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Evaluation of Motion Compensation Dynamics of the Handheld Robot MINARO HD

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Abstract

Current surgical robotic systems consist either of a large serial arm, resulting in higher risks due to their high inertia and no inherent limitations of the working space, or they are bone-mounted, adding substantial additional task steps to the surgical workflow.

The robot presented in this paper has a handy and lightweight design and can be easily held by the surgeon. No rigid fixation to the bone or a cart is necessary. A high-speed tracking camera together with a fast control system ensure the accurate positioning of the burring tool, while automatically compensating for movements of the surgeon or the patient's bone.

To evaluate the motion compensation capabilities of the developed robot, an experiment was conducted in which movements of the patient were simulated on the robot's real time control system and the actual robot had to follow those virtual movements. The positioning error, measured with a tracking camera, was recorded for different velocities of the disturbing movement.

A linear relation between the positioning error and the speed of the disturbing motion could be discovered, with a slope of 24 ms and an offset of 0.044 mm.

The slope can be interpreted as the latency of the robotic system while following a moving target. Therefore, with a measured latency of 24 ms, the developed robotic system should easily be able to compensate for the patient's breathing as well as the tremor of the operator, whereas the latter can reach frequencies of up to 12 Hz according to literature.

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1 Introduction

Current robotic systems for computer-assisted orthopedic surgery are usually large serial arms, comparable to anthropomorphic industrial robots. Examples of such systems are the Mako (Bell et al., 2016), Mazor X (Kochanski et al., 2019) and ExcelsiusGPS (Zygourakis et al., 2018). Due to their large mass and the resulting inertia, they must be slowed down during operation, as required by ISO 10218-1 and ISO/TS 15066. Nonetheless, this design induces specific risks due to a lack of inherent workspace limitations (Davies, 1996). Another disadvantage of these systems is the large footprint of the robot base, i.e. a cart placed next to the operating table in an already crowded operating room environment.

In order to overcome the problems of a large serial arm, small application-specific kinematics have been developed that are mounted directly on the patient's bone, such as the MINARO (Heger et al., 2010), Arthrobot (Ko et al., 2003), MBARS (Wolf & Jaramaz, 2006) or Mazor Renaissance® (formerly SpineAssist) (Beasley, 2012). Their main advantages are the partially inherent safety due to a limited working space, low inertia and small space requirements (Berkelman et al., 2004). Nevertheless, the required rigid fixation to the patient's bone has a significant impact on the conventional surgical workflow (for fixation and, if necessary, sterile draping). The average insertion time per screw is about 10 minutes for operations with the Mazor Renaissance (Barzilay et al., 2008; Devito et al., 2010), compared to about 5 minutes for conventional techniques (Laine et al., 2000). Unicompartmental knee arthroplasty surgeries with the MAKO RIO system were found to take on average 27 minutes longer than using the Oxford approach (Banger et al., 2013).

Handheld robots have been proposed to combine the advantages of having a small robot system, being easy to handle in the intraoperative workflow without the need for a rigid fixation to the bone and with the benefit of versatile robotic tool guidance. The patient’s bone can also be tracked utilizing the tracking system used to localize the robot. Thereby, not only unintended motions induced by the operator can be compensated for but also movement of the bone due to forces applied by the surgeon or due to breathing (Knappe et al., 2003; Wagner et al., 2004). Examples are the intelligent tool drive for drilling (Pott et al., 2003) and the micron for eye surgery (MacLachlan et al., 2012).

A new handheld, highly dynamic mini-robot (MINARO HD) has been developed for burring applications based on the original MINARO kinematic structure (Korff et al., 2009; Niggemeyer et al., 2012) The workspace of the robot is specially adapted for unicompartmental knee arthroplasty resulting in inherent safety. The objective is to provide a versatile robotic tool which improves the accuracy of implant positioning and reduces the revision rate, as reported in literature (Batailler et al., 2019; Bell et al., 2016), while optimizing its integration into the conventional surgical workflow.

2 Material and Methods

A miniaturized robot with a total weight of 2.5 kg was designed (Figure 1), based on a five-bar linkage mechanism and a linear drive. A standard surgical high-speed burr is mounted onto the end of the kinematic chain together with a rigid body for the localization of the tool. The user can hold and position the robot using a single-hand grip at the rear end, which also hosts a button to activate the burr. The second hand can be placed at the front end of the robot for stabilization and further support.

The burring tool is localized using the tracking camera fusionTrack 500 (Atracsys LLC, Puidoux, Switzerland) and a real time control loop running on a dSpace system (dSpace GmbH, Paderborn, Germany) stabilizes the burring tool and follows the planned trajectory, similar to (Wagner et al., 2004).

To evaluate the motion compensation capabilities of the developed robot, an experiment is conducted in which movements of the patient are simulated. For this, a movement of $50\ \mathrm{mm}$ amplitude and with various speeds is programmatically added to the tracked position of the patient’s dynamic reference base. Those disturbing movements range from 1 up to $40\ \mathrm{mm/s}$. Due to the motion

Figure 1: The MINARO HD.

compensation control loop of the robotic system, the burring tool will follow the virtually moved dynamic reference base. For each speed, the maximum positioning error of the burr tool tip during the experiment is recorded, i.e. the difference between the actual tool tip position as recorded by the tracking camera and the target tool tip position from the optically measured dynamic reference base together with the virtual disturbing movement.

3 Results

The positioning error (Figure 2) is mostly linear. The slope of a linear fit is $0.024\ \frac{\mathrm{mm}}{\mathrm{mm}/_{\mathrm{s}}} = 24\ \mathrm{ms}$ with $0.044\ \mathrm{mm}$ error offset.

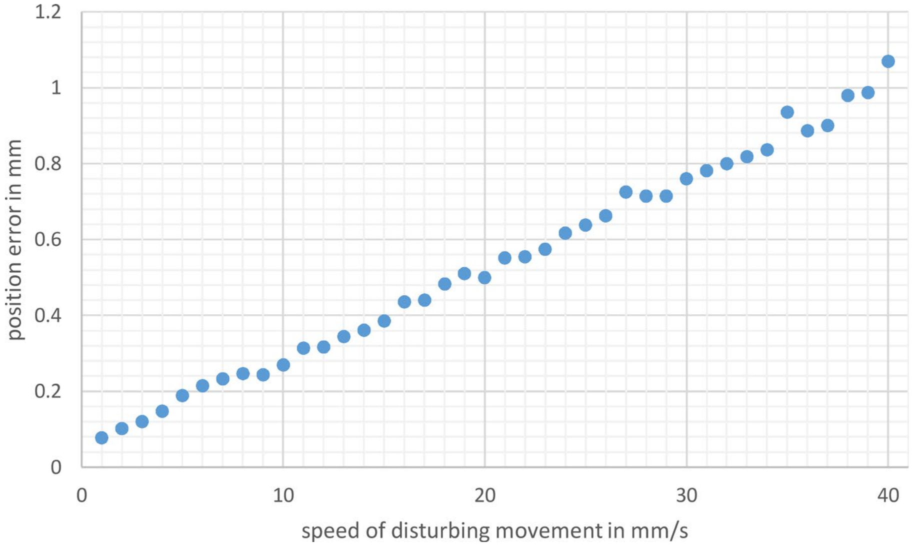

Figure 2: Positioning error over speed of disturbing movement for a positioning task of the MINARO HD.

A positioning accuracy of $0.5\ \mathrm{mm}$ can be achieved with relative movements between the patient and burring tool of up to $18\ \mathrm{mm/s}$.

4 Discussion

The 24 ms slope of the positioning error against the disturbing movement speed can be interpreted as the latency of the complete robotic system, i.e. the time it takes from measuring a small disturbing movement with the tracking camera until the manipulator compensates for that movement and the burring tip is again at its target position. The 44 µm error offset can be explained by the noise of the tracking camera.

Sources of unintended movement between the robot and the patient can be the breathing of the patient as well as tremor of the operator. While the first is rather slow, tremor can reach frequencies up to 12 Hz (Takanokura & Sakamoto, 2001). With the measured latency of 24 ms for the developed MINARO HD, it should be easily possible to compensate for this sort of disturbing motion. In further experiments, the performance of the robotic system in actual burring tasks has to be evaluated.

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