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Positioning and Stabilization of a minimally invasive Laser Osteotome

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INTRODUCTION

Robot-assisted surgery allows surgeons to surpass limitations of human performance. In particular, surgical robots increase the surgeon's performance by functionalities like movement scaling and tremor suppression. Surgical robots also allow transferring preoperatively planned interventions precisely into practice. Particularly for frequent orthopedic interventions such as hip and knee surgeries, surgical robots can produce cuts with high fit accuracy. Commercially available systems for robotic and robot-assisted hip and knee replacement surgeries include the ROBODOC (THINK Surgical, Inc., Fremont, CA, USA), the Mako (Stryker Corporation, Kalamazoo, MI, USA), the NAVIO Surgical System (Smith and Nephew, London, UK) and iBlock (OMNIlife Science, East Taunton, MA, USA). Until today, the standards for cutting bone in surgical interventions are oscillating bone saws and drills. This is also true for cutting bone with robots. However, using a laser to cut bone offers multiple advantages. These advantages are: i) higher flexibility in the ablation geometry, ii) smaller cut width compared to mechanical tools, iii) high accuracy, and iv) faster healing of the bone ([1],[2]). The CARLO system is the first medical robot that can cut bone in open surgery without contact due to cold laser ablation technology [3].

Currently, we are developing a computer-aided laser osteotome which aims at combining the advantages of robot-assisted laser osteotomy and minimally invasive surgery (MIS). The final system will consist of a serial robot which manipulates a robotic endoscope. The end-effector at the tip of the endoscope will contain the laser optics as well as additional devices for laser ablation such as irrigation and vision (see Fig. 1). As a first application, we focus on uni-compartmental knee arthroplasty (UKA). We consider UKA as a benchmark application for MIS laser osteotomy since it involves cutting of thick bones such as the femur. UKA also allows testing any other functionality required for endoscopes in MIS laser surgery such as irrigation, laser ablation, endoscope manipulation, visual feedback, planning and execution of pre-planned movements, registration and tissue characterization.

One main challenge from the robotics point of view is the positioning and stabilization of the end-effector at the intervention site. Since the end-effector is far away from the robot's base, many sources of disturbance can influence the pose of the end-effector. This way, disturbances can prevent the irrigation device and the narrow laser beam from precise targeting. Thus, carbonization, unprecise cuts, or undesired tissue damage could be the result. To prevent disturbances from influencing the laser osteotome's performance, this paper presents for the first time a stabilization mechanism for a laser osteotome.

MATERIALS AND METHODS

Based on a preceding evaluation, we have decided to stabilize the end-effector of the laser osteotome using a bone mounted mechanism. This mechanism first attaches the end-effector to the bone. In a second step the endoscope's shaft is decoupled from the end-effector by decreasing the stiffness of the endoscope's flexible shaft. In this way, disturbances on the robot's side that holds the endoscope are not transferred to the end-effector.

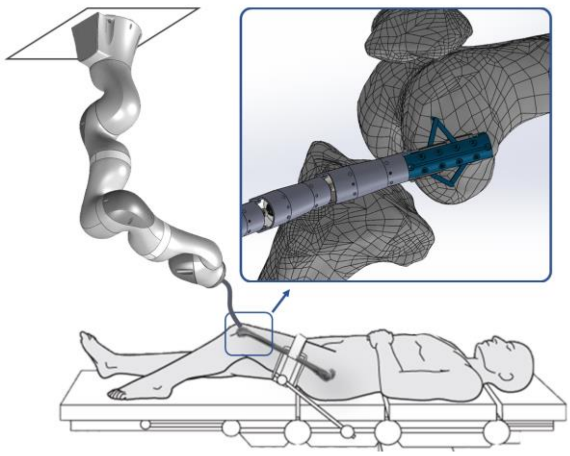

Fig. 1 Laser osteotome consisting of a serial robot that holds a robotic endoscope (Ø 15 mm). The end-effector (blue) of the robotic endoscope consists of a parallel robot which carries the laser optics and can be fixed to the bone which is to be cut. Figure adapted with permission from [4] and [5] (Copyright by AO Foundation, Switzerland).

More importantly, movements of the patient's bone are directly transferred to the endoscope's end-effector that will move together with the bone. Hence, the relative pose of the end-effector with respect to the bone can be maintained. A key component of the stabilization mechanism is a planar parallel manipulator integrated into the end-effector. This manipulator (six bar mechanism) is connected to the bone at two anchoring points. For example by means of suction. To position the laser, the mechanism has three planar active degrees of freedom (DoF) (see Fig. 2). In addition, the laser optics will have a long depth of focus that allows us to adjust the ablation location in vertical direction.

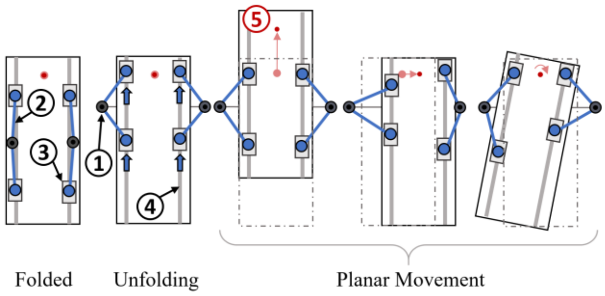

Fig. 2 Schematic illustration of the mechanism's DoF. From left to right; Folded during insertion, unfolding and attaching by moving the four sliders accordingly, planar movement in two translations and a rotation. The mechanism's parts are: Two fixed anchoring points (1) and four legs (2) mounted on actuated sliders (3) that can move on linear rails (4) (designated by grey lines). The laser (5) operates orthogonal to the end-effector.

The main components of the six bar mechanism are: the base, the body of the end-effector, and two legs on each side. Each of the four legs is mounted on one side on a separate slider which can glide on a separate linear rail (see Fig. 3). The other side of each leg can pivot about the corresponding anchoring point. All four sliders are actuated from outside the endoscope using cables with pre-tension springs controlled by motors. During insertion and extraction of the endoscope into and out of the patient, the legs can be folded away, making the mechanism suitable for MIS.

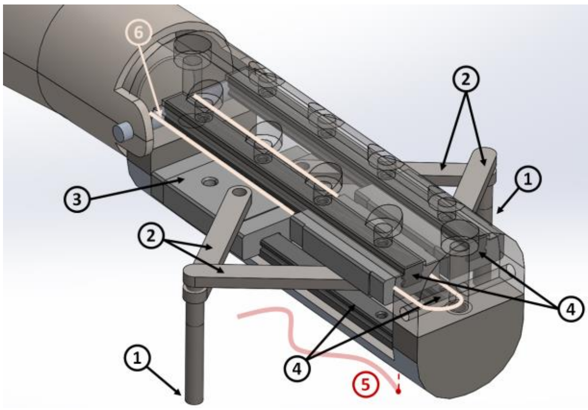

Fig. 3 CAD-model of the mechanism mounted on the robotic endoscope. (6) illustrates the cable actuator of the upper right leg. The other part numbers are described in Fig. 2.

One crucial characteristic of the mechanism is the space in which the end-effector can place the laser optics when the anchoring points are set. The shape and size of this workspace depends on four mechanical parameters of the mechanism, namely the length of the legs, the length of the linear rails, the distance between the anchoring points, and the distance between the linear rails on the right and left side of the mechanism. In order to maximize the workspace of the laser, the respective optimal set of parameters needs to be found. This is known as "the synthesis problem" in parallel robotics [6]. We used a custom written search algorithm in MATLAB to find the four parameters which result in a maximal workspace in terms of the covered area by the laser.

RESULTS

From all the parameter sets investigated, the largest workspace calculated has a size of 759 mm^2. It is obtained with the largest considered rail length of 35 mm, a leg length of 6 mm, the minimal considered rail distance of 4 mm and an anchoring distance of 15 mm. The resulting workspace is shown in Fig. 4. The simulation results also showed that the shape of the workspace is symmetric and has a similar form for all parameter sets which lead to large workspaces.

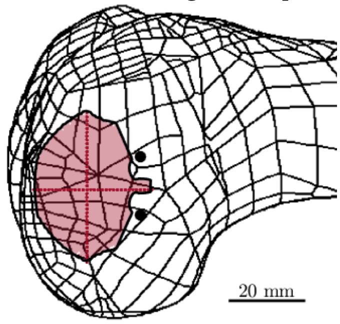

Fig. 4 Illustration of the largest obtained planar workspace of the mechanism (in red) projected onto the femur for size relation. The anchoring points are marked by black dots. The dotted lines represent the maximal straight cuts parallel (39 mm) and orthogonal (30 mm) to the virtual line that connects the two anchor points.

DISCUSSION

This paper describes the design of a parallel robot that is connected to the surface of bone and provides a stable platform for minimally invasive laser osteotomy. The mechanism enables up to 39 mm long straight line cuts parallel and 30 mm orthogonal to the base of the robot as illustrated in Fig. 4. It enables a workspace which is approximately 1.5 times larger than the footprint of the mechanism.

ACKNOWLEDGMENT

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