MAXILLOFACIAL SURGICAL SIMULATION SYSTEM WITH HAPTIC FEEDBACK

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ABSTRACT. Due to the complexity of the maxillofacial surgery, the novice should be sufficiently trained before one is qualified to carry on the surgery. To reduce the training costs and improve the training efficiency, a virtual mandible surgical system with haptic feedback is proposed. This surgical simulation system offers users the haptic feedback while simulating maxillofacial surgery. An integrated model is introduced to optimize the system simulation process, which includes force output to a six-degree-of-freedom haptic device. Based on the anatomy structure of the bone tissue, a two-layer mechanism model is designed to balance the requirement of real-time response and the force feedback accuracy. Collision detection, force rendering, and grinding function are studied to simulate some essential operations: open reduction, osteotomy, and palate fixation. The proposed simulation platform can assist in the training and planning of these oral and maxillofacial surgeries. The fast response feature enables surgeons to design a patient-specific guide plate in real-time. Ten stomatology surgeons evaluated this surgical simulation system from the following four indexes: the level of immersion, user-friendliness, stability, and the effect of surgical training. The evaluation score is eight out of ten.

1. Introduction. With the external and congenital injuries in the face and jaw, many people are involved in the maxillofacial and oral surgery [35]. These injuries include the malocclusion, craniofacial fracture, asymmetry, and malformation in the maxillofacial region. Due to the anatomic intricacies, surgical operations to treat these diseases are sophisticated [19]. Human error may have a negative impact...
on velopharyngeal status and resonance [3][24]. Before qualified to carry out the surgery, the medical student should participate in insufficient training to avoid human error. The training in the operating theatre is the best approach to obtain these operation skills. However, medical students do not have enough chances to get involved in real operation. The other traditional training methods include the rapid prototyping models and the application of animals and cadavers model. Nevertheless, the anatomy of animals is different from that of humans, and the cadaveric model is expensive and under strict supervision. The application of the computer-aided technique can take over these disadvantages. Compared to the previous method, it has more advantages of better reusability, accuracy, and lower costs. Many hospitals start to use 3D simulation software [1]. Computer-aided surgery overcomes the disadvantages that the treatment of complicated maxillofacial bones almost depended on the experience of the surgeons exclusively [5] [20]. Some researchers transmit the virtual reconstruction planning into the operating room using the CAD-CAM [9] [18][39]. VR(Virtual Reality) technique is applied in the surgical simulation system too [4]. The application of computer technology can help doctors planning and studying. There is no approach to help novice doctors training. Moreover, all theses works lack the force feedback which is important for clinical training in maxillofacial surgery. It was stated that the implementation of force feedback in training could widely reduce task completion time and error rate[29]. The systems that deliver force feedback while focusing on workflow, could break down the barrier in maxillofacial training surgery [27] [38]. Some researchers have applied the haptic technique to surgery training [33] [32], especially dental surgery. Pohlenz et al. designed a Voxel-Msn simulator for dental school. It claimed that the spatial 3D perception, force feedback, and image resolution of the simulator were sufficient for surgical training [26]. Tseen al. designed a virtual dental training system (hapTEL) based on haptic technique [34]. The training system with force feedback is stated to improve surgical skills[12][22]. Researches have applied the haptic technique to maxillofacial surgery. Konukseven et al. (2010) described a training system for simulating basic dental operations such as the diagnosis of caries and drilling named Vision-Haptic Device Integrated Dental Training Simulation System [16]. Sonhmura et al. simulated orthognathic surgery with a haptic device and 3D data of cranial bones. With this system, the basic function such as cutting, dividing, and rearranging bone to restore the normal structure were realized [31]. However, due to the anatomic intricacies in the maxillofacial region, the bones might overlap each other when the surgeon moves the bone. Wu et.al develop a simulated training system with a 3D immersive workbench and a 6-DoF (degree-of-freedom), high-fidelity force-feedback haptic device of Omega6. In this system, the Le-Fort I osteotomy has been simulated [36]. The maxillofacial surgery included: open reduction [14], osteotomy [28], and plate fixation [13]. The existing work could not cover all parts of the maxillofacial surgery. The design of the guide plate is an essential part of the maxillofacial operation [17]. Computer-aided surgery can simulate the design of the plate [40]. However, there is no existed simulation system covering the plate fixation of maxillofacial surgery. In order to overcome this difficulty and improve the effect and efficiency of training and planning, a novel virtual maxillary surgical system with haptic feedback technology is designed for oral and maxillofacial surgical training.
In this study, a training and planning system for maxillofacial surgery is developed. A 6-DoF force feedback device is adopted to manipulate the virtual instrument and output the force feedback. In the system, the 3D models of anatomic structures and surgical instruments are reconstructed respectively from CT and laser scanning data. The AABBs (axis-aligned bounding boxes) are selected to realize the collision detection. The interaction of the software and users is based on integrated-model architecture. The virtual grinding, fixing, and design of the guide plate are developed. This paper proposes a system based haptic feedback device with optimized 3D models for simulating the maxillofacial surgery. The simulation results are judged by the doctors. The haptic feedback device is newly used in the area of the maxillofacial surgery simulation.

The manuscript is organized as followed: section 2 introduces details of the methods; Section 3 presents the processing of the simulated surgery and the experiment results, and Section 4 concludes the paper and gives an outlook on the future work.

2. Method.

2.1. Operation targets. The main clinical manifestations of the maxillofacial include fracture segment displacement, and malocclusion. Moreover, facial deformity and uncoordinated appearance could also result in functional issues. For instance, many patients with maxillofacial deformity have occlusion issues [15]. In this situation, grinding the bones to the desired shape is necessary. Since the mandible may be very fragile and unstable after surgery, a specific plate designed for the patient is needed to fix the bones [25]. In brief, maxillofacial surgery includes three essential operations: open reduction, osteotomy, and plate fixation.

2.2. System structure. In this mandible surgical simulation system, as shown in Figure 1, integrated-model architecture is used to develop the scenario of the rigid tissue and the surgical tools and the interaction between the two parts. The integrated model composed of three models: a visual model, a collision model, and a mechanical model. The visual model is used to store the primary coordinates and rendering information of the models. The distance of the collision models is used to detect collision between the surgical tools and rigid issues and the collision between the different parts of rigid issues. The parameters of the object are stored.

![Figure 1. The architecture of the virtual surgery system](image-url)
in a mechanical model. The mechanical model is used to calculate the position of the object and the value and direction of the output power. The system uses two engines to connect the three models, the scenario and the haptic device: a graphics engine and a physics engine [21] [2]. Figure.1 shows the structure integrated-model diagram of the system.

Moreover, Figure.2 shows more details of the interaction between the two engines. When the haptic device inputs a force, the collision detection detects whether a collision happened. Then the haptic engine calculates the output force based on the mechanical model. At the same time, the position and rotation of the deformation of the visual model are transferred to the graphics engine. It is noted that the two engines operate at a different frequency. In order to provide a consistent and vivid scene, the graphics rendering must be refreshed at more than 30 frames per second. Also, the haptic rendering refresh at 1000Hz to simulate realistic and stable force feedback. The graphics engine is based on OpenGL (Open Graphics Library), which is mainly used for modeling the skull in the scene, rendering the surgical tools, and setting the scene lighting illumination. The physics engine aims at detecting the collisions and calculating the corresponding deformation and haptic force.

The physics engine is implemented by SOFA (Simulation Open Frameworks Architecture) to calculate the feedback force. When the system detects the collision between the surgical tool and the craniofacial model, the collision force with its direction will be calculated. Then, the force would be transmitted to haptic devices in real-time. The scene data structure could be constructed quickly, and a variety of algorithms offered by SOFA could be applied in the system [7]. It is mostly used to develop newer algorithms, but can also be used as an efficient prototyping tool or as a physics engine. Two fundamental algorithms are needed in implementing the simulation platforms: collision detection and force rendering.

![Figure 2. Interaction between the two engines and the system](image)

2.3. Basic function.

2.3.1. Collision detection. The deformation and force feedback are based on collision detection. Accurate and fast collision detection is essential for the surgical simulation system. The bounding-box based algorithm is used in the simulation for
its efficiency. There are several kinds of bounding-box for collision detection—for instance, AABB, oriented box, discrete orientation polyhedral bounding sphere, etc. [23]. AABB is easy to construct with less computation [37]. Thus, AABB is chosen for collision detection in the surgical simulation. AABB sets of cubes containing an object in which its edges are parallel to the coordinate axes. By recursion, AABBs of maxillofacial could be constructed top-down. When users move the phantom, in reality, the tool in screens moves accordingly. And the system updates the DoFs of the mechanical model. At the same time, the visual model updates the screen. To avoid the intersection, the collision system traversing the root nodes of two objects in a broad phase. The coordinate and velocity are updated to the collision model. In order to avoid the intersection, the collision system traversing the root nodes of two objects in a broad phase.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{interaction_graph}
\caption{Interaction between the input force and the system}
\end{figure}

2.3.2. Force rendering. A 6 degree of freedom (6-DoF) mechanical model is used in the simulation to match the position of the device in the real-world and virtual world. When the users move the phantom, the system reads the current position of the phantom and move the tool. Meanwhile, the system detects a collision in 1000Hz to ensure an in-time response and decide if the collision actually happened. The integrated-model would update especially the visual model, if there is no collision detected. If a collision is detected, an output force is calculated. There are more details in Figure.3 to illustrate the relationship between the collision detection, force rendering and grinding. While the collision happened, the mechanical parameter, stored in the mechanical model, is used to calculate the output force. By comparing the value of the input force and the threshold, grinding action should be simulated. In the last, the integrated-model is updated. In the system, the force feedback depends on the mechanical properties of the colliding objects. However, the mechanical properties of the bones are complicated as their thickness and hardness differ in different areas. Considering the complex structure of the bone tissue, there is a contradiction between the in-time response and the accurate haptic feedback. To balance the contradiction, the mechanical model comes from the...
CT-image after image segmentation. The mechanical parameter is decided by the real physical properties which are provided by the West China Dental Hospital of Sichuan University. Since discrete force signals and material removal during the process will cause the vibration of the device. The parameter of the digital filter is used. To solve this problem, we use a quadratic second-order digital filter whose discrete transfer function is [11]:

$$H(z) = g(z) \cdot \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$  \hspace{1cm} (1)

Discrete transfer functions are represented by corresponding difference equations [6]:

$$F_{out}[n] = g[n] \cdot \left[ \sum_{k=0}^{2} b_k F_{in}[n-k] - \sum_{j=1}^{2} a_j F_{out}[n-j] \right]$$  \hspace{1cm} (2)

The filter consists of $n$ cascaded double four segments, $g[n]$ is the total gain of the filter, $b_k$ is the feedforward filter coefficient, $a_j$ is the feedback filter coefficient, $F_{in}[n]$ is the input force signal, $F_{out}[n]$ is the output force signal. The parameters used with the filter equation can be easily adjusted based on the dynamic characteristics of the force feedback device without changing the algorithm. Finally, the filtered force signal is sent to the haptic feedback device and rendered with a 1 kHz tactile sensation.

3. Results. The computing platform used for this simulation platform is Lenovo ThinkStation workstation, using Intel Xeon (R)E5-2630 2.60GHz CPU, 64GB memory, Windows 7. The haptic device is Geomagic Phantom desktop X, whose maximum power is 7.9N. Its working space is 160 mm. The Phantom series provide X (horizontal translation), Y (vertical translation), Z (after translation), R (around each axis) directions of 6-DoF. Also, 3-DoF force feedback output also makes it more realistic in space. Visual Studio 2008, an Integration Development Environment (IDE), and QT is used for developing GUI programs. The integrated-model structure is adopted by SOFA. Thus, the SOFA is used to define and modify the relation between models and create a medical simulation scene. SOFA can efficiently simulate the dynamics of interacting objects using abstract equation solvers. Most parameters of the simulation can be modified by directly editing an XML file for the scene. With the included API, the complex simulation can be realized.

3.1. Performance. The simulation experiment is composed of three parts of maxilla surgery: open reduction, osteotomy, and palate fixation. The performance of the surgical simulation system is evaluated after the experiment.

3.1.1. Open reduction. As shown in Figure.4, the red part, which is marked by an ellipse, is the replaced bone. The blue parts are the pathological skull, the brown parts are the other parts of the skull, which is damaged by the external impact, and the other parts are the undamaged parts. Figure.4 (a) shows an initial organ model. Figure.4 (b) shows a part of the surgery simulation. Figure.4 (c) shows the model after the joint. It can be seen that the collision is detected, and the injured part is moved to the right position. First, the users should make the replaced bone close to the bone parts with the haptic device. Moreover, as shown in Figure.4(b) in the system, a surgical tool represents the haptic device and interacts with the visual model in this scene. Because of the collision detection, once the replaced bone touches the damaged parts of the skull, the collision is detected. The feedback
force will be calculated and transferred to the haptic device to stop moving the bone. At the moment when two objects contact, the operator will feel the opposing repulsion coming from the haptic device because of collision detection and force rendering. This force feedback is the same as the real world. In this way, the operator could put the target object to the expected position precisely compared to other 3D modeling software (such as Mimics), which has no collision detection and force-feedback mechanism.

3.1.2. Osteotomy. In some situation, the maxillofacial need to be re-sharpened by grinding the unnecessary parts. Figure.5 shows the simulation of grinding the mandible for craniofacial plastic surgery. Figure.5 (a) shows the original model, and Figure.5 (b) presents a model after grinding. The essence of grinding the model in the scene is to change the geometry topology of the integrated-model structures. In order to achieve surface cutting, removing the 3D surface mesh of models is used to implement the function. The higher the mesh density of the model is, the more precise the system is. Typically, the mesh density of the model affects the simulation of the rendering. The system uses points, lines, triangles to link topology between points to compose the basic topology shape of the model. The light texture rendering is used on the triangles to get the realistic craniofacial rigid model. An interactive grinding algorithm based on surface rendering is presented, which can be executed as the following steps: processing the model data, calculating the result of
collision detection, reconstructing the mesh, using the method of removing separation, and searching. In the process of constructing the model, the triangular mesh is composed of thousands of small triangular meshes because of the high accuracy of CT scanning \[8][30\]. It will result in a huge load in the drawing, storage, and calculating. The original model is simplified to meet the precision and real-time requirements of the virtual surgical system.

With the function of the grinding, operators could plan the mandible cutting path before the real surgery. Moreover, they could grind the bones to the planned shapes using the virtual tool by removing the contacted tetrahedrons of the model. Compared to traditional teaching or pre-surgery approaches, it is more intuitive and has better effects. Thus, the model used in the experiment is optimized to avoid delay in the simulation process by evaluating different geometry topology. At the same time, there are enough details in the graphical display for the operator to observe during the simulation.

3.1.3. Plate fixation. Figure.5(c) and Figure.5(d) shows the plate fixation. In plate fixation, the surgeon should first confirm the size and number of lesions of the mandible then design the guide plate accordingly. Touching the anatomic structure of the patient using the haptic device could help the surgeon to have a whole picture of the lesions on the mandible \[10\]. Thus, real-time force feedback is necessary for the plate design. As shown in Figure.5(c) and Figure.5(d), users can adjust the guide plate on the surface of the mandible model and magnify the part of the virtual model to make sure the plate matches the patient. This procedure can help the users to design the palate for a different patient.

3.2. Evaluation.

3.2.1. Simulation without the function of grinding. The interaction between the user and the virtual scenario differs the system from the traditional way of training and pre-surgery planning. The force feedback and the screen refresh rate should be high enough, especially for the design of the guide plate and mandible fixing. However, the vast calculation of virtual surgery is conductive to the authenticity of the system. Due to the high real-time requirement of the system, the performance of the system is evaluated. Moreover, the grinding is not a necessary part of some surgical operations. Since it involves a massive amount of new grid files, the simulation performance with/without the function of grinding is discussed, respectively. Table1 and Table 2 show the frames per second (FPS) in the same virtual surgical environment in the above two situations. For the simulation without the function of grinding, from Table 1, it is evident that the FPS maintains at a high value in the simulation of the model with enough details. It could ensure high precision and real-time performance and meet the requirements of virtual surgery.

| Points | Lines of tool | Points of bone | Lines of bone | Triangles of bone | Draw frame (FPS) |
|--------|--------------|---------------|--------------|-----------------|-----------------|
| 35     | 34           | 23175         | 69454        | 46280           | 72.2            |
| 35     | 34           | 17728         | 53190        | 35460           | 145.8           |

When the function of grinding is added, the newly imported grid file has a significant amount of computation of the cutting algorithm. There are some delays in
Table 2. Performance of virtual surgical system with grinding function

| Points | Lines of tool | Points of bone | Lines of bone | Triangles of bone | Draw frame (FPS) |
|--------|---------------|----------------|--------------|-------------------|------------------|
| 35     | 34            | 23175          | 69454        | 46280             | No response      |
| 35     | 34            | 535            | 1526         | 4994              | 16.6             |
| 35     | 34            | 535            | 1526         | 2996              | 30.0             |

the simulation. The solution is to sacrifice parts of the mesh of the model to make a compromise between the details of the model and the FPS. Thus, the model is optimized by removing parts of the geometry topology. Then the simplified corresponding mesh model is generated, and its number of triangles is reduced obviously. Table 2 shows that the performance of the virtual surgical system could meet the requirement. In the simulation system, the calculation power of collision detection is the largest. If the model data is too large, which means too many details in simulation, the performance of the system declines. By simplifying the collision model, the performance of the system is improved. At the same time, it does not change the authenticity of the model rendering with less detail of the model.

3.2.2. System Usability Evaluation. To test the system usability, three experienced surgeons and seven novices are invited as volunteers to carry out the system’s functions. Each experienced surgeon has a number from E1 to E3, and novices have numbers from N1 to N7. Firstly, the sense of visual and haptic feedback are scored and evaluated by volunteers. Each of them should give two scores about visual and haptic feelings. The full score is 10, and 0 is the lowest. The more realistic they feel in the test, the higher score will be given.

![Figure 6. Visual and haptic authenticity](image)

As shown in Figure 6, visual evaluation is all above 6, which means the rendering of the model is relatively real. Different parts of cranial-maxilla could be distinguished easily, which supplies surgeons with more surgical operation space. The evaluation of haptic feedback is better than the other three factors. All the volunteers could feel the feedback force when the collision happens. It could provide better training results for novices. During this process, all of them touch the bones and feel the feedback force. The tool keeps detecting the collision all the time while it touches the bones. Moreover, they conduct the basic surgical operation in the process of system simulation. The most important indexes of evaluation are listed
as follows: 1. The level of immersion in the surgical process. 2. User-friendliness of the system. 3. Stability. 4. Effect of surgical training.

![Figure 7. Evaluation of the system](image)

As shown in Figure 7, the comprehensive score section is from 6 to 9, and the volunteers are full of interests to use such a system as their training approach. Because of the two-layer mechanical model, the system output the different haptic feedback based on the anatomy structure of the bone tissue. The novice and the experienced surgeons think the system could help them improve operation skills.

4. Conclusion. The paper focuses on the availability of the virtual surgical system for the mandible. The whole system has realized the virtual surgical process and the simulation of mandible osteotomy, which provides operators with a realistic simulation environment and preoperative planning conditions. With the system, surgeons can perform more accurate surgical planning in the 3D scene. Moreover, better training effects could be acquired because of the haptic mechanism of the system. At the same time, novices could be trained anywhere without real surgical instruments. Also, the system can be used many times in one day, which could spend several weeks in the real-world for training. Compared to other virtual surgery without grinding function, the virtual system in the paper provide real-time feedback. The high FPS enables the surgeon to have real-time force feedback once touching the skull.

5. Discussion. This system is meant to simulate the whole process of real maxillofacial surgery. And the appearance of the simulated maxillofacial system can optimize the teaching process of surgery for medical students and novice surgeons. Unlike the other simulated training systems, this surgical simulation system could contribute to the design of the guide plate as well. The system achieves the function of grinding in a lower FPS, and the FPS is acceptable to the surgeon while using the system. In general, diverse kinds of cranial-maxillofacial bones with different accuracy are simulated to evaluate the performance of the system. The surgical system achieves expectations and receives favorable reviews from surgeons and novices in experiments. However, there are still a lot of technical challenges in the development of virtual surgery. In the real world, surgery is much more complicated than that in the virtual world. The cranial-maxillofacial surgery actually needs to
consider the factors of skin, muscle, blood, and some other organs. That means the different hierarchy of soft tissue and fluid should be simulated in the surgical system. There are some problems that need to be resolved about the soft tissue. Another problem is the authenticity of the operation. If the model is very precise, the grinding function looks real.

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