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Robotic Assistant System for Precise Bone Repositioning in Orthognathic Surgery

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Orthognathic surgery deals with congenital anomalies, namely, anomalies in the form and position of the jaws resulting from growth disturbances in the facial skull. In order to correct this problem a translocation of bone segments is necessary. The aim is to achieve both a good occlusion and an ideal, aesthetic balance to the face. The maxillary osteotomy at the LeFort I level is among the most common surgical interventions for the correction of anomalies of the jaws. As computer technology is increasingly being applied in medicine, new methods have been developed for medical diagnosis, education, and training, as well as for planning, assistance, treatment, and assessment in surgery. In the field of orthognathic surgery too, such modern digital technologies have the potential to put preoperative planning and surgical execution on a more quantitative footing through the combination of extraoperative simulation and intraoperative image guidance. Several attempts in this direction have already been made. The major problem remains how to implement the preoperative planning during the actual operation: the precision achieved in the planning phase is usually not translated to patients. Traditionally, the transfer of the parameters obtained preoperatively is realized with bite splints. One alternative pursued in more recent approaches uses navigation systems intraoperatively, but this lead to only limited precision, due to systematic limitations. Another alternative is the introduction of robots for parts of the surgery, with the aim of combining the surgeon skill and experience with the high precision of a robot.

The intelligent robotic assistant system presented in this thesis is aimed precisely at the accurate transfer of the preoperative planning into the intra-operative phase. Its role is essentially that of ensuring the correct positioning of the resected bone segments in their planned position during the procedure of fixation.

The architecture of the new robotic system was developed based on a series of clinical and technical requirements. From a medical point of view, the system had to be easily sterilizable and allow for a smooth integration in the operating room; it had to be intuitive to use so that medical personnel (not robotics specialists) would be able to learn how to use it. From a technical point of view, the system was centered on a modified industrial robot which had to be adapted to the clinical use. For this, various sensors were introduced for controlling and monitoring of the system, an innovative end effector was developed in order to provide an interactive interface between the patient and the robot.

In order to ensure safety, the system architecture was designed and developed redundantly, independent of the robot controls. Furthermore, an important requirement was that the system should at no time act actively on the patient. Thus, the robot is only used as an intelligent tool, working most of the time interactively – with the surgeon conducting the robotic arm in force controlled mode. The only case when the robot moves autonomously in the operative phase is when it executes the planned repositioning. For the implementation of the system, all involved processes were identified. The workflow was modeled using UML activity diagrams. In the preoperative phase the planning is done conventionally without the use of complex planning systems and hence the new workflow remains almost unmodified. In the intraoperative phase, the robot is used only for the patient registration and for performing the repositioning, and so no drastic change in the workflow occurs here either. Hence, as the overall new workflow doesn't differ significantly from the conventional workflow for the LeFort I osteotomy surgery, a smooth integration of the robotic system in the clinical workflow is possible.

In order to obtain an overall system design that is sufficiently safe to satisfy the operating room's safety criteria, a process of risk management was conducted. This consisted of risk analysis and evaluation, which then formed the basis for risk control. For the risk analysis a fault-tree method was used, which focuses on a failure outcome and examines the components, processes, and conditions involved in order to identify all possible contributing factors that could have caused the outcome and determine the appropriate reliability measures. This analysis was the basis for risk minimization, which was achieved through a series of system design modifications.

The suitability of our robotic system was evaluated in an accuracy test analyzing the performance of the surgical robot system in transferring the preoperative planning in the operation phase by means of three plastic skulls specially prepared for the simulation of the maxillary repositioning. The data obtained indicated the accuracy of the planning transferring with deviations in the range smaller or equivalent to 1.4 mm, which considering the complexity of the whole setup as well as the fact that the accuracy of the Stäubli RX90maq robot is guaranteed up to 0.2 mm was deemed as satisfactory.