NOTA TÉCNICA
Vol. 33, Núm. 2, Diciembre, 2012, pp. 147-158
Revista Mexicana de Ingeniería Biomédica

Development of a Virtual Simulator for Planning Mandible Osteotomies in Orthognathic Surgeries

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ABSTRACT

Surgery knowledge and training is typically transmitted by the teacher-student method. In particular, the training process is carried out during real surgical interventions and under supervision of an experienced surgeon. Recent advancements in computer interaction technology and virtual environments allow a wide variety of surgical procedures to be simulated. Virtual reality (VR) applications range from art to engineering, science and medicine. In medicine, virtual simulators are being developed for pre-operative planning and training purposes. In this way, the transferring process of surgery knowledge and training can be enhanced and speed up. Medical VR simulators are characterized by their large demands on visual and physical behavior, and more recently the demand for the sense of touch, which is an essential aspect in surgery. Regarding the maxillofacial surgery, one of the most common surgical procedures is the 'Bilateral Sagittal Split Ramus Osteotomy Mandibular" (BSSROM), which is used to relocate the jaw at the correct position, fix jaw deformities, get better functionality of the jaw and improve the patient aesthetic. In this paper the development of a 3D virtual simulator for planning mandible osteotomies in orthognathic surgeries is presented; in particular the work is focused on the BSSROM procedure. The proposed system has been developed in an open-source platform that provides a high level of realism and interaction, and where the surgeons are able to cut bone in a 3D free-form way; thus enhancing the traditional virtual osteotomy approach which is based on cutting planes. Some of the main functionalities of the system include: virtual reality environment and real-time response; 3D visualization of anatomical models and tools; free-form manipulation and interaction of cutting tool, bone, and bone fragments; simulation of single and multiple osteotomies; cutting planes osteotomies and free-form cut osteotomies. The description, development and implementation of the system are presented in this paper. The results have shown that the proposed system is practical and can be used for planning and training mandible osteotomies.

Keywords: virtual simulator, surgical planning, BSSROM, osteotomies, jaw.

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Fecha de recepción:
31/Octubre/2012
Fecha de aceptación:
27/Noviembre/2012

RESUMEN

El conocimiento y entrenamiento quirúrgico normalmente se transmite por el método maestro-alumno. En particular, el proceso de entrenamiento se lleva a cabo durante las intervenciones quirúrgicas reales y bajo la supervisión de un cirujano experimentado. Los recientes avances en la tecnología computacional y la interacción con entornos virtuales han permitido que una amplia variedad de intervenciones quirúrgicas puedan ser simuladas. Las aplicaciones de la realidad virtual (VR) abarcan desde el arte hasta la ingeniería, ciencia y medicina. En medicina, los simuladores virtuales están siendo desarrollados con propósitos de planeación y entrenamiento pre-operatorio. De esta manera el proceso de transferencia de conocimiento y entrenamiento quirúrgico puede mejorarse y acelerarse. Los simuladores médicos de realidad virtual se caracterizan por sus grandes demandas visuales y comportamiento físico, y más recientemente la demanda por el sentido del tacto, que es un aspecto esencial en la cirugía. Con respecto a la cirugía maxilofacial, una de las procedimientos quirúrgicos más comunes es la 'Osteotomía Sagital Bilateral de Rama Mandibular' (OSBRM), la cual se utiliza para relocalizar la mandíbula en la posición correcta, corregir deformidades de la mandíbula, conseguir un mejor funcionamiento de la mandíbula y mejorar la estética del paciente. En este artículo se presenta el desarrollo de un simulador virtual 3D para planeación de cirugías de osteotomía mandibular ortognática, en particular este trabajo se enfoca en el procedimiento OSBRM. El sistema propuesto ha sido desarrollado en una plataforma de código abierto y ofrece un sistema más realista e interactivo, en donde los cirujanos pueden cortar hueso de una manera libre y en 3D, mejorando así el enfoque tradicional de la osteotomía virtual basada en planos de corte. Algunas de las funcionalidades principales del sistema son: un entorno de realidad virtual y respuesta en tiempo real; visualización en 3D de biomodelos y herramientas; interacción y manipulación libre de herramientas de corte, huesos y fragmentos de huesos; simulación de osteotomías simples y múltiples; osteotomías con planos de corte y de forma libre. La descripción, el desarrollo y la aplicación del sistema se presentan en este documento. Los resultados han demostrado que el sistema propuesto es práctico y puede ser utilizado en la planeación y entrenamiento de osteotomías mandibulares.

Palabras clave: simulador virtual, planificación quirúrgica, OSBRM, osteotomías, mandíbula.

INTRODUCTION

Virtual Reality (VR) is one of the main areas of knowledge that have taken advantage of the computer technological development 1. It has been used in different applications such as engineering, education, entertainment, astronomy, archaeology and medicine, among many other 2. In the area of medicine, virtual environments can be created to reproduce different scenarios that enable the interaction with the human body anatomy 3.

The practice of medicine is performed through a teamwork and a complex decision making process 4. Practitioner abilities in medicine are gained by experience and training, which is a slow process and takes several years. To get experience and abilities, a student of medicine must be the protagonist of his/her training, taking into account as a main priority the avoidance of risks and unnecessary inconveniences for the patient 5. The use of VR in medicine may allow the student or practitioner to understand and confirm concepts and to improve skills in surgical practice, while experienced surgeons can plan or diagnostic with more accuracy 6.

In general, a VR application in medicine is composed of three main modules:

1. 3D model reconstruction module, which is responsible of generating 3D anatomical models from medical data such as CT and MRI images.
2. 3D visualization module, which is responsible of the graphics rendering of the virtual environment.
3. Manipulation module, needed to provide the interaction between the user and the virtual environment 7.

The Bilateral Sagittal Split Osteotomy Ramus Mandibular (BSSROM) procedure is a common technique used for the correction of facial deformities in an individual; it allows performing mandibular movements in different planes 8. The BSSROM represents the most commonly used procedure orthognathic surgery 9. Over the years, it has been gradually modified in terms of design, extension and instrumentation 10. These modifications make it technically friendly, predictable, biologically acceptable and versatile.

This paper presents the development of a VR system for planning and training of mandible osteotomies in orthognathic surgeries. Currently the development has been focused on the BSSROM procedure. The description, development and implementation of the proposed system are presented.

LITERATURE REVIEW

Several works related to the use of VR techniques in surgery simulation, maxillofacial surgery and virtual osteotomies, have been reported in the literature. The following paragraphs summarize some of these works.

Virtual maxillofacial surgery

Virtual surgery is an effective, definitive and objective tool for reconstruction and correction of facial deformities 11. The use of virtual surgery enhances the diagnosis and treatment planning. It can also simulate the results after performing surgery. In 12 the differences between virtual and real surgical outcomes were measured using a voxel-wise rigid registration of the cranial base with construction of pre- and post-surgery 3D models. The use of surgical templates to perform mandible reconstruction surgery according to the preoperative simulation was presented in 13. The accuracy was evaluated by means of cadaveric surgery in a 3D environment. The reconstructed mandibles showed high similarity to the surgical planning in terms of the mean translation, angular deviation, and rotation of segments of the reconstructed mandibles. A comparative analysis between the surgical outcomes achieved with Computer-Aided Surgical Simulation (CASS) and the traditional methods was presented in 14. A 3D skull model of twelve consecutive patients with Cranio Maxillofacial was generated. These models underwent 2 virtual surgeries: 1 was based on CASS (experimental group) and the other was based on traditional methods 1 year later (control group). The results showed that the surgical outcomes achieved with CASS are significantly better than those achieved with traditional planning methods.

A computer imaging software that enables surgeons to perform 3D virtual orthognathic surgical planning was presented in 15. This software can provide a realistic and accurate forecast of the patient's facial appearance after surgery. A new method for conducting mandibular model surgery, which provides an improved 3D assessment of the prescribed mandibular yaw movements, was presented in 16. A total of 670 students were evaluated in the use of simulated patients in conjunction with anatomic and tissue task-training 17. The results suggested that the combination of simulated patients and simulation models yields to reliable scores for procedural and interpersonal skills. On the other hand, a virtual simulator to evaluate dental surgeries was presented in 18. A group of 53 dental students provided their impressions after virtual simulation. The results showed that 51 of the 53 students recommended the virtual simulation as an additional training modality in dental education. A new method to automatically compute the mid-facial plane for planning cranio-maxillofacial interventions based on 3-dimensional (3D) virtual models was presented in 18. The study included experienced and inexperienced clinicians defining the symmetry plane by a selection of landmarks; this manual definition was systematically compared with the definition resulting from the new automatic method. The results showed that the new automatic method is reliable and leads to significantly higher accuracy than the manual method when performed by inexperienced clinicians.

A virtual reality tool for CASS, named 'The Hollowman', was presented in 20. 'The Hollowman' was used in orthognatic surgery to control the translocation of the maxilla after Le Fort I osteotomy within a bimaxillary procedure. The tool was proved to be very valuable especially in complex nonlinear translocations of the maxilla because the surgeon could directly visualise the position of the mobilised bone in relation to the preoperatively planned situation. The use and combination of volumetric tomography and 3D dental software programs, as tools for oral and maxillofacial surgery, was discusses in 21. The results suggest that the combination of these technologies is useful for expanding information in dentoalveolar, preprosthetic, trauma, pathology and reconstruction, orthognathic, craniofacial, and surgical cases of esthetic implant. Moreover, the precision, accuracy, and 3D visualization capabilities of these technologies open avenues for the oral and maxillofacial surgeon in the diagnosis, planning, and surgical management. In 22 it was presented a study to examine 3D virtual anatomical features of the sphenoid sinus and adjacent structures during virtual surgery, and to explore their relevance to actual transsphenoidal surgery. The study primarily focused on performing a virtual surgery to get measures and data needed in the real surgery. The study provided virtual anatomical information about the sphenoid sinus and important surrounding structures, which is essential for a successful real life transsphenoidal surgery.

Virtual osteotomies

The use of computer-assisted three-dimensional surgical planning in condylar reconstruction by vertical ramus osteotomy was described in 23. The results showed that the combination between surgical planning system and simulation makes the surgery more accurate and convenient, and avoids damage to vital structures. On the other hand, the amount of interference between the mandible proximal and distal segments generated by 3 different osteotomy methods using computer simulation was assessed in 24. They demonstrated no difference in severe prognathism and asymmetry cases. In 25 the surgical outcomes in free fibula mandibular reconstructions planned with virtual surgery were evaluated. From a total of 19 mandibular osteotomies, the results showed that virtual surgical planning have a positive impact on accuracy because it is possible to get more accurate measurements than manually, even by the hands of experienced surgeons.

Some virtual tools have been designed to assist the sagittal split osteotomy, after or before of the surgical procedure. In 26 the course of the mandibular canal at three positions using computed tomography (CT) was evaluated. The risk of injury to the inferior alveolar nerve in classical sagittal split osteotomy, based on the proximity of the mandibular canal to the external cortical bone, was assessed and alternative surgical techniques using computer-assisted surgery were proposed. The use of 3D finite element analysis to compare the biomechanical stability of bilateral sagittal split ramus osteotomies fixed by lag screws with linear and triangular configuration was presented in 27. Posterior occlusal loads were simulated to calculate the stress fields on both the segments and the fixing appliances by the MSC Marc software.

From the literature, it can be observed that virtual reality in medical applications has been widely used. Most of the surgical simulators have been designed for specific applications and they are based on a traditional manipulation of virtual models using the 2D mouse. On the other hand, virtual osteotomy simulators are based on cutting planes defined by the user, which is far from real osteotomy procedures where the bone is cut manually and the hand accuracy of the specialist is important. Thus, in this paper the development of a virtual osteotomy simulator is proposed in order to enhance the traditional virtual osteotomy approach based on cutting planes and 2D interaction. The proposed system provides a more realistic and interactive system where the surgeons are able to cut bone in a 3D free-form way. Also the system allows the free 3D manipulation of tools and anatomical models.

BSSROM PROCEDURE

The Bilateral Sagittal Split Osteotomy Ramus Mandibular (BSSROM) procedure starts with the cutting of the internal wall in the upper part of the ascending ramus of the mandible 28. The mark that leaves the tool serves as a guide to saw the rest of the jawbone 29. Figure 1 shows this procedure 29.

Fig. 1. Cutting with the mill 29.

Fig. 2. Cutting with the sagittal saw 29.

The next cut is performed following an oblique path from top to bottom and using a saw 10. The saw leaves a line mark as showed in Figure 2. The surgeon can then change the direction of the saw to cut only about 5 mm from the bottom edge 31.

The manual separation of the bone fragments is then carried out by pushing downwards and doing lateral movements along the ramus 10. The last step is to set both parts with mini plates and screws of titanium 10, 31, Figure 3.

Fig. 3. Fixation with titanium miniplates and screws 29.

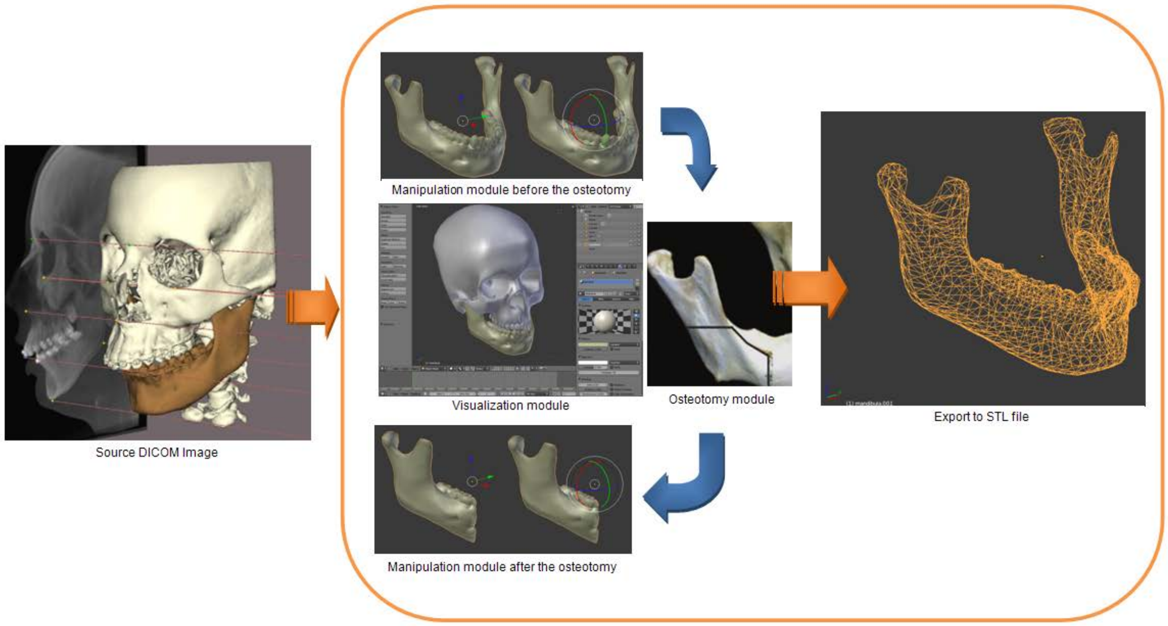


Fig. 4. VOSS architecture.

SYSTEM DESCRIPTION

The proposed Virtual Osteotomy Simulator System (VOSS) for 3D osteotomy planning and training has the architecture shown in Figure 4. The VOSS system comprises four main modules:

1. Visualization module, responsible of carrying out the graphic rendering of virtual objects and virtual environments.
2. Osteotomy module, to perform virtual osteotomies.
3. Manipulation module, to enable 3D free-form movement and manipulation of objects and surgical tools.
4. Data exportation module, to export any information regarding the osteotomy planning (e.g. STL files of models).

The GUI of VOSS is shown in Fig. 5, which has been implemented using Phyton and Blender 2.59, in a PC with a 1.73 GHz processor, 2.0GB of RAM and Windows XP. At the present, the VOSS systems allows for:

- Virtual reality environment and real-time response.
- 3D visualization of anatomical models and tools.
- 3D free-form manipulation and interaction of cutting tool, bone, and bone fragments.
- Simulation of single and multiple osteotomies.
- Free-form cutting path osteotomy.

Figure 6a presents the methodology to define the VR environment in the VOSS system. This methodology comprises the following steps in Blender:

- *Create a scenario*: The first stage is to create a scene in Blender to generate a real environment (lights, cameras, and background image).
- *Load skull and jaw anatomical models*: The bio-models are uploaded as STL or 3DS files, and can be obtained from reconstruction of medical images such as CT.

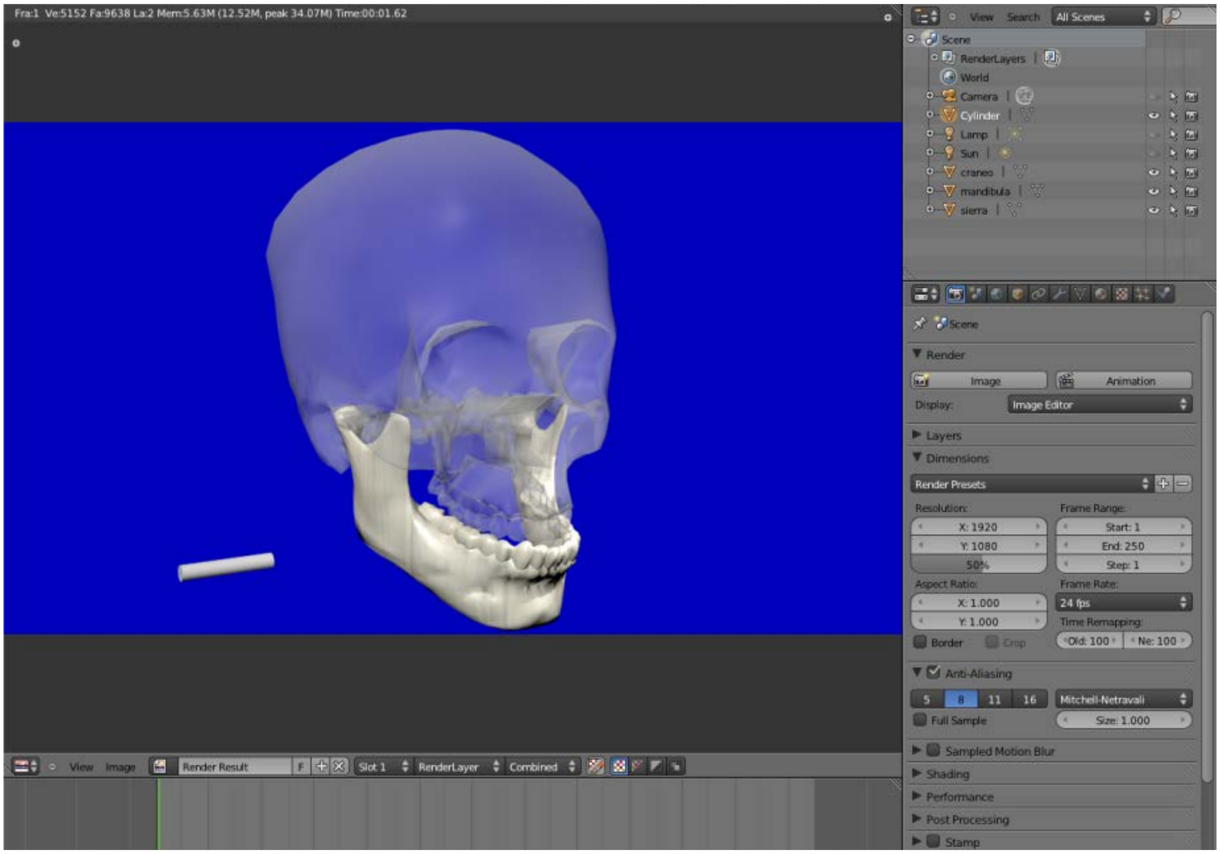


Fig. 5. Graphic user interface (GUI).

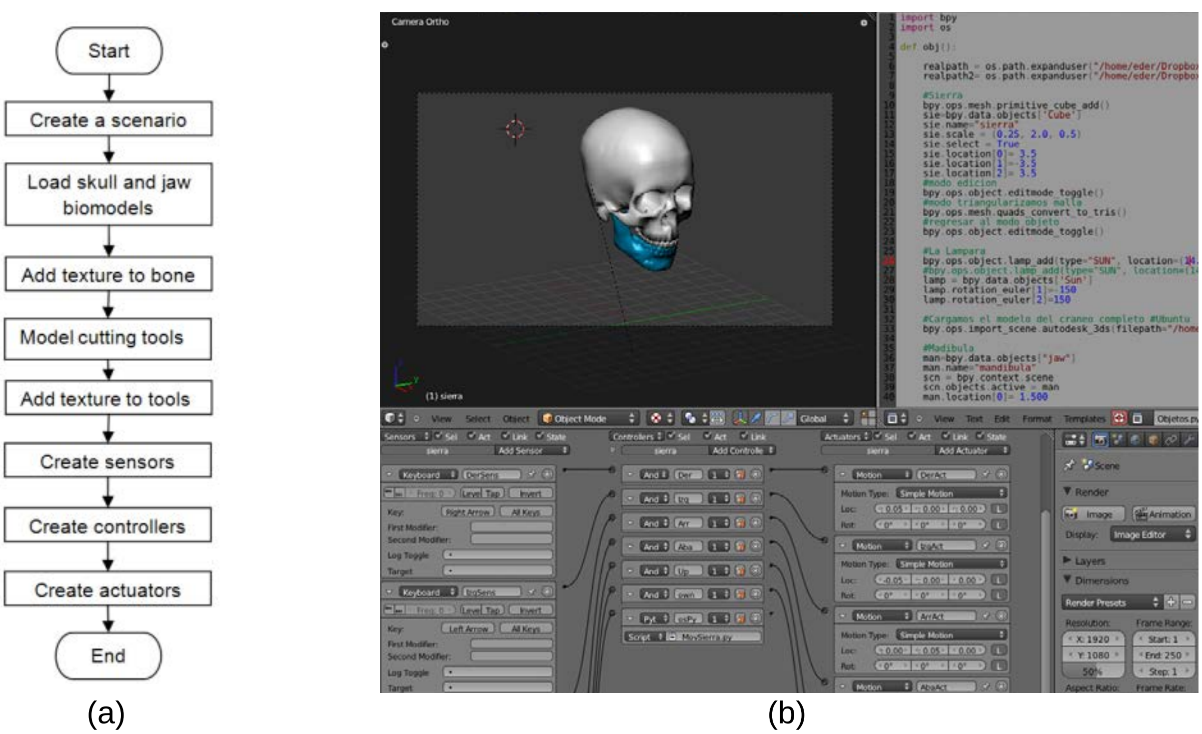


Fig. 6. VR environment: a) methodology, b) implementation.

- *Add texture to bone*: In order to increase the realism of the VR environment, texture to the jaw bone is added by means of an image. Since the skull is used only as reference and visual support, the texture is set as a transparency.
- *Model cutting tools*: Cutting tools (saw and drill) are modelled using the 3D modelling commands of Blender. They can also be imported as STL or 3DS files.
- *Add texture to tools*: The tools (drill and saw) are texturized with image to reproduce their real appearance.
- *Create sensors*: Sensors are created to establish the keyboard and/or mouse buttons to control objects in the virtual environment.
- *Create controllers*: Controllers are used to specify the next action to be performed after a sensor is activated.
- *Create actuators*: Actuators perform the movement or manipulation of the virtual objects according to the sensors. Movements can be linear or rotational.

The movement or manipulation of virtual models within the platform can be made using the numeric keypad, alphanumeric keypad or the computer mouse. These movements are defined by sensors, controllers and actuators. Figure 6b shows the graphic interface whit all the methodology and manipulation elements.

VIRTUAL OSTEOTOMY

The virtual osteotomy approach used in the VOSS corresponds to the BSSROM procedure, Figure 7. This procedure is described in the following paragraphs.

- *Move the tool*: Move the tool and place it at the point where the cut is needed. The user can select the tool to perform the cut.
- *Mesh edit*: A Boolean operation is performed between the jaw (bone) and the tool models. The tool is subtracted from the jaw. Virtual models are mesh models so they can be edited with Booleans operations.

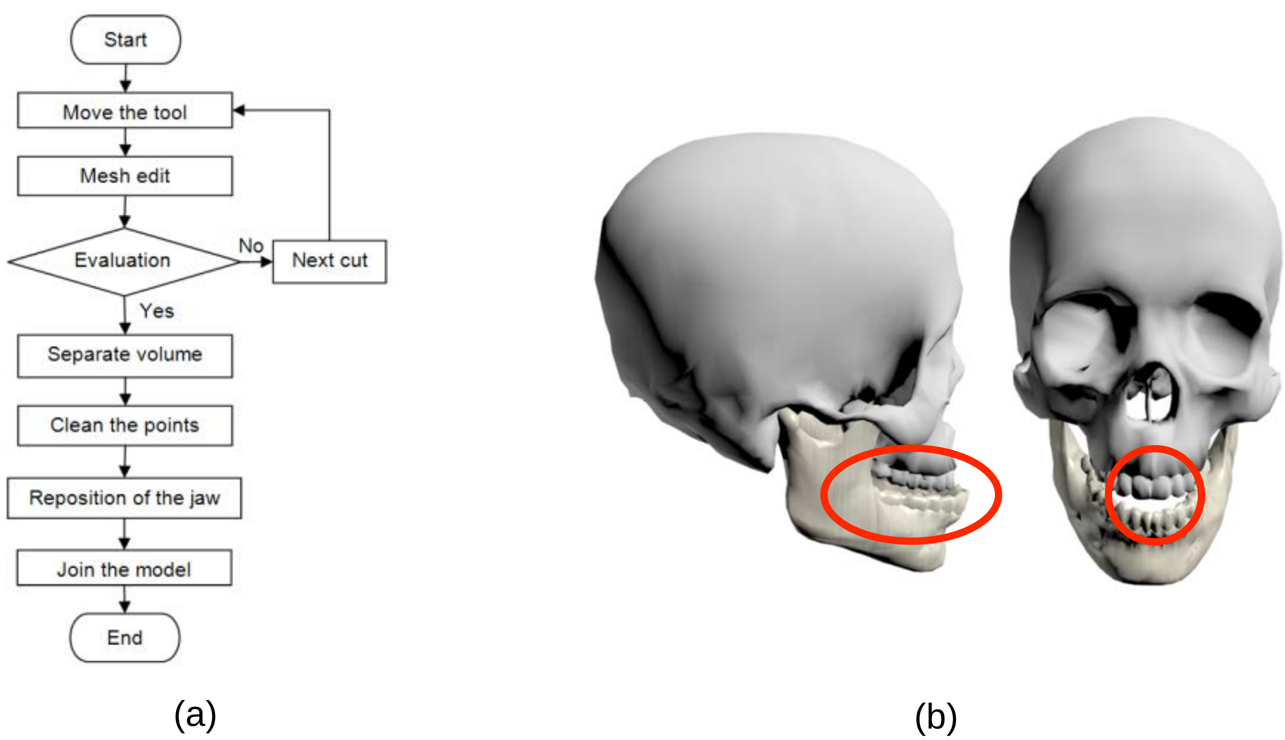


Fig. 7. Virtual osteotomy: a) procedure, b) virtual model with mandibular deformation.

- *Evaluation*: When the cut is performed with the sagittal saw, it is necessary to evaluate if the jaw was separated into two parts. If the model is not separated yet, a new cut is performed with a new tool position.

- *Separate volume*: After the evaluation, the mesh model is then separated according to the volume occupied in the scene. This will reduce the amount of data used in further processing.

- *Clean the points*: Many times some points would be out of the main jaw mesh, leading to additional volumes. It is important to eliminate those volumes because the algorithm only moves the two jaw main fragments (Jaw 1 and Jaw 2).

- *Reposition of the jaw*: Once the jaw has been separated into two parts, the largest part (Jaw 1) is moved or manipulated to its final position at the other part (Jaw 2).

- *Join the model*: The final step is to align and join the two parts of the jaw.

The procedure may be also performed to the other side of the jaw bone. Normally the BSSROM procedure requires the cutting of booth jaw ramus. In this case the previous methodology is then repeated to the other jaw side.

RESULTS AND DISCUSSION

To evaluate the feasibility of the VOSS, a case study is now developed. The BSSROM procedure begins by selecting a cutting tool and placing it at the position where the first cut is mean to be made, Figure 8. Once the tool is positioned, the cut is performed and it can be repeated as many times as necessary to make a longitudinal cut along the jaw.

The manipulation and location of the tool can be made in a free-form way, i.e. the user can freely move the tool in any 3D path while performing the cut. Figure 9a shows the simulation of a vertical cut path using a drill,

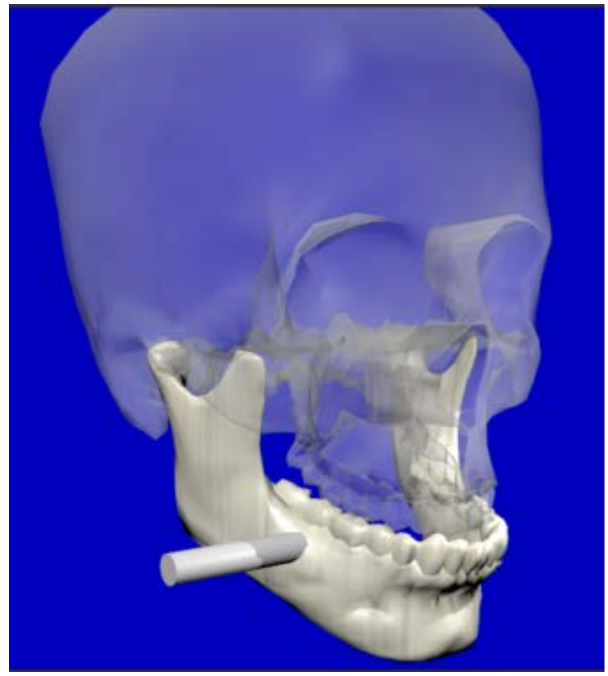
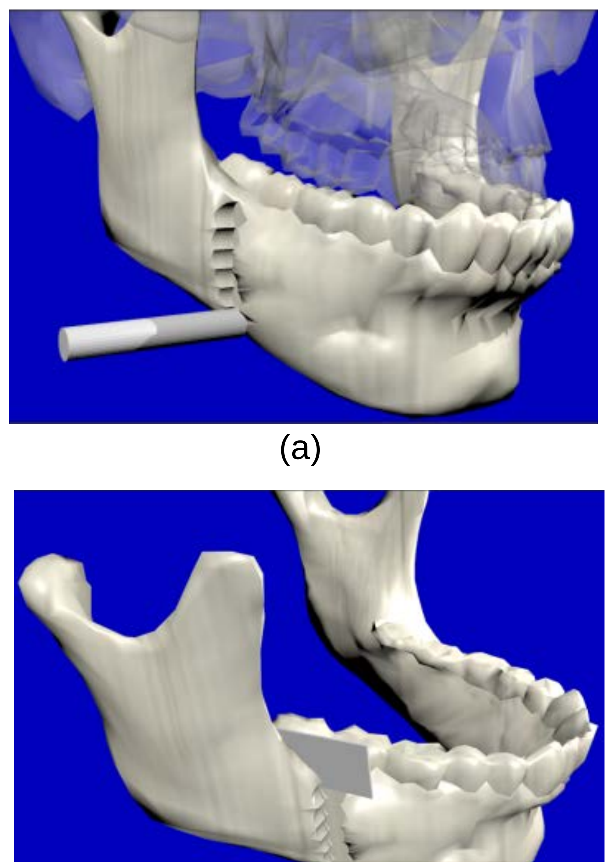


Fig. 8. Initial positioning of the tool.



(a)

(b)

Fig. 9. Available cutting process: a) drill b) sagittal saw.

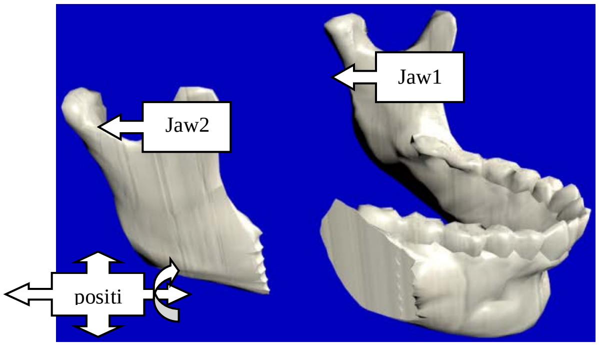


Fig. 10. New position from jaw 1 to jaw 2.

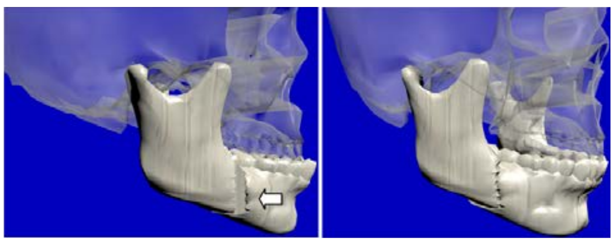


Fig. 11. Final step in the virtual osteotomy.

while Figure 9b shows the cut using a saggital saw to separate the jaw bone.

As in the real procedure, the jaw can be separated into two parts which can then be moved or manipulated independently. Figure 10 shows the bone fragments after the separation.

After the manipulation and relocation of the jaw parts, a Boolean operation can be carried out to join the jaw parts. Figure 11 shows the last movement and final relocation of the mandible.

The proposed VOSS system allowed the 3D rendering of anatomical models corresponding to an upper maxillary and a jaw. Different textures, lighting and visual properties can be used to increase the realism level. It has been proved that 3D virtual osteotomy procedures can be performed using the proposed system. The time performance of the cutting procedure depends on the size of the anatomical models (in particular on the number of elements in the mesh); the average time to perform a cut varies from 250 to 300 milliseconds, for a standard jaw and tool size. Anatomical models can be reconstructed from CT images (DICOM) and be imported into the VOSS system as STL files.

CONCLUSIONS

The development of a virtual simulator for planning a Bilateral Sagittal Split Osteotomy Ramus Mandibular surgery has been presented in this paper. The system has been developed using open-source software and without sacrificing the level of realism. The results of the implementation and evaluation have demonstrated that it is possible to perform virtual osteotomies using the proposed system. Future work comprises the incorporation of haptic devices to manipulate tools and virtual objects in the VOSS system.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support from CONACYT (National Science and Technology Council), research grant CB-2010-01-154430. They also thank to UASLP, HWU and ITC for the support provided to this research work.

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