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High Fidelity Virtual Reality Orthognathic Surgery Simulator

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Abstract

Surgical simulators are powerful tools that assist in providing advanced training for complex craniofacial surgical procedures and objective skills assessment such as the ones needed to perform Bilateral Sagittal Split Osteotomy (BSSO). One of the crucial steps in simulating BSSO is accurately cutting the mandible in a specific area of the jaw, where surgeons rely on high fidelity visual and haptic cues. In this paper, we present methods to simulate drilling and cutting of the bone using the burr and the motorized oscillating saw respectively. Our method allows low computational cost bone drilling or cutting while providing high fidelity haptic feedback that is suitable for real-time virtual surgery simulation.

1. INTRODUCTION

Virtual simulators are becoming common in surgical training [1], thanks to the evolution of Head Mounted Devices (HMD) and haptic controllers. A large number of these simulators employ multimodal (visual, touch, sound, smell etc.) virtual reality (VR) in order to fulfill various aspects of the training. Of the many advantages, VR simulators are cost effective, easily deployable, can automate scoring and assessment and provide objective feedback measures [2]. More importantly, these tools can be developed as open-source free-software to enable easy access and continuous improvement of the system. VR surgical simulators are becoming a better alternative to surgical video channels and books, since they improve general surgical knowledge as well as providing an immersive surgical experience that enhances the necessary strength, speed and dexterity.

Orthognathic surgery to restore the proper anatomical and functional relationship in patients with dentofacial skeletal abnormalities. The bilateral sagittal split osteotomy (BSSO), is the most commonly performed mandibular surgery, either with or without upper jaw surgery. To our knowledge, very little simulators exist that are specific to Oral and Maxillofacial Surgery (OMFS) [2, 3], and none of them address the simulation of Bilateral Sagittal Split Osteotomy (BSSO). BSSO is a common OMFS procedure for the correction of mandibular deformities. While adverse side-effects from BSSO are not very common, improper surgical cuts can result in paresthesia and profound bleeding [4]. In addition, incorrect bone cuts prolong surgery, require future repair surgery, prolong healing, and can compromise

outcomes. The proposed VR OMFS simulator will contribute to a reduction in the prevalence of adverse surgical outcomes after BSSO surgery. Educators and Program Directors of OMFS training programs can use the proposed system to allow residents to practice complex, technique sensitive surgical procedures and refine their skills before entering the operating room and working on actual patients.

Surgical steps in BSSO involve exposing the bone, cutting it, moving it, positioning surgical cuts to achieve proper occlusion (with a surgical splint) and fixating it. These surgical steps are common to other orthognathic surgery types such Le Fort -type osteotomies, vertical ramal osteotomy, inverted L and C osteotomies, and other types of orthognathic surgeries in the mandible. In this paper we present two novel low computational cost methods to simulate bone cutting and drilling through the use of an oscillating saw and motorized burr, respectively. All of these bone manipulation tasks are common to many surgical procedures, in addition to orthognathic surgery, such as temporal bone surgery or orthopedic surgery. The methods presented in this paper aim to simulate erosion of the bone under the action of a drill rotating or a saw oscillating at high speeds. There has been prior work related to simulation and visualization of the cutting action of the drill. Pflesser et al. [6] developed a visualization of cut surfaces with extended ray casting method. A point sampling approach [7] where each point representing the bone contributes to the forces rendered to the user can be cost effective but fails to factor bone density, drill speed into the simulations. Y. Lin et al. [8] consider these variables (saw speed, feed velocity, bone density) in computing forces with the saw blade but could lead to penetration artifacts especially when large forces are applied. The proposed algorithm accounts for material properties of the bone such as density, hardness, drill angular velocity, normal force exerted by the user while (a) avoiding all the aforementioned limitations of previous methods (b) keeping the runtime costs as low as possible.

The paper is organized as follows: Section 2 describes the patient data and the tools we used to acquire the patient data. Section 3 describes the methods we implemented to simulate bone manipulation using burr and the oscillating saw. Some preliminary results are described in section 4, which is followed by a discussion of the summary in section 5.

2. MATERIALS

A single patient who received BSSO advancement for open bite and skeletal malocclusion correction at the University of North Carolina was selected to generate the surgical scenario for the proposed system. The Institutional Review Board of the University of North Carolina approved the study. A Cone Beam Computed Tomography (CBCT) image was acquired immediately before surgery New Tom 5G CBCT Scanner (AFP Imaging, Elmsford, NY). The imaging protocol involved a 30-second scan time with a 12-inch field of view. All CBCT scans were acquired in centric occlusion in the supine position with a voxel resolution of $0.3 \times 0.3 \times 0.3$ mm. The CBCT file was de-identified before segmentations of the hard tissue structures were generated (see figure 1).

3. METHODS

The bone drilling and sawing algorithm consists in determining the rate of removal of the nodes internal to the bone surface, as well as their density values that is initialized before the simulation starts. The node removal depends on two different geometrical primitives associated to two different surgical tools. A particular node is removed if its density value is equal to or below zero. This approach erodes the density values of nodes in a discrete setting in order to simulate material erosion in near continuum setting of the real world. The rate of removal of the material is proportional to the angular/linear velocity of the burr/saw, torque capability of the drill, normal force exerted by the rotating drill and is inversely proportional to the bone density, hardness. These observations should be well captured by the algorithm that prescribes the rate of removal of the density of the nodes. The proposed algorithm is described below.

Initialization

CT scans are used to determine the anatomical model composed of a set of points that represent the anatomy. Each point in this set has a scalar density attribute value (ρ_i) that are initialized based on the CT image (proportional to the intensity values of the image) which will evolve during the interaction with the drill. During the initialization, the nodal density values are scaled by a normalizing factor in order for the algorithm to stay independent of the density of the nodal points representing the anatomy.

Runtime

During the simulation of the drilling, the nodal density values evolve based on the method described below for each of the tools. The nodal point is removed when this value reaches zero or negative ($\rho_i \leq 0$). The burr and the oscillating saw are modeled as rigid objects that are controlled by the user. A virtual coupling mechanism is employed in order to provide haptic and visual perception of interaction with the material being eroded. A drill axis is also identified and tracked during the simulation for both the tools.

To simulate bone drilling, we treat the burr as a virtual coupling object (see figures 2, 3). The virtual coupling object comprises of a physics geometry, a colliding geometry and a visual geometry which in this case are modeled as a spherical object for the burr and thin finite plane for the blade of the oscillating saw. The position of the physics geometry is controlled by an external device. The visual geometry is actually rendered in the scene during the drilling process, and it is always projected to the surface of the bone. The colliding geometry is the scaled version of the visual geometry about the point p_v . To evaluate the force (that is also rendered to the user via the haptic device), we assume a spring and damper attached between the physics and the visual representations. A separation of $d_{vc} = p_v - p_h$ between the physics and the visual object will result in the following spring and damper force $F_{vc} = k_{vc} d_{vc} + c_{vc} \dot{d}_{vc}$ where k_{vc} and c_{vc} the stiffness and damping coefficients of the virtual coupling respectively. Below we describe the methods used to simulate bone cutting with both the burr and the oscillating saw. Specifically, we provide details of the virtual coupling mechanisms and the node removal process for both the tools.

Burr tool

The rate of material removal at a point on the eroding object in the drilling process can be attributed to various factors such as (a) the force exerted by the drill on the bone: F_{vc} (b) angular speed: ω (c) the radius of the drill: r_{drill} (d) bone density: ρ (e) bone hardness: H .

One can write the expression for the negative rate of change of density as a function $f(k_{vc}, d_{vc}, \omega, H, r_c)$ of these parameters as follows: $\dot{\rho}_i = -c_0 \omega r_{i-axis} H^{-1} a_1 a_2$ where r_{i-axis} is the distance of the nodal point i from the drill axis and $a_1 \in [0,1]$ is exponential attenuation coefficient w.r.t r_i the distance of the node i from the center of the drill and is given as

$$a_1 = \left(1 - e^{\frac{r_c - r_i}{c_1}} - 1 \right) \left(1 - e^{\frac{r_c - r_v}{c_1}} - 1 \right)^{-1} \quad \text{and } a_2 \in [0, H \dot{\rho}_{\max} (c_0 \omega r)^{-1}] \text{ is the inverse}$$

exponential attenuation coefficient w.r.t the normal force exerted by the drill $F_{vc} (k_{vc} \cdot d_{vc})$ and takes the form $a_2 = \min (e^{k_{vc} d_{vc} c_2} - 1, H \dot{\rho}_{\max} (c_0 \omega r)^{-1})$.

The attenuation factor a_2 ensures that the material is removed in a fashion that is highest at the immediate periphery of the visual geometry of the drill and falls off exponentially along the normally outward direction and reaches zero at the periphery of the colliding geometry of the drill. The attenuation factor a_2 ensures that the rate of material removal increases exponentially with the normal force F_{vc} applied by the drill on the eroding material. The value of a_2 is however bounded by the maximum material removal rate up to a constant. a_2 also ensures that a non-zero force is applied to onset the bone erosion process.

Oscillating saw

The oscillating saw consists of a thin blade mounted at the end of the motorized tool that moves the blade in a sawing motion along the axis of the tool. The velocity v_{saw} of the blade at a given instant is proportional on the oscillation speed chosen by the user. In order to implement virtual coupling, we will first detect the collision of the blade geometry that follows the pose of the haptic device with the bone. Let p_h, p_v be the position of the center point of the blade for the collision and the visual geometries (figure 3(a)). Unlike the case of the burr tool, the collision detection of the saw is complicated by the fact that the blade geometry is thin and therefore can prove costly. In order to reduce the cost of collision, we compute oriented bounding box (OBB) and bounding cylinder at each frame. An axis aligned bounding box (AABB) of the OBB is also computed as shown in Figure 3(b). At a given frame, the collision of the nodal points belonging to the bone are first checked against the AABB. All the points inside the AABB but outside the bounding cylinder are then discarded. Next, the projection distance d_{blade} to the plane containing the blade is computed for each of these points. If the distance is greater than the half length of the side of the OBB along that direction, the points are discarded.

In order to find the position of the proxy, we compute the projected distance of the remaining points in the previous step on to the surface of the bounding cylinder along the direction d_{saw} (see figure 3(a) inset). Then the position of the proxy is computed as $p_v = p_v + \max(s_j) d_{saw}$ where $\max(s_j)$ is the maximum projection to the surface of the cylinder for all the points in the OBB. The force feedback is computed in a similar fashion as described

above. In the case of the saw, the rate evolution of the density is simply computed $\dot{\rho}_i = -c_0 v_{saw} d_{blade} H^{-1}$ where c_0 is a constant. Figure 4 shows the screenshot of the sawing of the mandible resulting from the above method.

Surgery Simulation Software

We implemented the physics-based bone manipulation methods described above in *interactive medical simulation toolkit*-iMSTK, an open-source, interactive medical simulation toolkit designed for rapid prototyping of interactive simulation applications [9]. iMSTK provides an easy to use framework that can be extended and interfaced with other third party libraries for the development of medical simulators without restrictive licenses. iMSTK provides a module oriented extendable framework consisting of four main modules: Core, Rendering, Simulation, and Hardware (Figure 5). iMSTK contains advanced algorithms for modeling of tool-tissue interactions that capture the behavior of aggregated tissue and organs at their boundaries or interfaces. These interactions have been demonstrated for surgical scenarios involving friction, adhesion, and cutting.

Surgery Simulation Hardware

The prototype hardware set up integrates graphical techniques to provide realistic visual feedback in real-time for each step using a Head Mounted Device altogether with the physical model for real-time simulation of tissue deformation and force-feedback devices to provide the necessary haptic feedback when osteotomies or collision between bone segments occurs. We used Oculus Rift HMD that has an OLED panel for each eye with a resolution of 1080×1200 and a refresh rate of 90Hz. Our prototype provides trainees substantial amount of forces when using cutting and drilling tools during the simulated surgery through a haptic device (Geomagic Touch™ with max. force of 3.4N) that can track position and orientation of the tools and render forces along three Cartesian coordinates.

We pair the hardware set up with the design of Proficiency Based Progression (PBP) metrics that will record surgical performance associated to each surgical simulation scenario. For the bone manipulation surgical tasks we will measure surgical performance via shape distances of bone cuts and drilling sites to important anatomical landmarks such as vessels, nerves, and dentition.

4. RESULTS

Simulations were implemented on a desktop computer with a 3.40 GHz Quad core CPU supported by 8 GB physical RAM and a NVIDIA Quadro K600 graphics card. All the computations were done with double precision arithmetic and executed in a single thread.

In order to generate the 3D model of the bony structures of the patient we employed 3DSlicer Segmentation Module to threshold the scan of the patient. The surface was further used to create tetrahedral mesh using Delaunay tetrahedralization algorithm. The resulting models (figure 7(a)) had 46.5K nodes for the mandible, 723K nodes for the maxilla. We used the VTK library in order to render the bone surface and the newly created surfaces due to the cutting process. A Geomagic Touch X haptic device (figure 7(b)) was used interfaced in order to simulate the force feedback.

We employed special voxel based data structure to detect collisions between the drill geometry, modeled as a sphere (figure 7(a)) and the point cloud of the mandible and maxilla. We achieved a framerate of around 400 Hz for the drilling algorithm. A moving average force filter was used to smoothen the forces across frames prescribed by the width of the window. Figure 7(c) displays the user interface of the developed surgical simulator.

5. DISCUSSION

OMF surgeons are mandated to have at least 4–6 years of specific training may particularly benefit from additional surgical training because of the complexity and finesse of the skill involved in surgeries such as BSSO. The proposed method is oriented towards helping build complex procedures in Orthognathic surgery that will provide reliable means to simulate the crucial part of the surgery i.e., the cutting of the bone in real-time. In the future, we will employ the methods proposed in this paper to build a prototype that simulates the full procedure of the BSSO. The prototype will then be face and construct validated using expert surgeons.

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Figure 1.

High-resolution model (obtained from CBCT) that illustrates the pre-surgical state of BSSO, with mandible rendered in full opening width. The model includes 3-dimensional reconstruction of craniofacial hard tissue (bone, in solid/semitransparent yellow) and soft tissue (vessels in solid red, gingiva in semitransparent pink) structures, rendered altogether with orthodontic appliances (brackets in solid blue)

Figure 2.
Illustration of the bone corrosion caused by the burr tool.

Figure 3.

Illustration of the bone corrosion caused by the oscillating saw: (a) virtual coupling mechanism showing the visual (blue) and collision representations of the saw. The inset shows the projection of the collision points on to the surface of the bounding cylinder (b) bounding cylinder (green), oriented bounding box (red) of the blade and axis aligned bounding box (yellow).

Figure 4. Screenshot of the simulation of the sawing action on the mandible. Please note that this figure does not illustrate the osteotomy performed in BSSO, but the effects of the bone sawing algorithm in the tetrahedral mesh.

Figure 5.
iMSTK software architecture.

Figure 6. System diagram of the interactive simulator showing all the key components: HMD, haptic device, simulation engine, surgical scenario and PBP and the human user working together in a closed loop.

Figure 7.

(a) User performing the bone drilling using Geomagic Touch haptic device (b) Screen shot showing the erosion of the mandibular bone. (c) User interface of the orthognathic surgery simulator.