state gait speed, the last 25 seconds (~15-20 gait cycles) of walking at comfortable speed were used as a reference walking (normal walking) (Lindemann et al., 2008). One gait cycle before the triggering (Pre-Cycle) and one gait cycle after the triggering (Post-Cycle) were determined (Figure 2), by synchronizing the VICON data with the stimulus presentation.

Figure 4.2 schematically illustrates gait-related parameters. Individual strides were defined by consecutive heel-strikes of the right foot, determined as the local maximum of the position of the heel marker in the AP-direction (Zeni, Richards, & Higginson, 2008). Stride length (SL) was measured as the AP-distance between heel markers at the instant of heel-strike plus treadmill translation during the stride. Step width (SW) was calculated as the ML-distance between heel markers at the moment of heel-strike. Step frequency (SF) was determined as the inverse of the duration between two subsequent heel-strikes.

Min-TC was measured at the local minimum of the vertical trajectory of the toe marker during mid-swing phase. When no local minimum occurred, Min-TC was measured at the moment in which the forward velocity of the foot was maximum. Maximum toe clearance (Max-TC) was measured as the highest vertical displacement of each foot before heel-strike (Figure 2B).

The mean and variability (i.e. the standard deviation) of parameters were calculated for each participant during normal-walking as well as Pre-Cycles and Post-Cycles during gaze-shift walking. All processing was performed with custom-written MATLAB R2015a programs (Mathworks, Inc., Natic, USA).

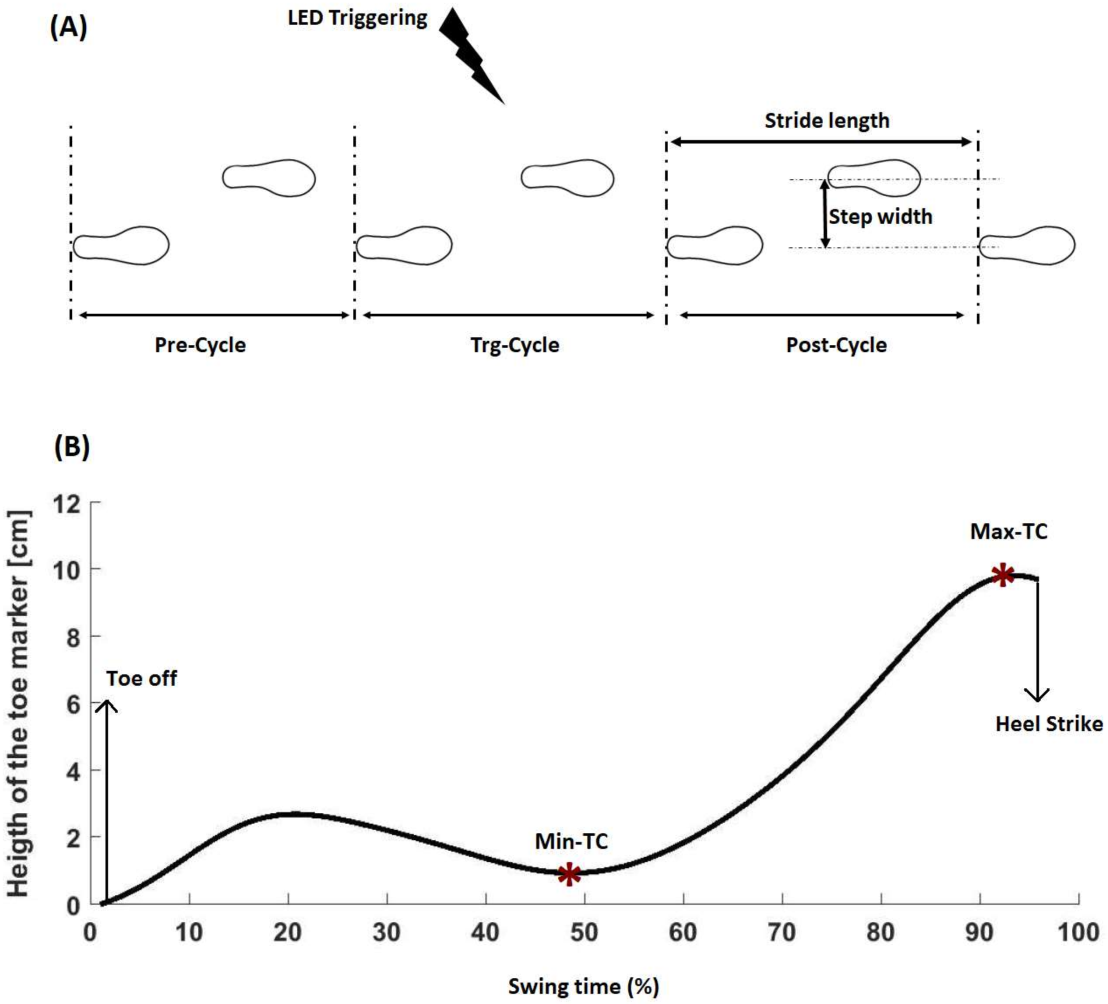

Figure 2. (A) Schematic presentation of analyzed gait cycles including the gait cycles during which the triggering was presented (Trg-Cycle), one gait cycle before the triggering (Pre-Cycle), and one gait cycle after the triggering (Post-Cycle). Stride length was measured as the AP-distance between heel markers at the instant of heel strike plus treadmill translation during the stride. Step width was calculated as the ML-distance between heel markers at the moment of heel strike. (B) The vertical trajectory of the toe marker during swing phase. Time is presented as the normalized time to the time interval of swing phase. Min-TC was measured at the local minimum of the vertical trajectory of the toe marker which occurs during mid-swing phase. Max-TC was measured as the highest vertical displacement of each foot before heel strike.

Statistical analysis

All statistical analyses were performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA). Statistical significance was declared if p≤0.05.

A t-test was used to compare normally distributed data of SW, SF, Min-TC, and Max-TC at the left and the right steps. There was no significant difference between parameters of the left and the right sides, therefore, an average of the left and the right sides for these parameters were used for the analysis.

To account for the repeated measurement structure, multilevel linear regression analyses were performed with the gait-cycle on the first level and the subjects on the second level. We assessed differences in the means of parameters between age groups (i.e., young and old) and for the gait cycles during walking conditions (i.e., Normal-walking, Pre-Cycles, Post-Cycles). Intercepts and subjects were allowed to vary randomly. Additionally, the differences in the individual standard deviation for each parameter between age groups (i.e., young and old) and for the gait cycles during walking conditions were calculated using linear regression models. Main effects, as well as their interactions, were included in the model. Paired comparisons were performed as post-hoc tests.

3. Results

Clinical and demographic data are presented in Table 1. All subjects completed the experiment with no fall. In total, 408 normal-walking gait cycles, and 1440 Pre-Cycles, as well as Post-Cycles, were extracted. Two subjects showed no Min-TC in their swing phase over 178 gait cycles, therefore, the corresponding data was removed from the analysis. Table 2 illustrates the comparison of differences of least squares means of gait parameters comparing walking conditions in young and older adults. The differences of the mean values as well as the individual standard deviations of each parameter are shown in Figure 3 (A, C, E, G, I) and Figure 3 (B, D, F, H, J), respectively.

As general observations independent of the effects of the gaze-shifting experiment, older adults walked with shorter SL (Est. = -21.60cm [95% CI: -29.7cm; -13.5cm]) and with about 30-40 % lower Max-TC (Est. = -3.18cm [95% CI: -4.5cm; -1.9cm]) compared to young adults during all walking conditions. However, no significant experiment unrelated differences between young and older adults were observed for the other parameters (SW, SF, and Min-TC).

Table 1. Clinical and demographical characteristics of the participants.

	Young adults	Older adults
N	11	13
Female/Male	3/8	6/7
Age [years]	25 ± 4.5	72 ± 3.9
Height [cm]	175 ± 5.6	170 ± 8.9
Body mass [kg]	74 ± 11	75 ± 16
MoCA score	30 (27-30)	27 (26-29)
iTUG 3m [sec]	9.9 ± 0.8	10.8 ± 1.3
Habitual gait speed [m/s]	1.4 ± 0.1	1.3 ± 0.1

Values are presented in mean ± Standard deviation and median (range); MoCA= Montreal Cognitive Assessment; i TUG= sensor-based timed up and go test.

Table 2. Comparison of differences of least squares means of gait parameters in young and older adults.

	General effects of the gaze-shift experiment		**Direct effects of the gaze-shift**	
	Pre-Cycle vs normal		**Post-Cycle vs Pre-Cycle**	
	young adults	**older adults**	**young adults**	**older adults**
mean				
Step length	→	↓	↓	↓
Step width	↓	↓	→	↑
Step frequency	→	↑	↑	↑
Minimum toe clearance	↓	→	→	↑
Maximum toe clearance	↑	↓	↓	→

Presentation of significant differences of least squares means of gait parameters in young and older adults. Significance level $p \leq 0,05$. ↑ = increase; ↓ = decrease; → = no change; red = marks the difference in the behaviour between young an old after a gaze-shift; green = marks the difference in the behaviour between young and old comparing normal walking and gaze-shift walking; normal = walking without presentation of visual stimuli; Pre-Cycle = gait cycle before visual trigger presentation while gaze shift walking; Post-Cycle = gait cycle after visual trigger presentation while gaze shift walking.

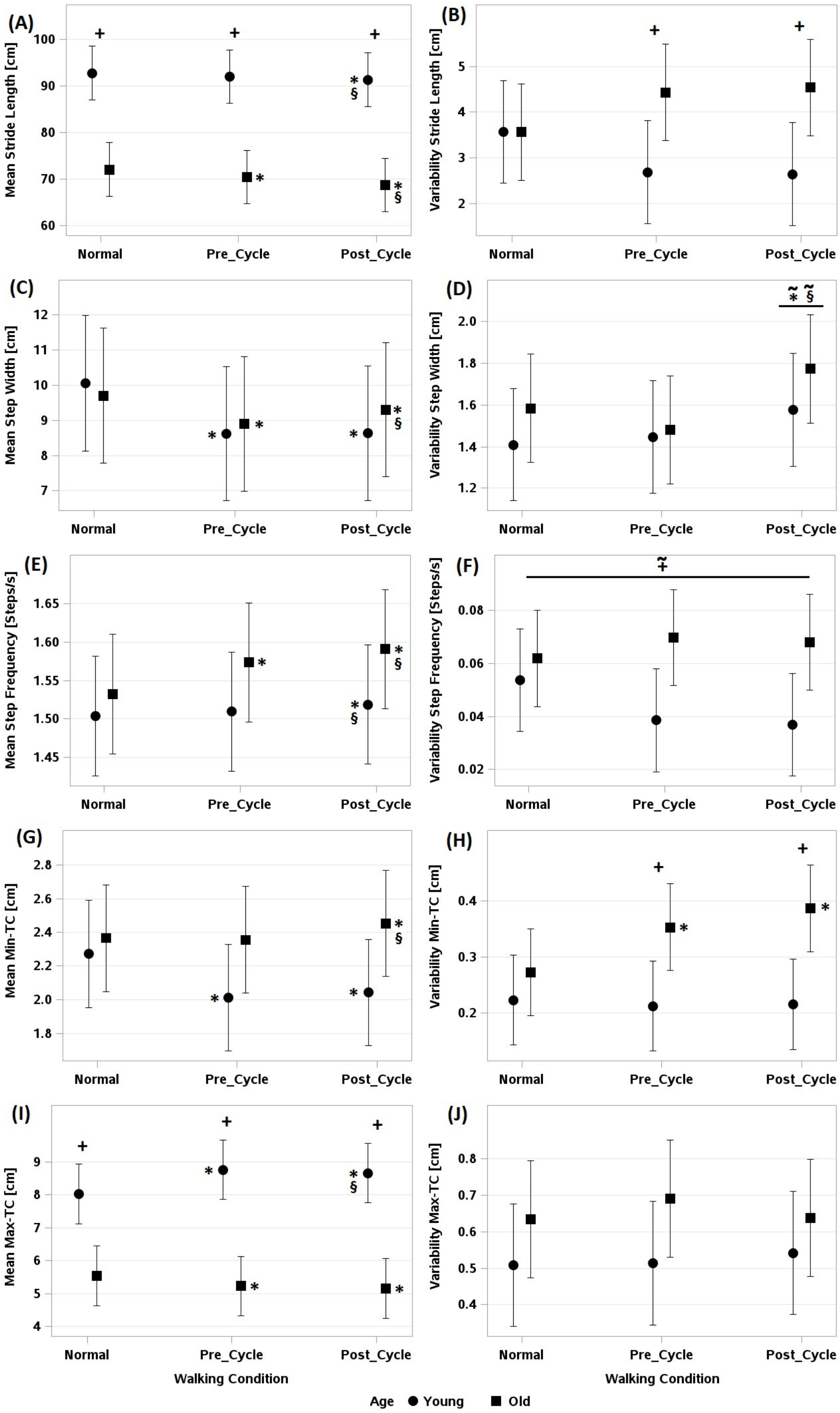
(A)
Mean Stride Length [cm]
100
90
80
70
60
+
*
§
Normal
Pre_Cycle
Post_Cycle
(B)
Variability Stride Length [cm]
5
4
3
2
(C)
Mean Step Width [cm]
12
11
10
9
8
7
(D)
Variability Step Width [cm]
2.0
1.8
1.6
1.4
1.2
~
(E)
Mean Step Frequency [Steps/s]
1.65
1.60
1.55
1.50
1.45
(F)
Variability Step Frequency [Steps/s]
0.08
0.06
0.04
0.02
(G)
Mean Min-TC [cm]
2.8
2.6
2.4
2.2
2.0
1.8
(H)
Variability Min-TC [cm]
0.4
0.3
0.2
(I)
Mean Max-TC [cm]
9
8
7
6
5
4
(J)
Variability Max-TC [cm]
0.8
0.7
0.6
0.5
0.4
Walking Condition
Age ● Young ■ Old

Figure 3. The results of the mean and variability of parameters during different walking conditions. (+) represents significant difference between young and old group under the same walking condition, $p \le 0.05$. (*) represents significant difference with normal-walking condition for the same age-group, $p \le 0.05$. (§) represents significant difference between Pre-Cycle and Post-Cycle for the same age-group, $p \le 0.05$. ($\tilde{+}$) represents the overall significant difference between young and old groups, $p \le 0.05$. ($\tilde{*}$) represents overall significant difference with the normal walking condition, $p \le 0.05$. ($\tilde{\S}$) represents the overall significant difference between Pre-Cycle and Post-Cycle, $p \le 0.05$.

Comparison of Pre-Cycle with Normal walking

Means of gait parameters in young adults

SL and SF of young adults were mainly uninfluenced by the task of walking while shifting gaze. During Pre-Cycle gaze-shift walking, they walked with narrower base of support (SW: Est. = -1.4cm [95% CI: -1.7cm; -1.1cm]), decreased Min-TC (Est. = -0.26 [95% CI: -0.3; -0.2]) and increased Max-TC (Est. = 0.7cm [95% CI: 0.6cm; 0.9cm]) compared to normal walking.

3.1.2. Means of gait parameters in older adults

Means of parameters changed relevantly in older adults during Pre-Cycle. Older adults walked then with shorter SL (Est. = -1.59cm [95% CI: -2.2cm; -0.9cmc]), reduced SW (Est. = -0.8cm [95% CI: -1.1cm; -0.6cm]) and increased SF (Est. = 0.04 [95% CI: 0.03; 0.05]), compared to normal walking. Moreover, older adults also decreased Max-C (Est. = -0.3cm [95% CI: -0.4cm; -0.2cm]).

Variability of gait parameters

No significant difference could be observed between age groups during normal walking; However, Min-TC variability was about 30% higher in older adults during Pre-Cycle compared to normal walking, whereas young adults did not show a relevant change in Min-TC variability. Gaze-shift walking had no significant effect on the variability of SF, SW, and Max-TC during Pre-Cycle.

Comparison of Pre-Cycle with Post-Cycle

Means of gait parameters in young adults

Comparing gait parameters during Post-Cycle with Pre-Cycle, young adults decreased their SL (Est. = -0.66cm [95% CI: -1.1cm; -0.2cm]), increased their SF (Est. = 0.01 1/s [95% CI: 0.002 1/s; 0.02 1/s]), and lowered their Max-C (Est. = 0.11cm [95% CI: 0.02cm; 0.2cm]). SW and Min-TC showed no significant changes.

Means of gait parameters in older adults

Similar to the young group, older adults decreased their SL (Est. = 1.74cm [95% CI: -1.3cm; 2.2cm]) and increased SF (Est. = -0.02 1/s [95% CI: -0.02 1/s; -0.01 1/s]) during Post-Cycle compared to Pre-Cycle. However, they increased SW (Est. = 0.4cm [95% CI: 0.2cm; 0.6cm]) and Min-TC during Post-Cycle compared to Pre-Cycle (Est. = 0.1cm [95% CI: 0.06cm; 0.13cm]).

Variability of gait parameters

Regardless of the age group, the variability of SW significantly increased during Post-Cycle compared to Pre-Cycle (Est. = 0.2cm [95% CI: 0.36cm; 0.06cm]. The results showed no significant difference in the variability of the other parameters during Post-Cycle compared to Pre-Cycle.

4. Discussion

We show that gaze-shifting while walking has an influence on various gait parameters in young and older adults, both on a “global” level (Pre-Cycle walking compared to normal walking) and directly when comparing Post-Cycle with the Pre-Cycle gaze shift. Moreover, we found an age-specific adaptation of gait patterns in response to gaze-shifting.

4.1 Gaze shifting effects

Both age groups showed different performance during gaze-shifting while walking on the treadmill (Table 2).

A reduction in SL and increase of SF was found in Pre-Cycle walking compared to normal walking in the older adults but not the young, whereas both groups reduced SL and increased SF during the Post-Cycle compared with the Pre-Cycle. A significant age-related reduction in gait velocity and SL was also reported by Menz et al. while walking on an irregular surface (Menz, Lord, & Fitzpatrick, 2003), as well as by Singh et al. during walking when turning the head (Singh et al., 2017). This observation is possibly associated with a higher risk of falls since shorter SL results in less dynamic stability in the forward direction (Hak et al., 2012). However, reduced SL seems primarily to be a compensation, as older adults but not the young showed a reduction in SL already in Pre-Cycle walking compared to normal walking. Young adults might have a sufficiently stable gait that needs no large “preparation” for visual stimuli as used in this study. Further, the reduced SL accompanied by increased SF in the younger during Post-Cycle could also reflect a protective adaptation or reaction effect of gait in response to a gaze shift in terms of a more cautious gait (Zijlstra, de Bruin, Bruins, & Zijlstra, 2008).

Surprisingly, the SW during gaze-shift walking was smaller than during normal walking in both groups. Visual fixation in this experiment might have had a stronger effect on gait than a gaze shift per se since participants were required to gaze at the central LED before and after performing gaze shifts. This hypothesis is supported by previous literature: the visual fixation on stationary targets has been reported to reduce sway during static balance tasks (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Taylor, Sutton, Diestelkamp, & Bigelow, 2015). Given the fact that an increase in SW may lead to increased lateral stability while walking (Young & Dingwell, 2012), our observed narrower base of support during gaze-shift walking compared to normal walking could be interpreted as a correlate for an increase in dynamic stability via the mechanism of gaze stabilization. The influence of visual fixation of a stationary target on dynamic balance is controversially discussed. Specifically, whether fixation increases gait stability (Cromwell, Newton, & Forrest, 2002) as it is supported by our findings or rather reduces dynamic balance (Thomas, Donovan, Dewhurst, & Bampouras, 2018), is yet unclear and so a common understanding is still missing.

Our finding of the increased mean of SW in the older adults, as a direct reaction to the gaze-shifting (i.e. by comparing Pre-Cycle and Post-Cycle) is consistent with a previous study (Vallis & Patla, 2004). They found an increased in-phase SW after unexpected head perturbations. This observation might be a compensatory strategy by increasing walking stability in the mediolateral direction in older adults (Hak et al., 2012; Hof, van Bockel, Schoppen, & Postema, 2007). However, young adults seem to have a more stable gait that does not need such a "reactive" strategy after perturbation. Moreover, several studies have described an increase of SW variability under challenging conditions, such as treadmill walking, walking on an irregular surface, faster gait speed, altered shoe condition, and dual tasking in older adults (Grabiner et al., 2001; Owings & Grabiner, 2004; Richardson et al., 2004). As SW variability was increased in both groups during the challenging walking condition, this greater SW variability might reflect a compensatory strategy to cope with gaze-shift perturbation.

In this study, gaze-shifting evoked a difference in Min-TC behavior between the two groups. Young adults decreased their mean of Min-TC, whereas older adults increased mean and variability of Min-TC. Previous studies described no increase in Min-TC by divided attention-walking in young adults (Santhiranayagam, Sparrow, Lai, & Begg, 2017), However, the authors showed a consecutive reduction of Min-TC variability in older adults. The authors interpreted this finding as an adaptive strategy to compensate for the increased risk of toe-ground contact due to lower Min-TC (Santhiranayagam et al., 2017). In addition, Begg et al. (Begg et al., 2007) demonstrated that tripping risk can be reduced by either elevating Min-TC or reducing Min-TC variability. An age-related increase in Min-TC variability, in the absence of an increase in Min-TC, increases the likelihood of tripping (Mills, Barrett, & Morrison, 2008). Therefore, we suggest that, in this study, the older group might have increased their Min-TC during Post-Cycle to compensate for the higher Min-TC variability.

Moreover, the restricted visual ground control as presented in our experimental setting (e.g. LEDs at eyes level, relatively dark environment) might have caused some gait changes, consistent with previous findings (Miyasike-daSilva & McIlroy, 2016). Specifically, older adults might have increased their Min-TC as a cautious control strategy to avoid tripping and stumbling. It has been shown that older adults have a greater reliance on visual perception (Cinelli et al., 2008). Conversely, young adults may have shown higher confidence in their ability to maintain balance (M. R. Paquette & Vallis, 2010).

Consistent with a previous study (Nagano, Begg, Sparrow, & Taylor, 2011), young adults increased Max-TC during gaze-shift walking compared to normal-walking, whereas older adults decreased Max-TC. This difference could be explained by weaker dorsiflexor muscle of older adults compared to the young ones (Nagano et al., 2011; Prince, Corriveau, Hebert, &

Winter, 1997). Interestingly, when focusing on the direct reaction after the gaze-shifting, the young adults showed a decrease of Max-TC (Table 2), which could reflect a perturbation effect on gait.

Our findings indicate that older adults could maintain balance while gaze-shifting but used a different balance strategy compared to young adults. Additional factors in the older adults, such as deficits in vestibular-ocular reflex suppression ability (Di Fabio, Greany, Emasithi, & Wyman, 2002; P. Di Fabio, 2001), decline in attentional capacity during dual-tasking (Yogev-Seligmann, Hausdorff, & Giladi, 2008) and decreased confidence in their ability to maintain balance (M. R. Paquette & Vallis, 2010) may have contributed to this difference in gait behavior and adaptation.

4.2 The age effects

Following age-related observations seem independent of the effect of gaze-shifting, but consistent with previous results on age effects on walking in the literature.

Older adults walked slower and with shorter SL compared to young adults, whereas, SF and SW were not affected by age-group. In line with previous studies (Elble, Thomas, Higgins, & Colliver, 1991), healthy elderly adapted their speed by taking shorter steps, and not by taking more frequent steps, compared to young adults.

Also consistent with previous studies, older adults walked with lower Max-TC during all walking conditions (Elble et al., 1991; Nagano et al., 2011). At Max-TC the swing foot attains peak dorsiflexion (Nagano et al., 2011; Winter, 1991) and age-related weaker dorsiflexor muscles resulted in decreased Max-TC (Nagano et al., 2011; Prince et al., 1997).

This is a hypothesis-generating study with a relatively low N of participants. However, previous studies found significant differences with a comparable number of participants (Chapman & Hollands, 2006; Cinelli et al., 2008; C. Paquette et al., 2006). Moreover, our findings have to be translated to persons with specific handicaps and diseases.

In conclusion, the present setup was able to detect age-specific changes of gait parameters during gaze-shift walking. The findings could serve as a basis for the development of specific training paradigms for the improvement of oculomotor and locomotor interaction. Whether there also exists a bottom-up influence of gait on oculomotor performance is topic of future analyses.

Acknowledgments

This study is funded by grants from the Forschungskolleg Geriatrie of the Robert-Bosch-Foundation Stuttgart, Germany (to K.S. and M.Sy.).

Forough Madehkhaksar was provided with a financial support from Gesellschaft der Freunde Universität Heidelberg e.V. and Graduate Academy of Heidelberg University.

We thank all participants who joined up in the study. We are grateful for the help in the recruitment of the office of Sport and Exercise, the city of Stuttgart, Germany (especially Mrs. Carolin Barz) and the Bosch BKK health insurance.

Authors would also like to thank Leila Borhani Haghighi for the English language editing.

References

Barrett, R., Mills, P., & Begg, R. (2010). A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking. *Gait & posture, 32*(4), 429-435.

Begg, R., Best, R., Dell'Oro, L., & Taylor, S. (2007). Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. *Gait & posture, 25*(2), 191-198.

Berard, J. R., Fung, J., McFadyen, B. J., & Lamontagne, A. (2009). Aging affects the ability to use optic flow in the control of heading during locomotion. *Experimental Brain Research, 194*(2), 183-190.

Callisaya, M. L., Blizzard, L., Schmidt, M. D., Martin, K. L., McGinley, J. L., Sanders, L. M., & Srikanth, V. K. (2011). Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. *Age and ageing, 40*(4), 481-487.

Chapman, G., & Hollands, M. (2006). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental brain research, 174*(4), 613-621.

Cinelli, M., Patla, A., & Stuart, B. (2008). Age-related differences during a gaze reorientation task while standing or walking on a treadmill. *Experimental brain research, 185*(1), 157-164.

Cromwell, R. L., Newton, R. A., & Forrest, G. (2002). Influence of vision on head stabilization strategies in older adults during walking. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 57*(7), M442-M448.

Di Fabio, R. P., Greany, J. F., Emasithi, A., & Wyman, J. F. (2002). Eye-head coordination during postural perturbation as a predictor of falls in community-dwelling elderly women. *Archives of Physical Medicine and Rehabilitation, 83*(7), 942-951.

Elble, R., Thomas, S. S., Higgins, C., & Colliver, J. (1991). Stride-dependent changes in gait of older people. *Journal of neurology, 238*(1), 1-5.

Francis, C. A., Franz, J. R., O'Connor, S. M., & Thelen, D. G. (2015). Gait variability in healthy old adults is more affected by a visual perturbation than by a cognitive or narrow step placement demand. *Gait & posture, 42*(3), 380-385.

Grabiner, P. C., Biswas, S. T., & Grabiner, M. D. (2001). Age-related changes in spatial and temporal gait variables. *Archives of Physical Medicine and Rehabilitation, 82*(1), 31-35.

Hak, L., Houdijk, H., Steenbrink, F., Mert, A., van der Wurff, P., Beek, P. J., & van Dieën, J. H. (2012). Speeding up or slowing down?: Gait adaptations to preserve gait stability in response to balance perturbations. *Gait & posture, 36*(2), 260-264.

Hof, A. L., van Bockel, R. M., Schoppen, T., & Postema, K. (2007). Control of lateral balance in walking: experimental findings in normal subjects and above-knee amputees. *Gait & posture, 25*(2), 250-258.

Hollands, M., Sorensen, K., & Patla, A. (2001). Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. *Experimental brain research, 140*(2), 223-233.

Hollands, M. A., & Marple-Horvat, D. E. (2001). Coordination of eye and leg movements during visually guided stepping. *Journal of motor behavior, 33*(2), 205-216.

Latt, M. D., Menz, H. B., Fung, V. S., & Lord, S. R. (2008). Walking speed, cadence and step length are selected to optimize the stability of head and pelvis accelerations. *Experimental Brain Research, 184*(2), 201-209.

Lindemann, U., Najafi, B., Zijlstra, W., Hauer, K., Muche, R., Becker, C., & Aminian, K. (2008). Distance to achieve steady state walking speed in frail elderly persons. *Gait & posture, 27*(1), 91-96.

Lo, O.-Y., van Donkelaar, P., & Chou, L.-S. (2015). Distracting visuospatial attention while approaching an obstacle reduces the toe-obstacle clearance. *Experimental brain research, 233*(4), 1137-1144.

Maki, B. E. (1997). Gait changes in older adults: predictors of falls or indicators of fear? *Journal of the American Geriatrics Society, 45*(3), 313-320.

Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Acceleration patterns of the head and pelvis when walking are associated with risk of falling in community-dwelling older people. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 58*(5), M446-M452.

Mills, P. M., Barrett, R. S., & Morrison, S. (2008). Toe clearance variability during walking in young and elderly men. *Gait & posture, 28*(1), 101-107.

Miyasike-daSilva, V., & McIlroy, W. E. (2016). Gaze shifts during dual-tasking stair descent. *Experimental Brain Research, 234*(11), 3233-3243.

Nagano, H., Begg, R. K., Sparrow, W. A., & Taylor, S. (2011). Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking. *Clinical biomechanics, 26*(9), 962-968.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., . . . Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American geriatrics society, 53*(4), 695-699.

Owings, T. M., & Grabiner, M. D. (2004). Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. *Journal of biomechanics, 37*(6), 935-938.

P. Di Fabio, A. E., John F. Greany, Saurav Paul, Richard. (2001). Suppression of the vertical vestibulo-ocular reflex in older persons at risk of falling. *Acta oto-laryngologica, 121*(6), 707-714.

Paquette, C., Paquet, N., & Fung, J. (2006). Aging affects coordination of rapid head motions with trunk and pelvis movements during standing and walking. *Gait & posture, 24*(1), 62-69.

Paquette, M. R., & Vallis, L. A. (2010). Age-related kinematic changes in late visual-cueing during obstacle circumvention. *Experimental Brain Research, 203*(3), 563-574.

Prince, F., Corriveau, H., Hebert, R., & Winter, D. A. (1997). Gait in the elderly. *Gait & posture, 5*(2), 128-135.

Richardson, J. K., Thies, S. B., DeMott, T. K., & Ashton-Miller, J. A. (2004). A comparison of gait characteristics between older women with and without peripheral neuropathy in standard and challenging environments. *Journal of the American geriatrics society, 52*(9), 1532-1537.

Santhiranayagam, B. K., Sparrow, W., Lai, D. T., & Begg, R. K. (2017). Non-MTC gait cycles: an adaptive toe trajectory control strategy in older adults. *Gait & posture, 53*, 73-79.

Singh, H., Sanders, O., Waller, S. M., Bair, W.-N., Beamer, B., Creath, R. A., & Rogers, M. W. (2017). Relationship between head-turn gait speed and lateral balance function in community-dwelling older adults. *Archives of Physical Medicine and Rehabilitation*.

Srulijes, K., Mack, D. J., Klenk, J., Schwickert, L., Ihlen, E. A., Schwenk, M., . . . Hobert, M. A. (2015). Association between vestibulo-ocular reflex suppression, balance, gait, and fall risk in ageing and neurodegenerative disease: protocol of a one-year prospective follow-up study. *BMC neurology, 15*(1), 192.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. t. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science, 19*(2), 203-220.

Taylor, M. R., Sutton, E. E., Diestelkamp, W. S., & Bigelow, K. E. (2015). Subtle differences during posturography testing can influence postural sway results: The effects of talking, time before data acquisition, and visual fixation. *Journal of applied biomechanics, 31*(5), 324-329.

Thomas, N. M., Donovan, T., Dewhurst, S., & Bampouras, T. M. (2018). Visually fixating or tracking another person decreases balance control in young and older females walking in a real-world scenario. *Neuroscience letters, 677*, 78-83.

Vallis, L. A., & Patla, A. E. (2004). Expected and unexpected head yaw movements result in different modifications of gait and whole body coordination strategies. *Experimental brain research, 157*(1), 94-110.

Winter, D. A. (1991). *Biomechanics and motor control of human gait: normal, elderly and pathological*.

Winter, D. A. (1992). Foot trajectory in human gait: a precise and multifactorial motor control task. *Physical therapy, 72*(1), 45-53.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement disorders, 23*(3), 329-342.

Young, P. M. M., & Dingwell, J. B. (2012). Voluntary changes in step width and step length during human walking affect dynamic margins of stability. *Gait & posture, 36*(2), 219-224.

Zeni, J., Richards, J., & Higginson, J. (2008). Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait & posture, 27*(4), 710-714.

Zijlstra, A., de Bruin, E. D., Bruins, N., & Zijlstra, W. (2008). The step length–frequency relationship in physically active community-dwelling older women. *European journal of applied physiology, 104*(3), 427.