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A Haptic Training Simulator for Maxillofacial Surgery

Un Simulateur Haptique pour l'Entraînement à la Chirurgie Maxillofaciale

A Haptic Surgery Training Simulator

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Traditionally surgeons have trained directly on patients with mentoring. To improve their training, surgery simulators have been developed, from tangible replicas to more complex virtual reality and haptics-based simulators. Yet, these existing solutions either do not provide realistic feedback, are not reusable and do not enable modifiable patient specificity, or they do but tend to be complex and expensive, thus limiting adoption. Thus, to increase adoption, gesture training simulators still need a haptic technology with a trade-off between feedback fidelity and cost, i.e. a technology that can render kinesthetic feedback with sufficient force while being compact, safe and preferably low-cost. Therefore, we propose a hybrid maxillofacial surgery simulator relying on a tangible replica and with embedded novel ultrasonic haptic brakes. This simulator can render customizable feedback, both vibrotactile and force feedbacks, and can reach forces up to 4.5N. This simulator enables the training on the first step of an Epker osteotomy, i.e. a jawbone drilling procedure.

CCS CONCEPTS • **Human-centered computing** → Haptic devices • **Human-centered computing** → User studies • **Hardware** → Sensors and actuators

Additional Keywords and Phrases: Active lubrication, haptic brake, kinesthetic feedback, medical training, vibrotactile feedback

Traditionnellement, les chirurgiens se forment directement sur les patients au cours du mentorat. Pour améliorer leur formation, des simulateurs de chirurgie ont été développés, allant de répliques tangibles à des simulateurs de réalité virtuelle et haptiques plus complexes. Pourtant, ces solutions existantes, soit ne fournissent pas de retour réaliste, ne sont pas réutilisables et ne permettent pas de modifier la spécificité du patient simulé, soit elles le font mais ont tendance à être complexes et coûteuses, limitant ainsi leur adoption. Ainsi, pour accroître l'adoption, les simulateurs de formation gestuelle ont encore besoin d'une technologie haptique avec un compromis entre la fidélité du retour et le coût, c'est-à-dire une technologie capable de restituer un retour kinesthésique avec une force suffisante tout en étant compacte, sécurisée et de préférence peu coûteuse. Par conséquent, nous proposons un simulateur hybride de chirurgie maxillo-faciale s'appuyant sur une réplique tangible et intégrant de nouveaux freins haptiques ultrasoniques. Ce simulateur peut restituer un retour personnalisable, à la fois vibrotactile et de force, et peut atteindre des forces allant jusqu'à 4,5N. Ce simulateur permet de s'entraîner à la première étape d'une ostéotomie d'Epker, c'est-à-dire une procédure de forage de la mâchoire.

Mots-clés additionnels : Lubrification active, frein haptique, retour kinesthésique, entraînement médical, retour vibrotactile

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1 INTRODUCTION

Learning motor skills is a slow process that needs many training sessions [15], yet crucial for surgeons as mistakes can have dire consequences on the patient. Traditionally, surgeons have practiced on cadavers and animals or directly on the patient. However, it can be complicated or inappropriate due to issues of availability, cost, ethics, limited resemblance between animals or cadavers and live surgery, and most of all, non-reusability in the long term [4,5,17,19]. In fact, in the domain of maxillofacial surgery, undergraduate surgeons often feel insufficiently trained [16]. To overcome this general issue, technological solutions have been developed relying on the use of physical models (i.e. tangible replicas) or simulators in virtual reality (VR) [4], as they aim to ensure countless training sessions, repeatability, flexibility and a certain level of realism [5].

Many simulators and tangible replicas have been created for surgery training [1–4,6–10,12,13,17–22]. Their use has been reported to help students be more confident, reduce their cognitive load and perform more quickly and accurately than those without any simulation training [4–6,17,19]. Haptic feedback, especially kinesthetic, not only provides more realism, but is also crucial in surgeries often relying solely on touch and with limited visibility inside the patient's body. Moreover, it has proven to enhance motor skills learning [5,14]. Maxillofacial jawbone drilling is a complex kinesthetic procedure as it requires high motor precision to avoid irreversible damages, such as the section of nerves [8], rather high forces to drill through bone and relies on the perception of different haptic feedback from both the different tissues and the interaction with the surgical drilling tool. However, simulators with haptic feedback for maxillofacial training tend to often lack reusability and patient specificity (i.e. simulation of different characteristics for a same pathology), realistic force feedback [17,19], or on the contrary are extremely realistic and reusable but use very expensive and complex parts [8]. To our knowledge, there are no existing low-cost tangible replicas or simulators offering reusability as well as patient specificity for this operation. Therefore, we propose a novel hybrid drilling simulator, based on two low-cost and compact ultrasonic haptic brakes, embedded inside a tangible 3D printed replica. Not only can it render different programmable haptic textures with both vibrotactile and force feedbacks, but it also offers the advantage of being inherently stable as it can only render resistive forces.

2 JAWBONE DRILLING

During operations like the Epker osteotomy, which is used to correct the jawbone alignment of a patient, surgeons need to drill precisely in the jawbone. It consists in drilling repeatedly along the Epker line (see left of Figure 1) to allow a clean fracture of the bone so that the surgeons can then move it in the desired position to correct the misalignment. To obtain a clean fracture, the surgeons need to drill completely in the cortical layer to avoid leaving remaining bone residue. Yet, they must minimize the penetration in the spongy bone to avoid damaging the alveolar nerve [8]. Therefore, the most critical task is related to controlling precisely the depth of the drill and thus, feeling the change of layers between cortical and spongy. Our prototype simulator thus focuses on this step.

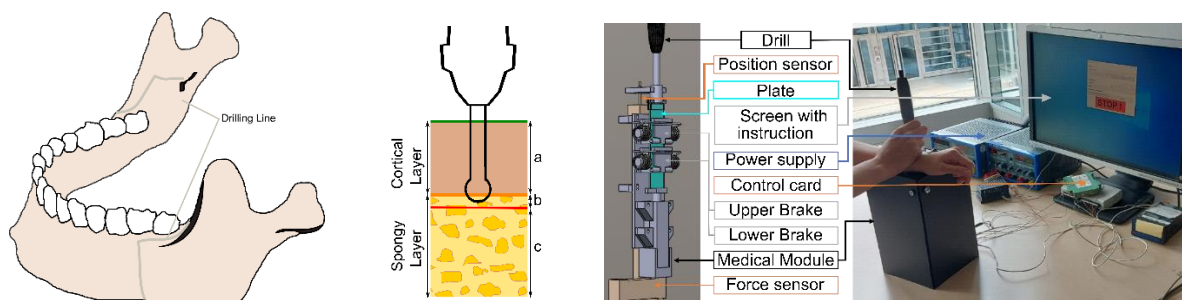


Figure 1: Left: jawbone drilling along the Epker line. Middle: schematic representation of the drilling task with the different layers: a) cortical sensation, b) transitory sensation, c) spongy sensation. Right: drilling haptic simulator and components.

3 DRILLING TRAINING SIMULATOR

The training module is a 3D printed replica of a drill handle glued to a glass plate. The force needed to move the drill is controlled by two ultrasonic brakes exerting a modulated friction force on the glass plate. In addition, the device uses two sensors to create a control loop for the brakes depending on the position and the force of the simulated drill and two power supplies. Indeed, the position in a layer needs to be monitored in order to convey the corresponding haptic rendering (typically cortical or spongy), as well as the force applied to match the corresponding drilling vibration [8]. For example, in the cortical layer, the force resistance applied on the drill by the brake and the frequency of vibration linked to the cutting head speed are higher than in spongy one. The simulator provides forces between 0 N and 4.5 N after subtracting the weight of 1.3 N of the drill, which is in the range of the average maximal forces applied by surgeons and measured in simulators during drilling (i.e. 4 N and 6 N) [8].

The simulated drilling task has two layers: cortical and spongy (see Figure 1). However, we decided to implement three distinct haptic sensations to better simulate the sensations involved in the drilling, with an additional sensation representing the state where the drilling head is in between the two layers. The first haptic layer (zone a in Figure 1) simulates the sensation of cutting in the cortical layer. The second sensation (zone b) simulates the transitory phase between the cortical and spongy layers. Thus, the depth of the transition layer is about half the diameter of the drill's cutting head. Indeed, after this depth the drill head would be exclusively in the spongy layer. The third sensation (zone c) simulates the sensation of cutting in the spongy bone. Due to the system latency of 0.1s, the depth of each layer is variable, this variation is about 0.1 s * User Speed. However, in reality this is not an issue as the depth of these layers vary from one person to another and with the localization in the jaw [11] at a scale of about 1.1 mm. Thus, the transition layer depth stays realistic for a speed under 11 mm/s; as the task is about precision, we assume such high speed will not occur as surgeons speed seems to stay under 5mm/s in other simulators [8].

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