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Evaluation of the Use of Haptic Virtual Fixtures to Guide Fibula Osteotomies in Mandible Reconstruction Surgery

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***Abstract*–When a tumour is found on the mandible, fibula free-flap mandibular reconstruction is often performed where the cancerous area is removed and replaced with the patient's bone from the fibula and soft tissue from the calf. Fibula bone segments used to reconstruct the mandible must closely match the removed sections of the mandible to ensure the optimal surgical outcome. In the current practice, surgical design and simulation of the reconstruction based on medical imaging data, 3D planning, and rapid-prototyped surgical guides ensure that the surgical plan is accurately followed in the operating room (OR). However, rapid prototyped guides are time-consuming to manufacture. As an alternative, haptic virtual fixtures can be used in surgery to constrain surgical tools to predefined regions or trajectories. The resulting haptic assistance can guide surgeons during fibula segmentation to ensure that fibula osteotomies are segments that correspond to the mandible resection according to the reconstruction surgical plan. In this paper, the feasibility and repeatability of using virtual haptic fixtures were tested experimentally on rapid prototyped fibula models. A haptics-enabled robotic system was used to guide participants' hands to the correct position and orientation in space according to the surgical plan using haptic feedback. The results based on ten participants cutting fibula replicas suggest that the accuracy achieved with the system was 3.7mm. Improvement in the registration process and registration accuracy, extended reach of the robot arms, and more intuitive virtual fixtures would be required before adoption for clinical use. However, this paper illustrates a workflow for integrating haptic feedback into the fibula mandible reconstruction procedure, identifies obstacles related to clinical implementation, and demonstrates how haptic feedback can be used as a guidance method to assist users complete fibula osteotomies.**

***Index Terms*—Cognitive human-robot interaction, Haptics and haptic interfaces, Human factors and human-in -the-loop, Human performance augmentation, Medical robots and systems, Surgical robotics: planning,**

I. Introduction

Head and neck cancer has a devastating impact on a patient's quality of life. When a tumour is found on the mandible (lower jaw), the tumour and affected tissues on the mandible are surgically removed, and a fibula bone segment and soft tissue from the calf are used to reconstruct the mandible [1,2]. This is a complicated surgery that needs to be performed accurately to provide the patient with an optimal functional outcome following surgery [3].

Surgical design and simulation is a process that allows surgeons to examine the patient's anatomy and walk through a surgery digitally in preparation for the actual procedure [3-5]. Patient-specific anatomical models, cutting and drilling guides, and reconstruction templates allow the surgical team to translate the virtual pre-surgical plan into the operating room accurately and effectively, improving the functional outcomes compared to freehand surgery [3-7]. However, producing physical medical models and surgical guides for mandible reconstruction surgery can be time-consuming – in fact, 3D printing surgical guides sometimes takes up to 50 hours. Once printed, the surgical guides cannot be modified or adjusted. Changes to the surgical plan may not be accommodated due to time, material and equipment constraints.

In this study, we explored the possibility of using haptic virtual fixtures as software-generated physical constraints to perform fibula osteotomies. By implementing forbidden-region virtual fixtures in fibula osteotomies, the saw blade attached to a robot and co-manipulated by both the robot and a human operator was guided into position as defined by the surgical plan. The largest advantage that virtual fixtures provide over template-based surgery is the opportunity to re-plan or adjust the surgery, even intra-operatively, without the need to fabricate new physical cutting, drilling and reconstruction guides. Such last-minute changes to the surgical plan may be necessary due to the growth of the cancerous area. Other benefits of virtual fixtures versus 3D-printed guides include time and cost savings due to the elimination of the need for 3D printing and sterilization of physical surgical guides. Haptic virtual fixtures can potentially provide the same high level of precision as rapid prototyped cutting and drilling guides without the long production time.

Collaboration between a surgeon and robot combines the mental abilities of a surgeon and the electromechanical abilities of a robot (e.g., high geometrical precision, repeatability, and accuracy), providing the patient with the benefits of both modalities to complete tasks with greater precision and reliability [8]. The purpose of a collaborative robot is not to replace the surgeon but to augment the surgeon's skill by enhancing the surgeon's dexterity and manipulability [9]. The surgeon remains in control of decision making, task advancement and gross positioning of the surgical instrument while the robot acts as a 'smart tool' to assist the surgeon by finely positioning or constraining the movement of a surgical instrument within a predefined pathway [10].

Haptic virtual fixtures rely on robot control software codes to guide motion along a desired path or prevent movement into a forbidden region to provide constraints for safety-critical procedures [8,11]. Haptic virtual fixtures have been explored as a means to provide guidance for many clinical interventions including skull base brachytherapy seed placement [9], vein tracing and membrane peeling in eye phantoms [12], total knee arthroplasty [13,14], craniofacial osteotomies [15, 16], endoscopic sinus surgery [17], and cardiac surgery [18]. Virtual haptic fixtures have been shown to increase the accuracy and safety of clinical procedures.

Our aim is to evaluate the feasibility and repeatability of using haptic virtual fixtures to assist participants to perform fibula osteotomies for fibula mandible reconstruction. Previous work has examined the possibility of using autonomous and teleoperation systems for fibula mandibular reconstructions with promising results [11,19, 20]. However, the greater the autonomy of a surgical robot, the greater the risk of injury in the case of system instability [9]. A fully-autonomous surgical robot operating within a dynamic operating room (OR) may be unable to interpret and respond to changes in the environment as competently as a surgeon [21]. A surgeon is capable of understanding the requirements of a patient and the surgical procedure and reacting to unexpected obstacles or uncertainties quickly based on years of training [21]. Discussions regarding collaborative robot-assisted surgery often centre around the balance between automation and surgeon control in such a way that patient safety and surgical outcomes are maximized [9]. Consequently, instead of a fully-autonomous robotic system, we developed a co-manipulated haptics-enabled robotic system that allows the participant to remain in control of the most safety-critical part of the procedure, the cutting, while the most accuracy-critical aspect of the procedure, the positioning and orienting the saw blade in the planned cutting plane, is delegated to the machine (i.e., the haptics-enabled robotic system).

II. Proposed Haptic Guidance Surgical Workflow

The goal of the haptics-enabled robotic system is to provide haptic assistance to the surgeon to help the surgeon in positioning and orienting the saw blade according to the surgical plan, when performing osteotomies. The proposed haptic assistance is contrasted to two common surgical workflows and schematically visualized in the flowcharts in Fig. 1.

In the *freehand surgery*, computed tomography (CT) data is available for visual inspection and the mandible resection and fibula harvesting are done without guidance. In a *template-guided surgery*, CT data is used to create digital models of the patient's bony anatomy and a digital patient-specific surgical plan including cutting planes. A surgical toolkit is 3D printed and includes models of mandible and fibula, mandible and fibula cutting guides, and a reconstruction/transfer template to guide the assembly and positioning of the reconstruction [3,22]. Clinicians at the Institute for Reconstructive Sciences in Medicine (iRSM) have pioneered template-guided surgery for fibula mandible reconstruction. Currently, *image-guided surgical navigation* offers the opportunity to precisely locate points in the skeletal anatomy and to depict osteotomy lines and implant positions. The navigation systems are capable of providing real-time and dynamic visual feedback to the surgeon by registering the navigation probe to the medical imaging data (e.g., CT scans). However, angular positioning is difficult to follow based on the multiplanar view offered by navigation systems. In contrast, a *haptic guidance* system coupled with a surgical navigation system has the potential of facilitating the positioning of the instruments. In Fig 1, the right-most column shows the proposed way of substituting the 3D-printed templates with virtual fixtures. The following paragraphs will describe the details of the envisioned haptic assistance system as part of a virtual surgical guidance system. However, for evaluation, a reduced system will be used to just assist in fibula segmentation and not mandible resection or fibula mandible reconstruction.

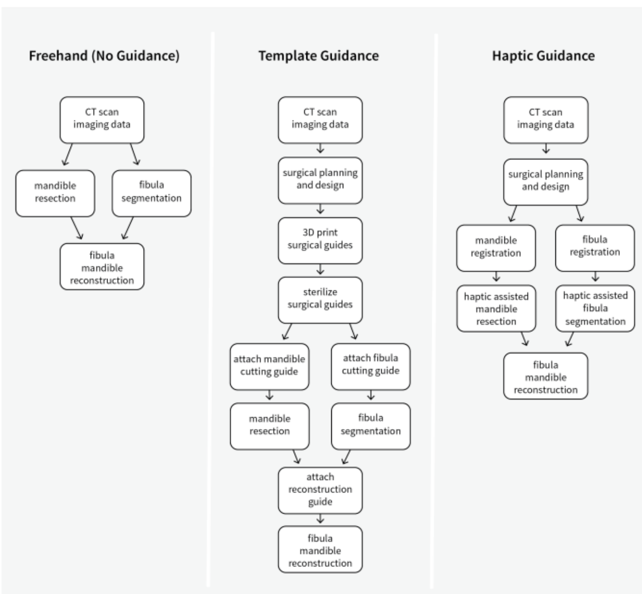

Fig. 1. The workflow of implementing haptic guidance

A. Preoperative Haptic System set up and Registration

A preoperative CT scan will be taken of the patient's mandible and fibula and used to generate digital standard tessellation language (STL) models of the patient's relevant anatomy; STL is the standard file format for communicating surgical plans. Surgical planning and simulation techniques are then used to create a surgical plan to reconstruct the mandible using the fibula as shown in Fig. 1 [3,4]. Planes are used to indicate where cuts will be made to segment the fibula. Fibula cutting planes are exported as STL file format from the surgical planning software. To identify these planes once they are uploaded into the control software for the robotic system, human interaction is necessary to pre-program the planes in the system before the surgery. Refer to Fig 2.

B. Haptic Feedback

Haptic feedback was delivered for orientation of the robot arm to ensure the correct orientation of the blade to the cutting planes. Tactile forces applied to the robot arm make it difficult for the human operator to overpower the haptic feedback and hold the blade in the incorrect orientation. A torque vector was applied by the robot to the user's hand in order to orient the saw connected to the robot end-effector parallel to the segmenting plane. The amount of torque applied is linearly proportional to the difference between the desired angles and the actual angles of the robot arm. k is a gain that can be adjusted to create stiffer or softer virtual fixtures. The gain, k, was set to 10. The k gain was set high so that it would be difficult to change the orientation of the blade away from the target orientation while avoiding system instability.

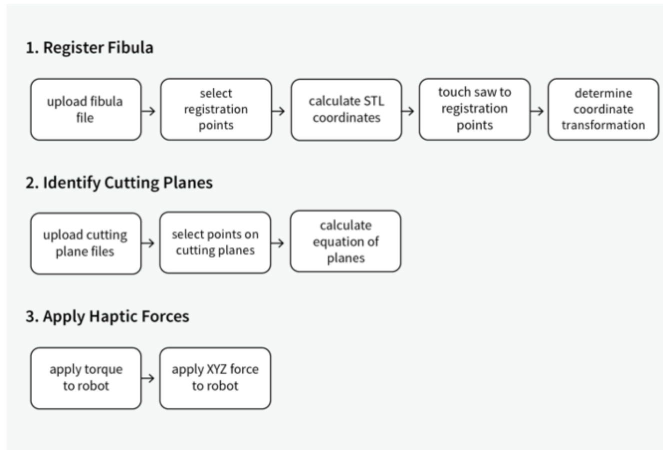

Fig. 2. The workflow of implementing haptic guidance for the surgeon

Haptic guidance forces were also applied to correct for the position of the surgical instrument relative to the fibula. A gentle force vector guided the controller to the position of the active cutting plane while the orientation of the blade was constrained. The design for the position-correcting haptic guidance was according to an attracting target plane model: The force applied was inversely proportional in magnitude to the distance from the target plane and directed towards the plane (parallel to the normal of the plane). As the blade came within 0.5 mm of the target plane, the force applied to the arm was turned off to avoid chattering around the desired position. The magnitude was scaled so that the translational forces never exceeded 2.5N in any direction. A torque of at most 0.3Nm was applied to the robot arm to keep the blade oriented parallel to the cutting plane.

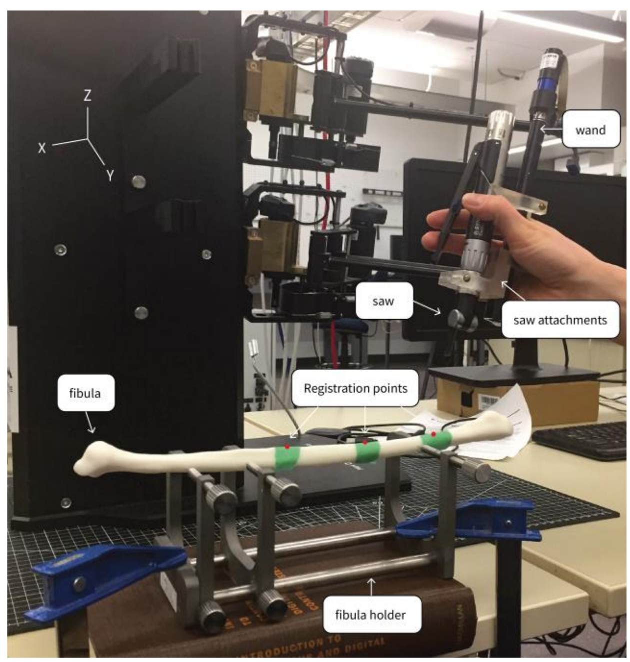

Fig. 3 Experimental Setup

Experiments

C. Experimental Setup

The haptic assistance system used for this study was implemented using a high-definition HD^2 haptics-enabled robot (Quanser, Inc., Markham, Ontario, Canada) that is controlled in the Quarc/MATLAB software environment. This robot provides haptic feedback in all 6 degrees of freedom (DOF). A Synthes electric pen drive including an oscillating surgical saw (Du Puy Synthes, Switzerland) was attached to the robot using custom 3D-printed attachments; see Fig. 3. 3D-printed saw attachments allowed the saw blade to extend beyond the end of the robot wand so that the robot wand did not impede the movement of the saw during the fibula osteotomy as seen in Fig. 3. Since the HD^2 gives the position of the middle of the wand, a frame transformation was needed to find the position of the saw blade tip. The distance between the two frames was measured using callipers and the rotation matrix was found using the Euler angles of the wand reported by the haptic device.

For mandible reconstruction, up to four segments of fibula may be used depending on the dimensions and shape of the mandible defect. For the evaluation of the present system, the surgical plan was designed to simulate a realistic surgical plan; fibula segments were planned to be longer than 20 mm with the first cut 90 mm from the distal end of the fibula according to the clinical requirements for this procedure. The fibula cutting surgical plan is shown in Fig 4. (a). The first fibula segment was 24mm in length, the second segment was 28.5 mm in length, the third segment was 24.9 mm in length, and the fourth segment was 31.5 mm in length. The digital STL model of the fibula used to 3D print a physical fibula model was created using CT scan imaging data of a real patient fibula; a waiver form was obtained to use CT scan imaging data to create the fibula models used in this study. Fibula models were printed in a standard white resin (Formlabs Inc., Sommerville,

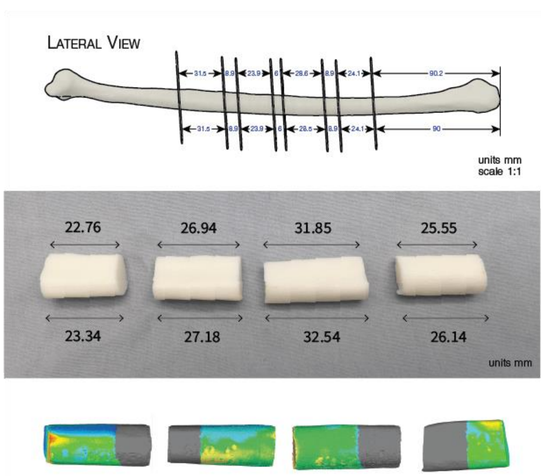

Fig. 4 (a) Fibula with cutting planes
Fig. 4 (b) Fibula segment measurements
Fig. 4 (c) Hausdorff heat map comparing longest and shortest lengths of each fibula

Massachusetts, United States of America) using a Form2 3D printer (Formlabs Inc., Sommerville, Massachusetts, United States of America).

The 3D printed fibula models were placed in a fibula holder that was affixed to the table in an orientation parallel to the *x*-axis of the haptic device. Manual and visual measurements were taken to rotate the STL about the *x*-axis so that the orientation of the digital STL file matched that of the 3D printed model in reality; this rotation was also applied to the segmenting plane locations. Since the orientation of the 3D printed model matched between the 3D model of the surgical plan, an identity rotation matrix was assumed for the coordinate transformation between the surgical fibula model {F} and robot coordinate system {R}, refer to Fig. 5. This simplifying assumption was made to facilitate in the registration process where unconstrained registration resulted in errors due to the almost cylindrical shape of the fibula. Since the purpose of this study was to evaluate how closely the participants were able to follow the cutting plan, the registration was partly hard-coded in the experimental setup.

The translation between the STL file and rapid prototyped model was empirically defined by locating three points in both the real world and the STL coordinate systems {C}, as defined in the robot coordinates {R}, refer to Fig. 5. The translation between the STL {C} coordinates and the robot coordinates {R} is taken to be the translation for the first registration point. The measurements form the other points were used to verify the correct orientation. The standard deviation for multiple contact points between the saw blade tip and the 3D printed fibula was 1.3mm in the z-axis, reflecting the inaccuracies in the registration process.

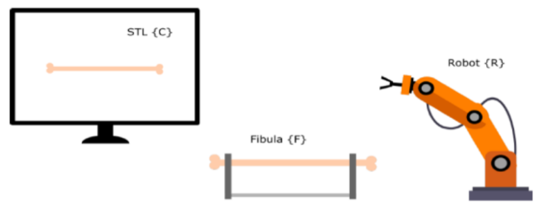

Fig. 5. Coordinate systems involved in fibula registration

D. Experimental Protocol

Ten participants were recruited. Every participant gave written consent after being informed about the study in line with the Declaration of Helsinki. The experimental procedure was approved by the University of Alberta Health Research Ethics Board under study ID Pro0008298. The participants were trained in using the oscillating saw and the haptic system was described to them. The participants had varying degrees of experience in surgery; four participants were familiar with mandible reconstruction surgery of whom one was a surgical resident while the other six participants had no surgical experience and were unfamiliar with the procedure. The participants used the haptics-enabled robotic system and a digital surgical cutting plan to complete eight osteotomies on 3D-printed fibula models, creating four fibula segments each. Each participant completed the fibula osteotomies using the same 3D-printed fibula model, surgical plan, and haptic virtual fixtures. When performing the fibula osteotomy with haptic assistance, participants were given a set of instructions for using the haptic assistance system and the surgical saw.

Results and Analysis

E. Fibula Segment Measurements

The fibula segments created by the participants were collected and measured using digital calipers Fig 4 (b). The longest and shortest lengths of each fibula segment were measured and recorded. The recorded lengths were analyzed using mixed effects modelling [23]. Mixed effect models are used to analyze fixed and random effects in the same model; for this study, we analyzed the lengths of the fibula segments as well as the differences between participants. Lengths were the dependent variables, the segments were fixed effects and the participants had random intercepts. The residual error was 3.7 mm, reflecting the accuracy of the haptic system to guide participants to complete fibula osteotomies. The standard deviation between random intercepts was 2.0 mm, indicating the variability between participants.

F. Digital Visual Presentation

The fibula segments that were most extreme in terms of length were scanned using a 3D surface scanner (Shapegrabber Inc., Ottawa, Ontario, Canada) to visualize the variation in fibula segments created by the participants see Fig. 4 (c). The digital STL files generated from the surface scan were superimposed over each other to create a Hausdorff surface map or "heat map" using Geomagic Control (3DSystems Inc., Rock Hill, South Carolina, United States of America) to visually compare the most extreme differences of the fibula segments. The heat map was used as a simple visual illustration rather than a measurement method. Fig. 4 (c) shows how the longest and shortest fibula segments were digitally superimposed over each other. The grey area indicates that there is no correspondence between the superimposed segments because one is shorter than the other, the coloured area indicates where the segments correspond. Green illustrates where the segments are closely matched while blue and red illustrate where the segments deviate from each other.

III. Discussion

Haptic virtual fixtures were created to support fibula osteotomies for mandible reconstruction surgery. The haptic robotic system and virtual fixtures developed for this study were suitable tools to support the surgical saw, access the fibula and register the fibula to the system, and guide the user to the position of the fibula segmenting planes.

The residual error was 3.7 mm, reflecting the accuracy of the haptic system to guide participants to complete fibula osteotomies. The standard deviation between random intercepts was 2.0 mm, indicating the variability between participants. Differences between the fibula segment lengths created by the participants using haptic assistance may be attributed to registration errors. Since this bench-top study did not use any registration posts, any movement of the fibula holder during the bench top study would create errors in the fibula registration which would impact fibula segment length.

The requirements of a clinical workspace prevent the haptic system used in this study from being transferred to the operating room (OR). In the future, our research will address the following limitations. The HD^2 haptic device-based setup and position relative to the surgeon is not the best for use in a sterile field; the limited workspace of the HD^2 poses a barrier to patient access in the OR. Haptic feedback alone is not enough to guide the surgeon; audible guidance, such as a detractor sound when the saw blade is not in the position of the segmenting plane, and a pleasant sound that would indicate when the saw blade is in the segmenting plane is desirable. A robot with better transferability to the OR is needed for future studies.

IV. Conclusion

In this study, 10 participants completed 8 fibula osteotomies on 3D-printed models with haptic assistance. The results show that the haptic virtual fixtures used for this study were suitable to operate a surgical saw, access and register the fibula to the system. The accuracy of the system is not yet sufficient for clinical use; however, this is a first step towards guiding fibula osteotomies using haptic virtual fixtures. This study showed the feasibility of the proposed idea through proof of concept experimentation. Future work will focus on clinical translation.

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