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Dissertations

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Robotic system for accurate minimally invasive laser osteotomy

Robotisches System für genaue minimal invasive Laser-Osteotomie

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Abstract: Within my thesis, I worked on the challenges of robotics in developing a system that enables minimally invasive bone-cutting with a laser. Knee replacement surgery was the first target application. One of the main challenges was achieving high positioning accuracy of the laser while maintaining a form factor that allows minimally invasive insertion of the robotic device and minimally invasive device manipulation during large-area surface treatments.

Keywords: robot, parallel mechanism, robotic endoscope, minimally invasive surgery, laser osteotomy, knee arthroplasty

Zusammenfassung: Im Rahmen meiner Dissertation beschäftigte ich mich mit den Herausforderungen der Robotik bei der Entwicklung eines Systems, das minimalinvasives Schneiden von Knochen mit einem Laser ermöglicht. Die erste Zielanwendung war die Kniegelenkersatzoperation. Eine der größten Herausforderungen bestand darin, eine hohe Positionierungsgenauigkeit des Lasers zu erreichen und gleichzeitig einen Formfaktor beizubehalten, der ein minimalinvasives Einsetzen des Roboters sowie eine minimalinvasive Handhabung des Geräts bei großflächigen Oberflächenbehandlungen ermöglicht.

Schlagwörter: Roboter, Parallel Mechanismus, Roboterendoskop, minimalinvasive Chirurgie, Laser Osteotomie, Knieendoprothetik

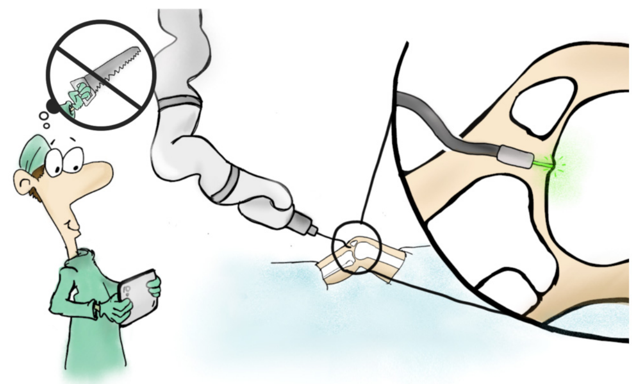

Figure 1: The aim is to develop a robotic system for minimally invasive laser osteotomy.

Bone cutting, so-called osteotomy, is an essential part of many surgical procedures. Nowadays, bone cutting is mainly performed using mechanical devices such as milling cutters, drills, and saws. Robotic laser osteotomy is a novel alternative for bone cutting with several advantages compared to conventional methods. However, existing robotic devices for cutting bone with laser require direct access to the entire bone, i. e., require open surgery and are, therefore, not minimally invasive. We aim to develop a tool for minimally invasive bone-cutting based on laser light using a robotic endoscope feasible for minimally invasive surgery (Fig. 1).

The development of robotic devices for minimally invasive surgery is challenging for several reasons. The devices must have a high degree of flexibility and a small diameter to adapt to the patient's anatomy without damaging the surrounding tissue. In addition to these requirements, the device must allow for accurate laser positioning in a large operating range to enable accurate and long bone cuts. Another challenge is that the exact environmental conditions for a robot in the body are difficult to quantify.

In this work, the following challenging and open questions were investigated:

1. How could a robotic device be implemented to stabilize and accurately position a laser for minimally invasive bone cutting?
2. How could minimally invasive UKA be performed using a robotic laser osteotome? How can requirements

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for robot design be derived from the environmental conditions and anatomic constraints in the knee?
3. Can the implemented robotic device be miniaturized to the required size? What are the limitations of the miniaturization process?
4. How can this robotic device be inserted and placed at the intervention site minimally invasively?

The first research question led to the development of a parallel mechanism that can position integrated laser optics, i. e., the laser, in 3 planar degrees of freedom. This mechanism can be integrated at the tip of the surgical instrument and will attach to the bone with two legs to increase the accuracy and stability of the cutting process [5, 1]. This mechanism has a 4-RRP structure and can also expand its workspace by successively repositioning its attachment points, i. e., by “walking” [4].

To answer the second research question, we performed studies on body donors to find the space available in the knee joint for manipulation of surgical instruments [7] and the contact forces that will act on the surgical instrument during minimally invasive manipulation inside the knee joint [6].

The miniaturization of the parallel mechanism (third research question) was achieved by implementing an actuation and sensing concept based on leadscrew-nut pairs integrated at the surgical instrument tip, which were actuated by externally placed motors with flexible shafts as rotation transmitters (Fig. 2). The evaluation of the miniaturized mechanism showed that submillimeter accuracy (maximal error: 0.176 mm, mean error: 0.07 mm) could be reached [3].

For insertion and placement of the parallel mechanism and the integrated laser (fourth research question), we developed and evaluated a concept and first prototype of an overall robotic system consisting of a serial manipulator guiding a robotic endoscope for minimally invasive insertion of the laser fiber with the bone-mounted parallel mechanism integrated at the robotic endoscope’s tip [2] (Fig. 3).

With this work, I contributed to the development of a robotic system for minimally invasive laser osteotomy. Specifically, I developed a concept and first design of the overall mechanical system, which is conceptually feasible for minimally invasive applications. Although many challenges are still open, the performed experiments’ results show that the realization of such a mechanical system for minimally invasive laser osteotomy is feasible in principle.

This dissertation was submitted in 2021 at the University of Basel, Switzerland, Faculty of Medicine (available at

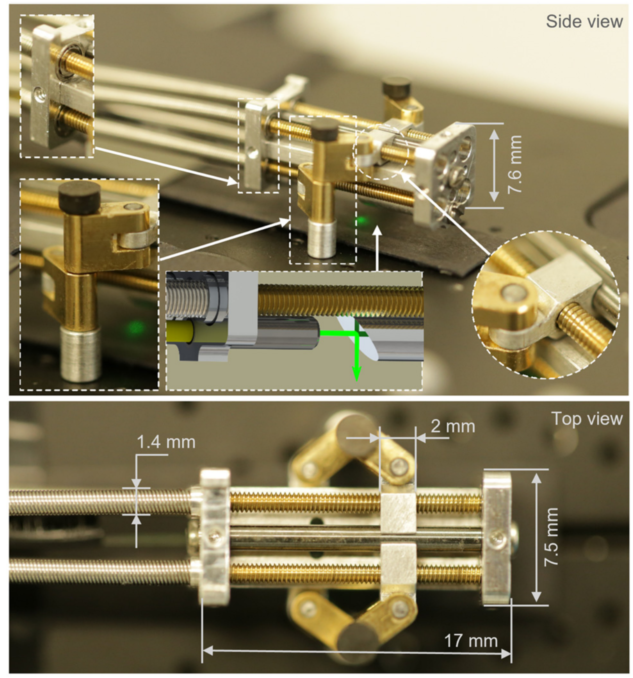

Figure 2: Miniature parallel mechanism for minimally invasive laser guidance.

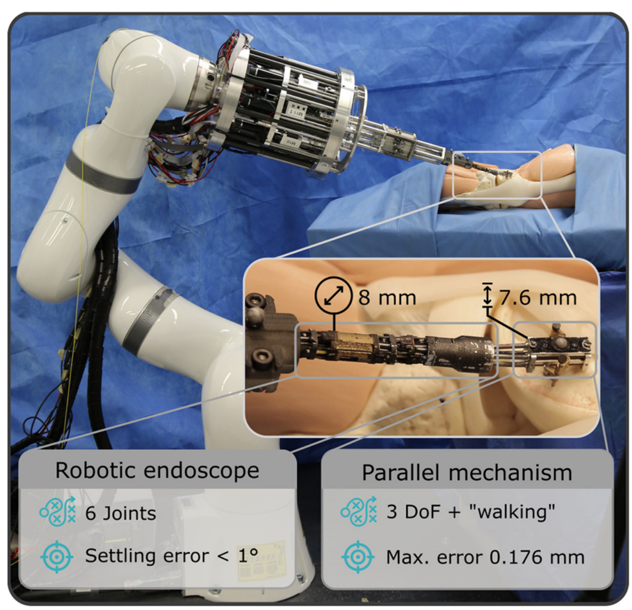

Figure 3: Overall mechanical system setup prototype.

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Bionotes

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