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Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill

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A B S T R A C T

Objective: Bone sawing or cutting is widely used for bone removal processes in bone surgery. It is an essential skill that surgeons should execute with a high level of experience and sensitive force perception. Surgical training simulators, with virtual and haptic feedback functions, can offer a safe, repeatable and cost-effective alternative to traditional surgeries. In this research, we developed a surgical training simulator with virtual and haptic force feedback for maxillofacial surgery, and we validated the effects on the learning of bone-sawing skills through empirical evaluation.
Methods: Omega.6 from Force Dimension was employed as the haptic device, and Display300 from SenseGraphices was used as the 3D stereo display. The voxel-based model was constructed using computed tomography (CT) images, and the virtual tools were built through reverse engineering. The multi-point collision detection method was applied for haptic rendering to test the 3D relationship between the virtual tool and the bone voxels. Bone-sawing procedures in maxillofacial surgery were simulated with a virtual environment and real-time haptic feedback. A total of 25 participants (16 novices and 9 experienced surgeons) were included in 2 groups to perform the bone-sawing simulation for assessing the construct validity. Each of the participants completed the same bone-sawing procedure at the predefined maxillary region six times. For each trial, the sawing operative time, the maximal acceleration, and the percentage of the haptic force exceeding the threshold were recorded and analysed to evaluate the validity. After six trials, all of the participants scored the simulator in terms of safe force learning, stable hand control and overall performance to confirm the face validity. Moreover, 10 novices in 2 groups indentified the transfer validity on rapid prototype skull models by comparing the operative time and the maximal acceleration.
Results: The analysed results of construct validity showed that the two groups significantly reduced their sawing operative times after six trials. Regarding maximal acceleration, the curve significantly descended and reached a plateau after the fifth repetition (novices) or third repetition (surgeons). Regarding safe haptic force, the novices obviously reduced the percentage of the haptic force exceeding the threshold, with statistical significance after four trials, but the surgeons did not show a significant difference. Moreover, the subjectively scored results demonstrated that the proposed simulator was more helpful for the novices than for the experienced surgeons, with scores of 8.31 and 7.22, respectively, for their overall performance. The experimental results on skill transference showed that the experimental group performed bone-sawing operation in lower maximal acceleration than control group with a significant difference ($p < 0.05$). These findings suggested that the simulator training had positive effects on real sawing.
Conclusions: The evaluation results proved the construct validity, face validity and the transfer validity of the simulator. These results indicated that this simulator was able to produce the effect of learning bone-sawing skill, and it could provide a training alternative for novices.

1. Introduction

Bone sawing or cutting is a complex hard tissue removal process applied in bone surgery (orthopaedic surgery or cranio-maxillofacial surgery) that involves many steps in which different essential skills are required. The surgeon must be very careful to apply appropriate forces and to operate the tools at appropriate speeds to avoid over-operation. Becoming a skilful surgeon with sensitive force perception requires rigorous training and iterative practice. Traditionally, surgical trainees have often watched and performed operations on models, animals or cadavers under the

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supervision of experienced surgeons, before performing the procedures themselves. This surgical education system has many drawbacks in terms of efficiency, cost, flexibility, and safety [1,2].

Visuo-haptic interactive simulators, with both visual and haptic (tactile) feedback, have been rapidly developed in recent years to provide a realistic, cost-effective, safe and repeatable alternative to traditional surgical training methods, and these simulators have played an increasing role in surgical education and training [1,3]. Virtual reality systems have used computers to create virtual environments for simulating real-world scenarios, and haptic devices have been employed to assist in surgical training through virtual simulations of surgical procedures with haptic feedback. These visuo-haptic simulators can provide tactile, visual and audio sensations or information to create a realistic training scenario, in which novice surgeons can practice surgical operations, thus allowing them to make mistakes without serious consequences. As a result, the pre-trained novice can practice to master the basic skills and can undertake cognitive planning of surgical tasks [4].

The aim of this research was to simulate bone-sawing operations and evaluate the validity of the learning of bone-sawing skill among trainees. For bone surgeries, bone-machining tasks are force skills, which require the trainee to operate the tools at an appropriate feed velocity with a stable hand and to remember the quantity of force applied to the tool. It is a challenging task to create realistic haptic interactions between a high spindle-speed saw, operating at more than 10,000 rpm (revolutions per minute), and stiff bone. In this study, we constructed a virtual bone model for haptic rendering, based on the voxel model [5], and it had the advantage of taking into consideration the heterogeneous properties of materials. Further, the major variables (bone density, feed velocity and spindle speed) were considered in calculating the haptic forces of the bone-sawing operation. Moreover, we employed the multi-point collision detection method [6] to test the interaction between the tool and the virtual bone model, with the hope of achieving more real haptic forces. To evaluate the construct validity, face validity and transfer validity of the proposed simulator, three experiments were included in this study to analyse the effects of the learning bone-sawing skill.

The rest of the paper is organized as follows: Section 2 introduces the related previous work. Section 3 presents the development of the simulator with graphic rendering and haptic rendering. The simulator validity is tested in Section 4 with a multi-tiered testing strategy. Section 5 is the discussion and conclusion.

2. Related work

Recently, many researchers have undertaken studies to improve the bone-machining interactions in arthroscopy [7], dental surgery [8,9], orthopaedic surgery [10,11] and cranio-maxillofacial surgery [12,13]. Most of the research into bone-machining simulations has focused on bone-drilling [10,14], burring [12,15,16] or milling [17] processes because the drill head can be easily approximated with a simple shape (sphere or cylinder), and the collision detection is less time-consuming [13]. As bone sawing or cutting is the one of the most important basic skills that is applied in bone surgeries, it was necessary to develop a visuo-haptic training simulator for bone-sawing procedures. Hsieh et al. [18] developed an amputation simulator with bone-sawing haptic interaction to simulate the distal femur being separated with an oscillating saw, but many major coefficients (cutting velocity and feed rate) were neglected in the haptic force computation. Wang et al. [19] developed a surgical simulator for mandibular angle reduction with a reciprocating saw and a round burr, based on an impulse-based rendering method with a surface mesh model. Chen et al. [20] presented a haptic and visual surgery training platform prototype to perform cutting of the cranium using a force feedback function, in which the cutting function module with only a single-point sensor.

In our paper, a visuo-haptic training simulator is proposed for bone-sawing based on voxel model and multi-point collision detection method. Bone density, feed velocity and spindle speed of the saw were considered to compute the haptic forces. Multi-threading computation environment was implemented to asynchronously rendering the graphic and haptic simulation.

For effective learning of surgical skills using surgical training simulators, many researchers have reported several methods to evaluate different types of validities [21]. There have been a number of studies of skill assessments for simulators of laparoscopy [22] and endoscopy [23], and many researchers have contributed efforts in bone-drilling or burring skill evaluations [11,24,25]. Morris et al. [24] showed that, for bone-machining simulations, learning with visuo-haptic feedback was significantly better than learning the same tasks with visual feedback alone [26]. However, to the best of our knowledge, the research into the training effects of the learning of bone-sawing skill has been very scarce [19]. Wang et al. [19] evaluated an impulse-based simulator regarding its ability to train. Fourteen volunteers, in two groups, were included in their study to confirm the face validity and construct validity of the simulator. However, the skill transference and skill retention were not discussed in their study.

In our paper, three experiments are conducted to evaluate the construct validity, face validity and transfer validity of the proposed simulator in learning bone-sawing skill.

3. Simulator development

In this study, Omega.6 from Force Dimension was employed as the haptic device. The Omega.6 is a pen-like haptic device, and it has 6 degrees of freedom (6DoF) and 3 degrees of force feedback (3DoFF). True 3D stereo performance in high resolution was shown on the Display 300 from SenseGraphices, which employs shutter glasses technology together with a high-performance 120 Hz LCD monitor. The following sections detail the design and development of the bone-sawing simulator.

3.1. Graphic rendering

For virtual surgery, high visualisation quality and real-time display are essential for a realistic simulation. This simulator utilised the well-known marching cube algorithm [27] to obtain polygon mesh from CT scans of 0.625 mm in slice thickness. The cranio-maxillofacial model, with important anatomical objects, including skin, teeth, gingiva, tongue and the inner oral wall, was refined, and the photo textures were added for visual interaction (Fig. 1). The bone removal process was represented by the voxel-based model [5], which enabled the implementation of volume structural changes and which considered the heterogeneous properties of the bone. During the bone-sawing simulation, once the virtual tool collided with the voxel-based model, the virtual model continuously changed and updated to simulate bone deformation. With the voxel-based haptic simulator, the interactive manipulation of huge datasets in real time was a challenging issue. The more complex the model, with voxels of small size, was constructed, the more computational time was needed for the simulation. To achieve a balance between computing complexity and realism in real time, we constructed the voxel-based model at a size of $0.3 \times 0.3 \times 0.3$ mm [28] in the vicinity of the operative region to simulate bone-sawing processes.

Virtual tool modelling was the other important part of the virtual environment because the geometry or representation of the tool was essential to collision detection, force computation, haptic

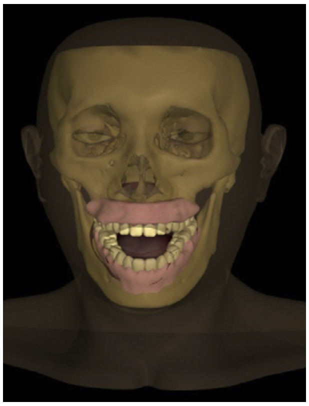

Fig. 1. Virtual environment with important anatomical objects for cranio-maxillofacial surgery.

rendering, and data updating. In this study, the reciprocating saw and other basic tools for cranio-maxillofacial surgery were constructed using laser-scan data and reverse engineering technology due to their complex shapes. By adding steel-like materials and texture, the realistic virtual saw was rendered in the visuo-haptic simulator (Fig. 2). The trainees were supposed to hold the pen-like end effector of the haptic device to operate the virtual tool. The tip position of the virtual tool was in the top point position of the end effector, and the tool attitude was set to coincide with the haptic device's attitude via the Omega.6 device, which was capable of providing the 6D position and orientation data of the virtual tool and of generating 3D force feedback for the user. During the simulation, the position and orientation of the virtual tool were continuously updated, according to the position of the end effector of the haptic device.

3.2. Haptic rendering

During bone-machining simulations, the surgeon must be careful not to apply excessive force to avoid over-operation, especially when the cortical bone is about to be pierced. Therefore, feedback force with high fidelity was required in the surgical training simulator. There were two key components for the interaction of bone machining: collision detection and haptic feedback.

Fast and accurate collision detection between the virtual tool and virtual bone model is a fundamental problem in simulating hard tissue removal and force feedback in bone-machining simulations. Multi-point collision detection methods [6] have been developed recently, which use multiple points on the surface of the tool to achieve more realistic simulations and tool–bone interaction. In this research, we set a group of sample points on the saw-tooth peaks, and each sample point was tested for contact with the bone voxels. In this manner, each sample point contributed a vector to the overall force, which was oriented along a vector of the saw's movement. Collision detection of each sample point in this research was achieved by employing the hierarchical volume-bounding method, in which the volume is described by a hierarchy of bounding volumes. In the bone-sawing simulation, once the simulator detected that the voxels collided with the sample point of the virtual saw, the simulator would feed back the haptic force to the operator by computing the direction and magnitude of the force in each active collision point force (Fig. 3). The voxels that came in contact with the tool were deleted if the force that was applied exceeded a certain threshold.

For the haptic force simulation, three major variables (bone density, feed velocity and spindle speed) were considered in this simulator to compute the haptic forces. For bone sawing, feed velocity was the moving speed of the saw in the direction of cutting line creation. In this study, feed velocity was calculated by recording the saw's previous and current position and orientation in haptic device. Spindle speed was the reciprocating speed of the saw blade along its own long axis. In this simulator the user can set the value of spindle speed. As the bone was non-homogeneous and non-isotropic material, its stiffness varied in different regions. It was necessary to build the bone model with cortical and trabecular bone structure, which have different bone density values. In this study we registered the density value of each voxel according to the Hounsfield values on CT images, which have strong correlations with bone density.

3.3. Software architecture

To run the components of the visual and haptic training simulator asynchronously, a multi-threading computation environment was implemented, which allowed us to maintain update rates of 1000 Hz for haptic rendering and 30 Hz for graphic rendering (Fig. 4). The continuous feedback force was computed according to the collision detection between the voxel-based bone model and the high spindle-speed tool, based on the inputted variables. Once the system detected that the virtual bone model collided with the virtual saw blade, the voxels that came into contact with the tool were deleted to simulate bone deformation, the continuous overall force was simultaneously fed back to the operator to simulate the tactile sensation of the bone-sawing procedure, and a sound signal was used for auditory rendering of tool–bone interaction. A graphical user interface (GUI) was designed and developed with the support of the OpenGL (http://www.opengl.org/) graphics library, and the haptic component of the simulation was developed using the Computer Haptics & Active Interfaces (CHAI3D, http://www.chai3d.org/).

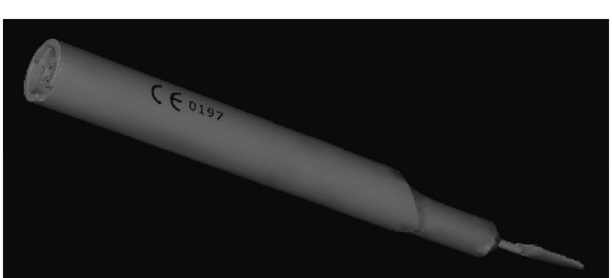

Fig. 2. Virtual saw with steel-like material and texture.

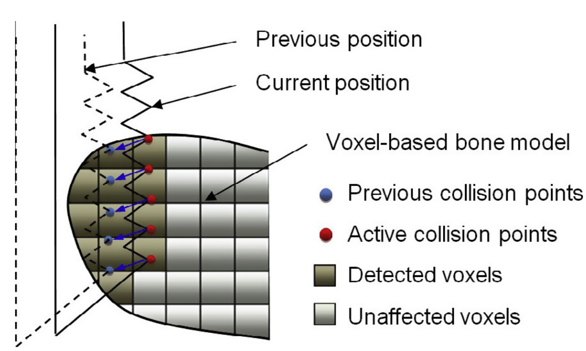

Fig. 3. Force calculation of bone-sawing procedures for two consecutive steps.

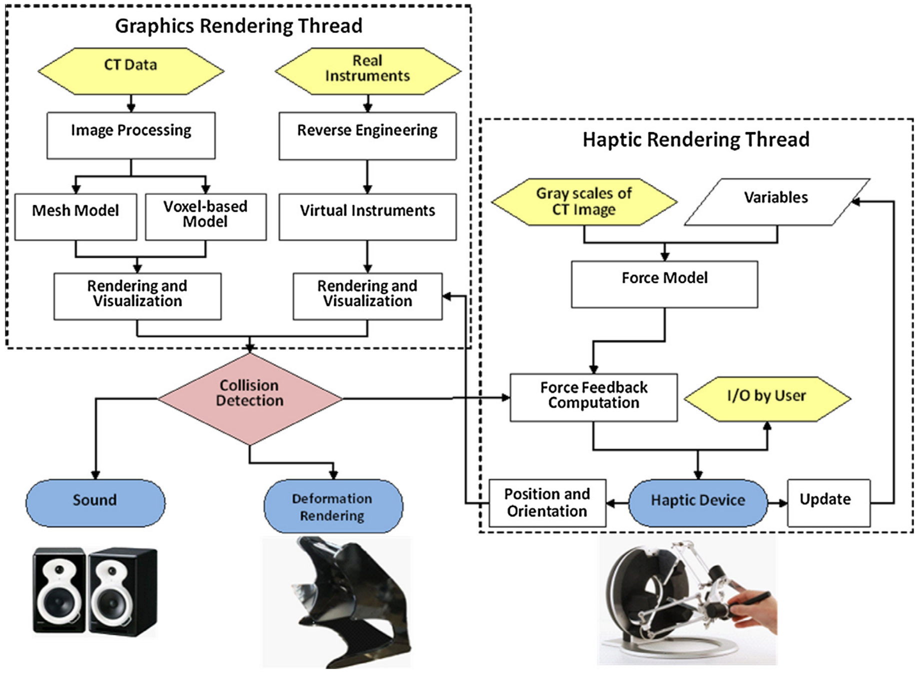

Fig. 4. System architecture of the proposed simulator with the multi-threading computation environment.

4. Experiments of simulator validation

A multi-tiered testing strategy was conducted to evaluate the simulator validation. Three experiments were described in this study to evaluate the construct validity, face validity, and transfer validity in learning bone-sawing skill. All experiments were conducted with approval from Internal Review Boards (IRB) of the involved institutions, and all experiments were single-blinded trials.

The first experiment was aimed at evaluating the construct validity of the simulator. The hypothesis for this experiment was that the simulator can improve the performance on virtual bone-sawing with repeated practice and the simulator can differentiate between surgeons and novices. Section 4.1 described this experiment.

The second experiment was designed to prove the face validity of the simulator, i.e., to determine the realism of the proposed simulator. The hypothesis for this study was that the simulator can represent what it was supposed to represent. This experiment was described in Section 4.2.

The third experiment was aimed at identifying the transfer validity of bone-sawing skill learning. The hypothesis for this study was that sawing skill learning on the virtual simulator can be transferred to real-world bone-sawing. A control group study was conducted to test this hypothesis. This experiment was described in Section 4.3.

4.1. Construct validity

4.1.1. Participants

For this experiment, a total of 25 right-handed participants, 19 male and 6 female, aged 21–45 years old, were included in 2 groups to execute the bone-sawing simulation. All of the participants were from the Shanghai Ninth People's Hospital. The participants included 9 experienced surgeons with 2–5 years of surgical experience in oral and maxillofacial surgery and 16 novices with no surgical experience (first year graduate students in medical school). None of the participants had previous experience with interactive simulators incorporating haptic devices.

4.1.2. Experimental procedure

Before performing the virtual bone sawing procedure, the novices were asked to become familiar with the surgical procedures through operative videos, pictures and texts. All of the participants were provided a tutorial of the bone-sawing simulation with guidance from the researchers. Each participant had 10–15 min to practice with the haptic device, using the interface indication of the haptic force and feed velocity.

The task for the participant was to perform the bone-sawing procedure along a predefined region of the maxilla at a constant spindle speed. Each of the participants was invited to perform the same bone-sawing procedure 6 times (Fig. 5). For each trial, the operative time and the haptic forces of the whole bone-sawing process were recorded for evaluation and study. Moreover, the feed velocity and acceleration of the tool were derived from the tool tip position, with a cut-off of 10 Hz (repeated every 100 ms).

4.1.3. Results

For each trial, we analysed the sawing operative time, the maximal acceleration, and the percentage of the haptic force exceeding the predefined threshold (10 N) for the 2 groups [19,29,30] to assess the surgical skills. The sawing operative time was the entire time from the haptic force's beginning to its end. The maximal acceleration was computed based on the feed velocity difference every 100 ms. The skilled surgeons were supposed to operate the tool with low acceleration, indicating control of the tool with a stable hand. The percentage of the haptic force exceeding the threshold was computed as the proportion of the haptic force exceeding the threshold divided by the total haptic force during each bone-sawing trial. This percentage was considered the criterion for bone-sawing skill with safe force control.

The tested results are shown in Fig. 6. As seen in Fig. 6(a), the bone-sawing operative time for both of the groups decreased significantly between the first and last trials using Friedman's test ($p < 0.001$), in which the novice group reduced the operative time from 29.08 to 23.42 s, and the experienced surgeon group reduced the time from 24.30 to 21.06 s. As seen in Fig. 6(b), the novice group significantly ($p < 0.001$) reduced the maximal acceleration from 12.78 to 8.51 mm/s^2, and the curve reached a plateau after

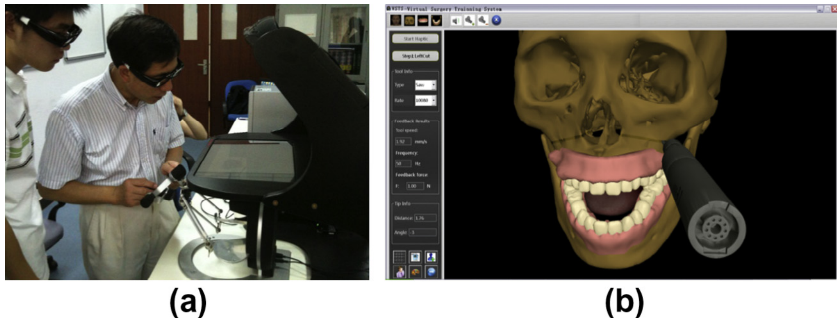

Fig. 5. Empirical study: (a) a surgeon evaluating use of the simulator and (b) the bone sawing procedure for six trials.

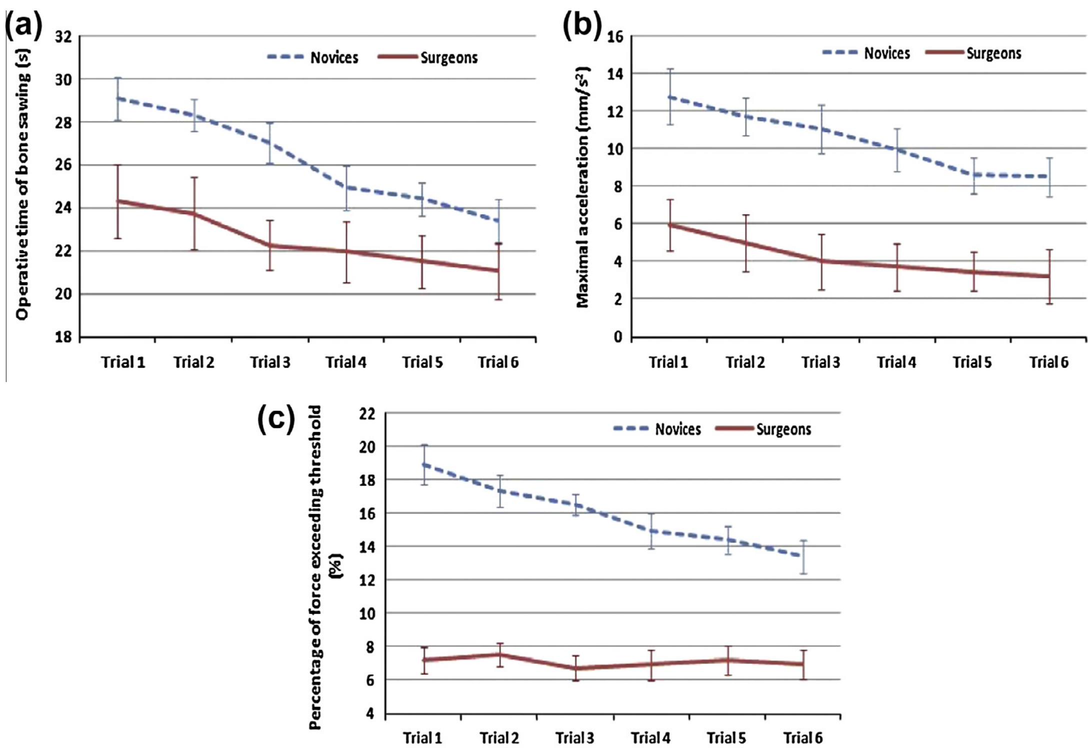

Fig. 6. Learning curves of the novices and surgeons for: (a) difference in operative time; (b) difference in maximal acceleration; and (c) difference in the percentage of the haptic force exceeding the threshold. Error bars indicate 95% confidence intervals.

the fifth repetition ($p > 0.617$). The experienced surgeons significantly ($p < 0.001$) decreased the maximal acceleration from 5.96 to 3.22 mm/s^2, and the curve reached a plateau after the third repetition ($p > 0.236$). As seen in Fig. 6(c), the novices obviously reduced the percentage of haptic force exceeding the predefined threshold from 18.91% to 13.42%, with statistical significance ($p < 0.001$), and after 4 trials, the percentage was not significantly different ($p > 0.144$). However, the experienced group did not show a significant difference ($p > 0.216$) in percentage, of approximately 7%. These clear differences between the novices and the experienced surgeons demonstrated the simulator's construct validity.

4.2. Face validity

4.2.1. Participants

For this experiment, all 25 participants were invited to answer a questionnaire for the utility of the simulator as a tool for learning force skills after performing 6 trials in the first experiment.

4.2.2. Experimental procedure

A 0–10 Likert scale was employed in this experiment for the participants to score the simulator, with 10 being excellent and 0 being poor. The participants were asked to subjectively evaluate the simulator in 3 parts: safe force learning; stable hand control; and the overall performance of bone-sawing simulation.

4.2.3. Results

Table 1 summarises the scored results of the participants. For safe force learning, a global score of 8.04 out of 10, with a standard deviation of 1.02 and a closed 95% confidence interval of (7.62, 8.46), was obtained. For stable hand control, a global score of 7.96 out of 10, with a standard deviation of 0.68 and a closed 95% confidence interval of (7.68, 8.24), was acquired. For the overall performance of the bone-sawing simulation, the simulator obtained a good global score of 7.84 out of 10, with a standard deviation of 0.85 and a closed 95% confidence interval of (7.49, 8.19). In fact, 64% of participants score the simulator at 8 or greater, and 94% of participants scored the simulator at 7 or greater,

Table 1
Scoring results of the two groups for the utility of the simulator.

Variable		For novices	For surgeons	Mean difference	Global score
Safe force learning	Mean (Std.)	8.56 (0.81)	7.22 (0.67)	1.34 (0.32)	8.04 (1.02)
	95% C.I.	(813,9.00)	(6.71,7.73)	(0.68,2.00)	(7.62,8.46)
Stable hand controlling	Mean (Std.)	8.25 (0.68)	7.56 (0.53)	0.69 (0.26)	7.96 (0.68)
	95% C.I.	(7.89,8.61)	(7.15,7.96)	(0.15,1.24)	(7.68,8.24)
Overall performance	Mean (Std.)	8.31 (0.79)	7.22 (0.44)	1.09 (0.25)	7.84 (0.85)
	95% C.I.	(7.89,8.74)	(6.88,7.56)	(0.58,1.60)	(7.49,8.19)

indicating that participants considered the proposed simulator useful for the learning of bone-sawing skills.

We compared the scores between the novices and the surgeons. For safe force learning, the mean difference of 1.34, with a 95% confidence interval of (0.68, 2.00), was statistically significant ($p < 0.001$). For stable hand control, the mean difference of 0.69, with a 95% confidence interval of (0.15, 0.24), was also statistically significant ($p = 0.015$), and for the overall performance of the bone-sawing simulation, there was a significant difference ($p < 0.001$) between the novices and the experienced surgeons, with a mean difference of 1.09, with a 95% confidence interval of (0.58, 1.60). These findings demonstrated that the novice group regarded the proposed simulator as more helpful than the experienced group did.

From the scored results regarding the effects of bone-sawing skill learning, we can affirm that the proposed simulator showed face validity.

4.3. Transfer validity

4.3.1. Participants

For this experiment, 10 novice participants (first year graduate students from the Shanghai Ninth People's Hospital) were chosen to indentify the transfer validity, and none of the participants had any experience in orthopedic surgical bone sawing. The participants were divided into two groups of 5 each.

4.3.2. Experimental Procedure

Ten identical rapid prototype (RP) skull models were prepared for this experiment. Their task was to perform the Lefort I osteotomy along the predefined location on the skull models. Participants were provided a power micro-reciprocating saw with a tracker for tracking purposes (Fig. 7). The feed velocity and acceleration of the saw can be calculated by tracking the saw's position and orientation with the optical tracking system (Polaris, NDI Canada). While the control Group A was directly put to the test of bone-sawing operation, intervention Group B was trained on the simulator prior to the test. The task presented to the participants in Group B for practice was similar to the tasks described in experiment 1. All participants in Group B were required that the maximal acceleration was under 8 mm/s^2 in at least three consecutive simulation trials before they were allowed to progress to the testing stage. This took between 7 and 12 trials for bone-sawing simulation.

4.3.3. Results

Fig. 8(a) compares the sawing operative time, indicating that there were no significant differences ($p > 0.05$) between the control Group A and the experimental Group B for two trials. Fig. 8(b) compares the maximal acceleration of Group A to Group B in Lefort I osteotomy. Group B performed Lefort I osteotomy with lower maximal acceleration than control Group A, and there was a significant difference ($p < 0.05$) in average maximal acceleration between Group A (15.14 ± 2.14 mm/s^2 in trial 1 and 14.6 ± 2.11 mm/s^2 in trial 2) and Group B (11 ± 1.42 mm/s^2 in trial 1 and 9.48 ± 1.55 mm/s^2 in trial 2). These findings suggested that the simulator training had positive effects on real sawing.

5. Discussion and conclusion

Bone sawing is a basic, typical skill in bone surgeries. The surgical training simulator with both visual and haptic feedback provides a training method for the users to perform bone-sawing operation with stable hand and sensitive force perception.

In this study, training in bone-sawing skill was the major aim of the development of the surgical training simulator for bone surgeries. A visuo-haptic training simulator was developed for bone-sawing interaction, to train surgeons operating at an appropriate feed velocity with a suitable force. The voxel-based model and multi-point collision detection method were applied for bone-sawing interaction, and three major variables were included in calculating the bone-sawing forces.

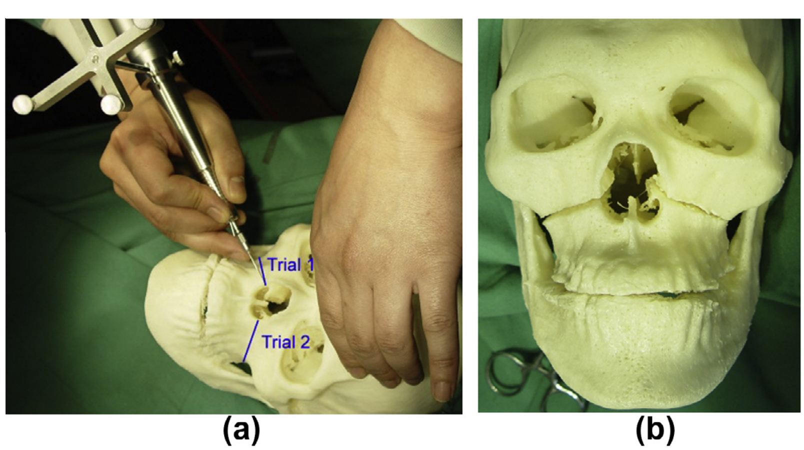

Fig. 7. Skill transference experiment setup: (a) performing the Lefort I osteotomy using the saw with a tracker and (b) sawing results on RP skull model.

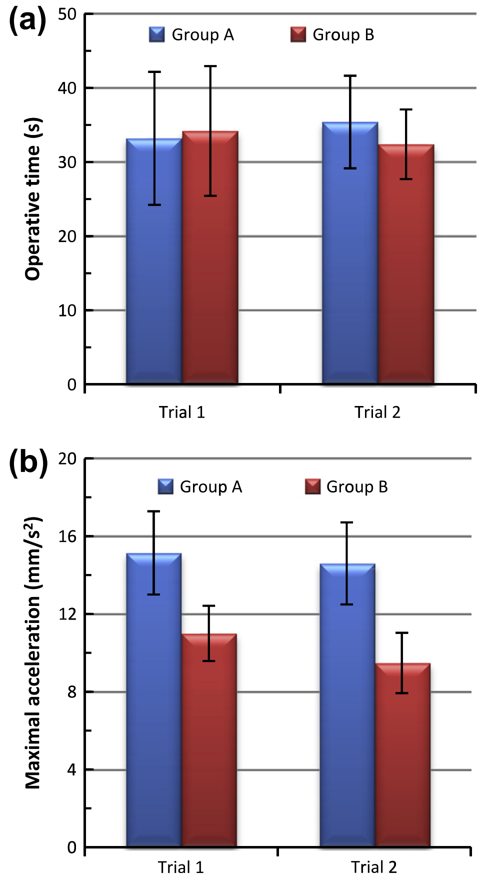

Fig. 8. Experiment results of the Group A and Group B for: (a) operative time and (b) maximal acceleration. Error bars indicate 95% confidence intervals.

Three experiments provided initial evidence on the validity of the simulator. The results of experiment 1 demonstrated that the bone-sawing tasks on the proposed simulator can be suitably learnt by repetitive practice and the simulator can differentiate between surgeons and novices, which confirmed the construct validity of the simulator. The subjective evaluation of experiment 2 showed that the proposed simulator was helpful for learning bone-sawing skill, which verified the face validity. The findings of experiment 3 suggested that bone-sawing training on the simulator was transferrable to real sawing operation, which proved the transfer validity. Based on observation and feedback of participants it was found that the proposed training simulator was well received from a usability perspective and was helpful to trainees for practicing and perfecting their bone-sawing skills, with safe force learning and stable hand control.

There were some limits for this study. One limitation was that only three major variables, namely, spindle speed, feed velocity and bone density, were considered for haptic force calculating. For refined bone-sawing haptic force, the difference of the cutting angle, tool's type and size should be considered in the future work. Another limitation was that the test model used in experiment 3 was synthetic model, which material was different with the real bone. Moreover, more experiments were needed to study the skill retention, i.e., to verify whether the bone-sawing skills retained over a period of time. The future work includes the development of more experiments to verify the validation of skill retention, and the extending study of skills transfer to real surgery.

In conclusion, the visuo-haptic simulation of Lefort I level osteotomy in the maxillofacial surgery was realized in this study. The experimental results demonstrated that the proposed simulator was validated to produce the positive effect of learning bone-sawing skill. This simulator can be used as a training alternative for trainees in bone-sawing operation. In the future, we will extend our research to more bone surgeries with typical bone-machining operations, and we will evaluate the validity with larger sample sizes.

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