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Contact Force Estimation for Minimally Invasive Robot-assisted Laser Osteotomy in the Human Knee

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INTRODUCTION

We are developing a robotic endoscope with an integrated laser osteotome. The goal of this laser osteotome is to combine the advantages of laser osteotomies with those of minimally invasive surgery. The robotic endoscope is controlled through teleoperation and the laser optics as well as a camera for visual feedback are integrated in the endoscope end-effector. In order to allow precise laser cuts, the end-effector needs to be positioned accurately and stabilized at the cutting location. Therefore, an active parallel mechanism [1] is integrated in the endoscope end-effector which allows attaching the tip of the endoscope to the bone and to manipulate the end-effector accurately within three planar degrees of freedom (DoF) (Fig. 1).
Precise bone cuts are relevant in many surgical areas, however, we focus on using our device for unicompartmental knee arthroplasty (UKA). This is a technically challenging surgery where the alignment of the implant and therefore the bone cuts are of uttermost importance with respect to the clinical outcome [2].

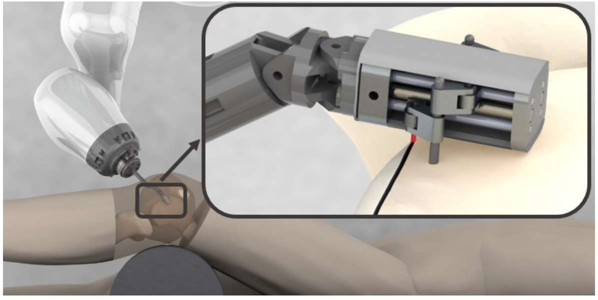

Figure. 1. The overall system setup consists of a serial robot which holds a robotic endoscope. The tip of the endoscope houses the laser optics and the laser beam exits the endoscope orthogonally to its longitudinal axis in order to ablate the bone below. An integrated parallel mechanism can position and stabilize the endoscope tip on the bone.

One of the main challenges when developing robotic tools for minimally invasive surgery is the lack of a formal design methodology [3]. It is especially difficult to find literature documenting anatomical manipulation requirements such as the forces required to manipulate a robotic tool inside a human joint or the available workspace within human cavities. There is some literature available on interaction forces during laparoscopic surgery [4], but to the best of our knowledge, no such information is available for manipulations within the human knee.

This paper presents experiments for the estimation of expected contact forces between the endoscope end-effector and the surrounding tissue inside the human knee joint. Our aim was to estimate the magnitudes of both axial and lateral forces which have to be overcome in order to move the endoscope tip inside the knee capsule on the femur along the necessary cutting lines for an Aesculap® univation® X knee implant (Aesculap AG, Tuttlingen, Germany).

MATERIALS AND METHODS

The necessary bone cuts for the femoral part of the knee implant were defined together with an orthopedic surgeon by fitting a 3D model of the implant on a 3D model of the femur that was segmented from a high resolution MRI scan and provided by numex GmbH (Dietikon, Switzerland). For the study, only the distal and posterior cuts were selected. These cuts were chosen based on the available workspace inside the knee joint. Thus, the distal cut will have to be executed from the medial side of the medial condyle at approximately 45° knee flexion and the posterior cut will be executed with the end-effector attached to the distal part of the condyle at about 90° knee flexion (Fig. 2). The chamfer cut, which adds a chamfer between the distal and posterior cutting planes, will most likely be executed in a similar fashion as the posterior cut and we therefore do not expect substantial differences in the required forces as compared to the posterior cut.

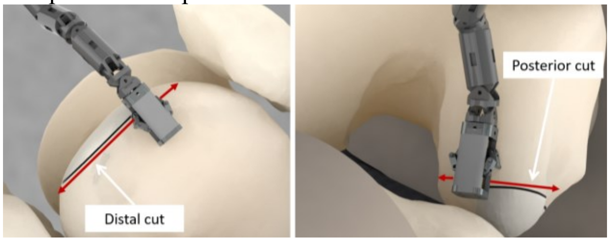

Figure. 2. Left side: path for the distal cut of the femur. Right side: path for the posterior cut of the femur.

A probe which in size and form is comparable to our current endoscope end-effector prototype was manufactured and connected to a 6 DoF Nano17 force/torque sensor with calibration SI-12-0.12 (ATI Industrial Automation, Inc., Apex, NC, U.S.A.) by a rod of 60 mm length. The sensor itself was mounted on a cylindrical handle that was manipulated by an orthopedic surgeon, experienced in knee surgery (Fig. 3). To record the measured forces, a control cabinet including an embedded PC which runs TWINCAT3 (Beckhoff

Automation AG, Verl, Germany), a real-time automation software, was used. Prior to measurement the probe was held vertically and offsets were removed. During the experiments, the surgeon was instructed to insert the probe into the knee joint through an incision similar in place to the ones used in current UKA surgeries but of smaller size. The probe was then navigated five times along each of the preplanned cutting paths. The whole experiment was recorded with a standard digital camera. The footage was then synchronized with the force measurements in order to assign the measured forces to the respective movements of the surgeon. All measurements were conducted on a deceased male subject, aged 76, Thiel-embalmed (Ethics Committee of Northwest/Central Switzerland, Basel, Nr. 2018-00158).

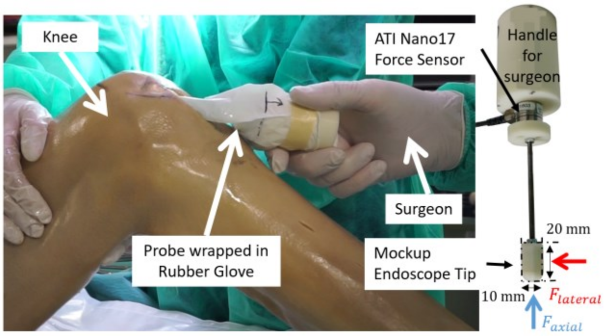

Figure. 3 Setup for the force measurements. Left: The surgeon navigates the probe along the preplanned cutting paths. Right: Probe attached to the force/torque sensor mounted on a handle.

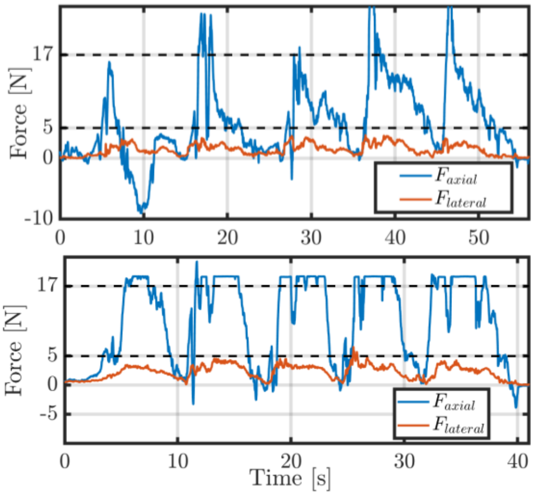

Figure. 4 Force measurement data from the experiments. Top: path along the distal cut of the femur; bottom: path along the posterior cut of the femur. Each cutting path was retraced five times.

RESULTS

The measured forces for the five trials of both cutting paths are shown in Fig. 4. Since the sensor's range limit is specified by the manufacturer to be 17 N, all forces exceeding this force might not be accurate and therefore the plot's y-axis is limited at 25 N. While the lateral forces remained mostly below 5 N, the measured axial forces were much higher and often exceeded the 17 N limit.

CONCLUSION AND DISCUSSION

The presented force estimation experiments provide a rough estimate of the expected contact forces in a minimally invasive UKA. However, it has to be emphasized that these experiments purely allow conclusions about the order of magnitude of the required actuator forces. In addition to the sensing range limit of the force/torque sensor, several other factors might have influenced the results: First, mounting the measurement probe on a rigid link led to the measurement of forces that were acting on the rod in addition to those acting on the endoscope tip. Secondly, since the probe was moved manually in a minimally invasive manner without any visual feedback, the probe tip and the rigid link were sometimes pushed against anatomical constraints such as the border of the knee capsule or the bone. We suspect that this, in combination with the first point, led to higher forces than we expect in the robot-assisted procedure since these constraints would be avoided by the robotic device. Thirdly, even though Thiel embalming conserves the properties of tissue relatively well, there are still significant differences to living tissue.

We conclude that the expected relevant contact forces for minimally invasive UKA will most likely be below 10 N laterally and at around 25 N axially. However, to confirm these values, we will in a next step repeat the measurements with a miniature force sensor attached directly to the mockup end-effector in order to overcome some of the abovementioned limitations.

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