

Haptic Simulator for training of Total Knee Replacement

Maria L. Pinto, Jose M. Sabater, Jorge Sofrony, F. Javier Badesa, Juan Rodriguez, Nicolas Garcia

Abstract—This paper presents a new and improved orthopaedic surgery simulator. Its capabilities are to analyze, process and display medical images, to reconstruct several three-dimensional models and to integrate them into a virtual environment. The main contribution of this work is to present a new mixed model (surface and volumetric) that allows to simulate bone machining on real time. The application is based on open source software and it also incorporates haptic technology to improve users immersion. The haptic immersion is computed using a 3D-3D collision detector.

The system consists of two stages; first, CT's images of a joint are analyzed, and a plan for intraoperative 3D sections is established. At next stage, the user integrates information from the different objects previously generated from the sectioned bones to interact with virtual models and prosthesis. Force rendering is computed using both the surface model and the volumetric model.

The developed simulator is particularized on this paper to simulate the cutting of a bone and implementation of a prosthesis in a Total Knee Replacement surgery intervention, although other surgical interventions are being modeled currently.

Index Terms—Surgery Simulation, Total Knee Replacement, Virtual Reality, Haptics.

I. INTRODUCTION

The individual characteristics of orthopedic and trauma surgeries have allowed fast development of training simulators. Bones are rigid parts, easily configurables in a software environment, and they allow good 3D visualization. Usually, commercial laboratories offer their customers simulators and planners which includes models of the prosthesis and equipment, and they are often integrated with surgical navigation software applications. These simulators can increase the benefits on a pre-operative stage of planning. However, almost all of these applications are geometric-based and kinematics simulations, i.e. are based on the location and 3D visualization of solid objects. Therefore, many of the operations that are performed in Total Knee Replacement (TKR) surgeries (removal of soft tissue, bone milling, drilling, cutting, sutures, ...) are not able to be simulated in these applications.

Previous work in interactive simulation of temporal bone surgery has focused primarily on haptic rendering of volumetric data. In [1] an analytical model of bone erosion as a function of applied drilling force and rotational velocity is developed.

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In [2] Visuohaptic is presented. This is a system for simulating surgeries involving bone manipulation, such as temporal bone surgery and mandibular surgery.

M. Agus [3] shows the instrument models that pierces a cloud of points, based on a modified version of the algorithm Voxmap-Pointshell [4]. The cloud of points are generated from information of computerized tomographies (CT) and magnetic resonances (MRI).

For specific applications of joint replacement, in [5] a simulated knee arthroscopy is included. This application also uses volume rendering and haptic feedback.

More related with our work, in [6] is presented a Virtual Total Knee Replacement System based on VTK. The main innovative feature of this surgery planning system is that it could help the surgeon to choose correct size, orientation and position of the prosthetic components, in order to restore the correct alignment of the mechanical axis of the lower limb, but it doesn't include haptics.

From the commercial point of view, the simulator insightArthroVR© presents a simulation and training testbed in a "real" arthroscopic minimally invasive, with a multi-purpose tool adaptable to various joints with a plastic casing of a shoulder or a knee and two Phantom Omni devices such as force feedback elements [7].

This document presents the development of a simulator based on open source software, as a support tool for training TKR's interventions. The application consists on one module of analysis and visualization of medical images, with the possibility of reconstructing three-dimensional models of bone tissue of a specific patient from DICOM images (Digital Imaging and Communications in Medicine). It also includes cutting tools for the sections of bone, obtaining a mixed model surface/volumetric for force rendering.

Despite only the tools and first simulation results of TKR simulation are shown on this paper, it also can be used to analyze other surgical interventions as total hip replacement (THR) or treatment of long bone fractures using intramedullary nails.

II. MATERIALS AND METHODS

II-A. Total Knee Replacement TKR

In total knee replacement surgery, sections of bone and cartilage of the joint are degrading, removed and replaced by artificial surfaces made of metal or plastic. The purpose of the TKR surgery is to correct the axial alignment of the lower extremity, maintain the joint stability, relieve the pain in the joints and thus restore the whole function of the knee joint [6]. In this intervention, it should be noted that the extraction of the components of the knee has minimal loss

of healthy bone, there are restored cavities and faults of segmented bones, restoring and stabilizing the joint with the ligaments equilibrium [8].

II-B. System Software Tools

- Visualization Toolkit VTK: The Visualization Toolkit (VTK) is an open-source, freely available software system for 3D computer graphics, image processing and visualization (<http://www.vtk.org/>).
- Insight Segmentation and Registration Toolkit ITK: is an open-source, cross-platform system that provides developers with an extensive suite of software tools for image analysis (<http://www.itk.org/>).
- GUI toolkits Qt: is a cross-platform application and UI framework (<http://qt.nokia.com/products>).
- V-COLLIDE is a collision detection library for large environments (<http://gamma.cs.unc.edu/V-COLLIDE/>). It is written in C++, designed for use in environments containing a large number of geometric objects composed of triangle meshes. VCollide was selected for the collision report and to record a lower average running time compared with other libraries like ICollide, Rapid, Swift, Solid and V-Clip, among others [9].
- Haptic Interface: The Phantom Omni device is an interface type joystick of serial configuration with 6DOF (degrees of freedom) and 3DOFF (degrees of freedom for force reflexion) and feedback of nominal maximum forces of up to 3.3N in three axes x, and, z. Software applications using Phantom Omni can be developed by using OpenHaptics© SDK and its libraries HLAPI and HDAPI.

II-C. Description of Training System

The simulator called SITKHR (Simulation of Interventions TKR and THR), is divided into two applications (figure 1). In a first stage (APPLICATION1), the user can visualize one or several images DICOM in any plane, mark anatomical landmarks, guide, preview and export virtual cuts of any section of the image being displayed. Also the user can indicate the section that he wants to turn in volumetric model (related to the division into small parts or particles that were used in haptic simulation and not by volume rendering algorithms).

In the second stage (APPLICATION2), the user imports the three-dimensional models of APPLICATION1 (tissues, bones, muscles, skin), and he indicates if they correspond to a superficial or volumetric model. The he interacts with tools that represent the haptic interface so he can have a real tactile sensation when the tools come into contact with any object added. The force feedback on the tools of exploration and sectioned for interventions simulator is performed by integrating the device Phantom Omni. Surface contact is easily programmed with OpenHaptics, while volume interaction with 3D surgical tools is programmed using VCOLLIDE libraries for collision and our own force reflecting generation algorithm.

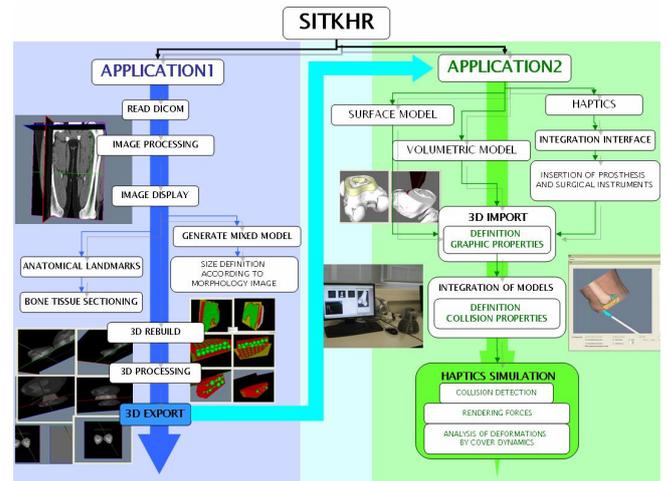


Fig. 1. General scheme SITKHR system

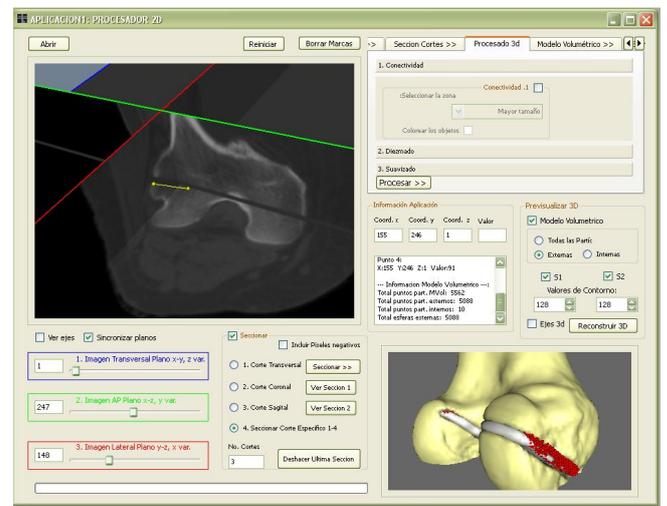


Fig. 2. APPLICATION1: processing and cutting of DICOM images

The simulator was developed in the programming language C++, compiled with Microsoft Visual Studio 2005, S.O Windows XP, CPU Intel Core(TM)2 Quad Q8200, 2.33GHz, 4GB of RAM.

II-D. Visualization, processing and reconstruction module

Using software tools VTK, ITK and QT, we have developed an application for the reading of medical images in DICOM format, in which a user can explore the image in three axes (x, and, z for slices); mark anatomical landmarks on a map transversal, sagittal or coronal (figure 2), according to a few options that are selected to turn the image in the coordinated axes (transverse plane, sagittal or coronal).

These options of visualization are important to analyze the capture of information for an intraoperative treatment. This way, for the intervention of total replacement of knee, note that the radiographic allows an approximation of the sizes of implants that are used. The Rx AP anteroposterior can assess the size of the tibial implant, with the lateral Rx the size of the femoral implant and with the axial Rx the patellar

implant.

The application includes tools for DICOM image processing with a stage segmentation and filtering for the separation of the components of the joints specific. It also proposes the allocation of cutting planes that splits the tissues and bones in several objects.

After that, the user can rebuild and preview solid or surface models, as a result of cuts but now in three dimensions. Processing options for smoothing, decimation and export of these models are also available.

As an important contribution of this paper, the application also provides a tool for the generation of a mixed model surface/volumetric of a specific section of bone from the pixel coordinates of three-dimensional images (2D and slices). See figure 3. The process to generate this mixed model is next:

II-D.1. Definition of cuts and sections of DICOM images: Starting with the definition of a plane on the DICOM images is possible to process the image depending on a cutting section. For this, a user can define a cutting plane by indicating two points in the rendering window, and project the line generated by these two points on the axial, lateral or transverse components image. Then, two output images are generated by means of the evaluation of a function corresponding to the equation of the straight line that joins both points. This function analyzes the location of every pixel of the input image and of the line.

The cutting strategy is defined as follows, the intensity value of pixels that are above the cutting line are set to a specific value. An example of applying the algorithm consists in creating a binary 1 (i.e. cut strategy: pixel value equal to $1024 \cdot itk :: Image < char, 3 >$) for pixels that are less than or equal to the values of cutting the line in the XY plane. Cuts in the actual implementation are obtained by the use of ITK iterators to generate two output images and VTK's contour filters to obtain the cutting surfaces.

II-D.2. Getting mixed model surface/volumetric: It is proposed an algorithm that generates three-dimensional model of the tissues, as a mixed model surface/volumetric. Volumetric model must be seen as a group of small surface models and not as volumetric rendering model. The mixed model was generated by the separation of components such as surface section on which are not proposed deformations or modifications and volumetric section composed of primitive surface (spheres or cubes) with independent properties of geometric transformations and collision reports, and a size that visually simulate a whole that are part of a surface model general (figure 3). This scheme allow us to analyze the deformation in terms of elimination or displacement of the particles of the volumetric model, without requiring re-meshing of surface models.

Previous definition of the cutting sections, the volumetric models are obtained by the storage of coordinates of the pixels of the image DICOM, which fulfill a condition of contour, for example that represents the pixel value of bone tissue. These coordinates are then exported as points of a data file as *vtkPolyData* for each volumetric section. The superficial models were obtained by the application of VTK's

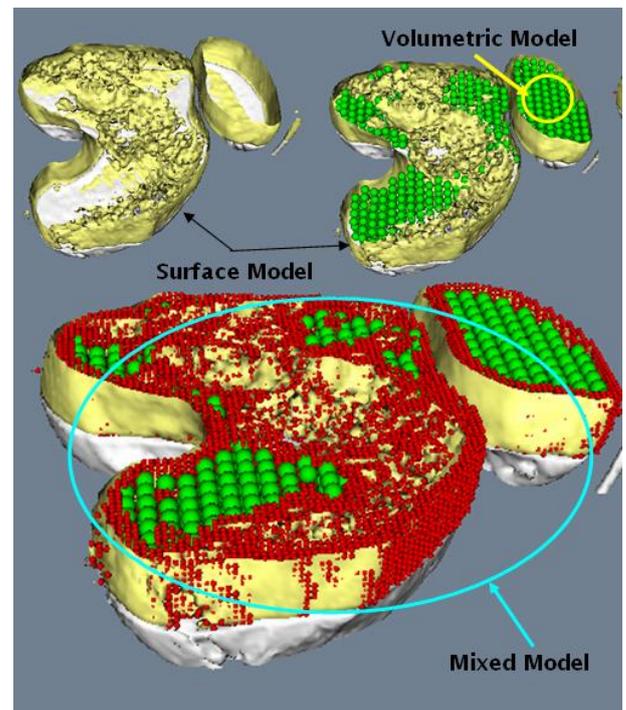


Fig. 3. Mixed Model Surface/Volumetric

contour filters and their posterior exportation in several formats for three-dimensional surface files (.vrml, .obj, .vtk).

II-E. Haptic simulator

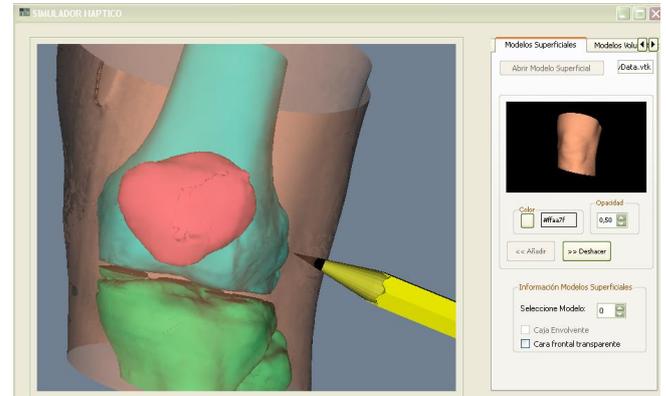


Fig. 4. APPLICATION2: Haptic simulator

The SITKHR's second application (APPLICATION2 figure 4) has three main features: to display surface models for tissue or tools, to integrate volumetric models and to simulate the tissue deformations of the volumetric part. This is done following next steps:

- Reading of three-dimensional models as surface objects (files *.vtk).
- Rendering of volumetric model with basic geometric primitives.
- Use of the Phantom Omni haptic interface to represent surgical instruments virtual.

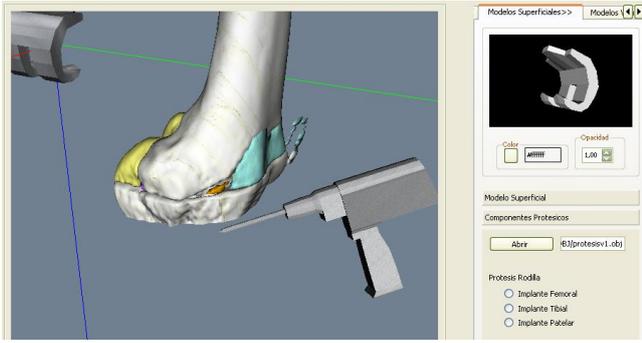


Fig. 5. Insertion of prosthesis and surgical instruments

- Analysis of collision detection in a virtual environment.
- Simulation of machining of bones for insertion of prostheses.

Functions were developed to read a volumetric model (pixel coordinates of voxel) with the possibility to choose the size and type of its components (primitives), according to the results of morphological allocation algorithm of sizes, the selection of a specific type geometry (spheres, cylinders or cubes) and a preliminary information charging the origin, spacing and dimensions DICOM image of the knee analyzed before in the APPLICATION 1.

The haptic interface was integrated into the scene rendering through the allocation of a three-dimensional geometry to represent virtually (haptic cursor), the position and orientation of the end effector of the Phantom Omni device. The collision properties of the cursor, were programmed using the capabilities of V-COLLIDE. It enables us to program 3D-3D collision between different tissues and 3D surgical tools. Force rendering algorithm was programmed based on the section that comes in contact with a virtual tool and volumetric approached of the surface cover generated by a cloud of points that are obtained as volumetric model output.

II-E.1. Other virtual models: For insertion of prosthesis and surgical instruments were developed functions to import, view and add properties collisions with other virtual models loaded from the VTK's class for reading file WaveFront *.obj (figure 5).

II-E.2. Haptic simulation for machining of bones: The machining of a bone were considered by an algorithm for dynamic generation of convex hull. The initial convex hull is generated from the cloud of points of a specific volumetric model obtained from the APPLICATION1 (figures 6 and 7).

With the coordinates information of origin, spacing and dimensions, it creates an image, assigning to the point cloud, a pixel value as similar to contour condition of APPLICATION1 (on which surface models were established). Again with a contour filter of VTK applied to the image, we obtain a particular convex hull.

The deformation of the surface, which gives dynamic character to the cover, consists of removing of the cloud of points, those that enter in touch with the haptic cursor. The coordinates they are known from the collision report of V-COLLIDE. Determined the objects and cells, can know the

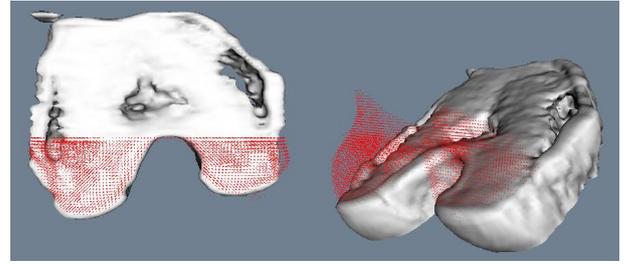


Fig. 6. Points cloud for dynamic generation of convex hull

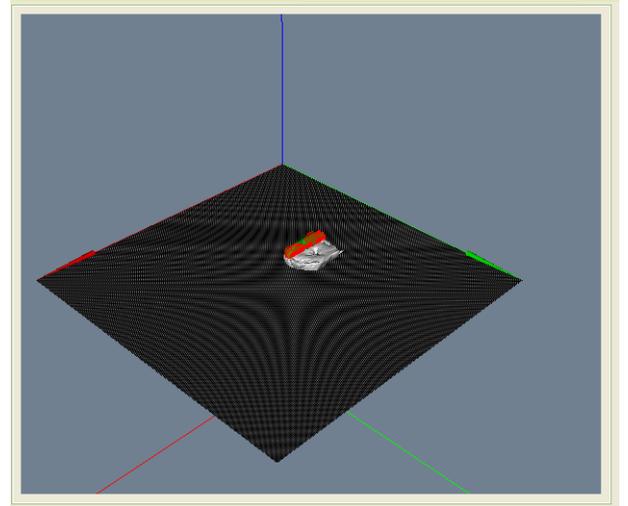


Fig. 7. ImageData of Points cloud

colliding vertices. Once deleted, the system updates the cloud of point, updates also the image and its associate convex hull. In the figure 8 there are examples of identification of cells and deformation of the convex hull.

III. RESULT AND DISCUSSION

The SITKHR allows:

- To visualize the image DICOM in any plane, marking anatomical landmarks, to guide, preview and export cuts of any section of the image. Also makes a specific section of the image, a mixed model Surface/Volumetric equally exportable with three-dimensional components.
- Import models, indicate whether they correspond to a surface or volumetric section and interact with three-dimensional instruments which can have a sense of touch across one force feedback interface.
- Integration with three-dimensional models of prosthesis and surgical instruments to perform the simulation specific interventions.

In the figures 9 and 10 some executions of the simulator are indicated. The models of the prosthetic components were scaled according to the dimensions of the bone, their movements were executed with the transformation matrix of the Phantom Omni© device. The synchronization between the haptic and visual thread is not satisfactory enough for loads of volumetric models that had more than 4.000 components,

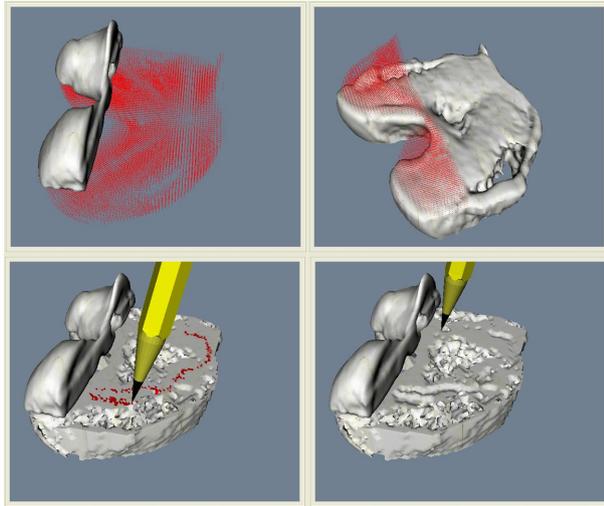


Fig. 8. A haptic simulation for machining of bones

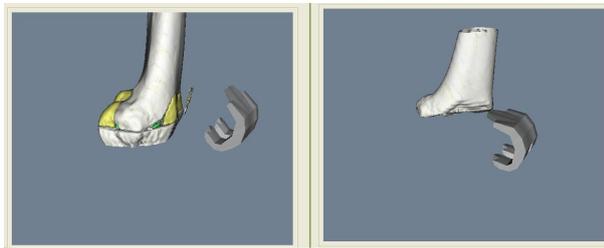


Fig. 9. Integration of femoral implant

due to the delay generated in updating the information of collision for all objects in the scene.

The number of images displayed and the spacing between pixels affect notably the execution of the system as for consumption of RAM memory and to the results of the managing of ITK iterators, specially in the management of the VCOLLIDE structures, as the members of these structures are continuously changing due to the disappearance of volumetric particles.

III-A. Future Works

- We are optimizing the memory allocation in order to improve the behavior of the collision subsystem.

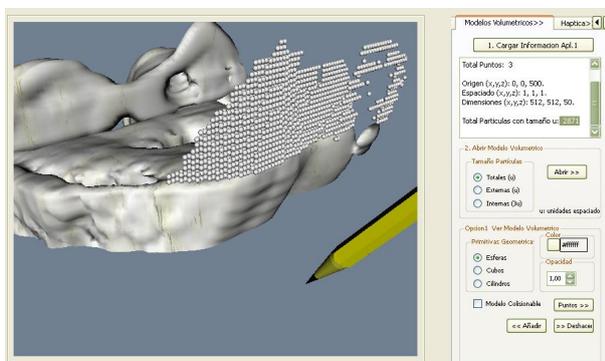


Fig. 10. Interaction with Mixed Model

- To improve the realism on the SITKHR simulator, we are developing three dimensional models of prosthesis and specific surgical instruments.

Our goal is to achieve a system with:

- Independence of prosthesis of the business firms with capacity for the design and simulation of the behavior of new prostheses.
- Capacity of process simulation of mechanized, milling and drilling.
- Possibility of using so much in exercises predetermined like in scenes of clinical reality of a patient.

IV. ACKNOWLEDGMENTS

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