A VIRTUAL REALITY SIMULATOR FOR TRAINING WRIST ARTHROSCOPIC SURGERY

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Keywords: Virtual Reality, Surgical Simulation, Convex Hull, Collision Detection, Healthcare Technology, Wrist Arthroscopy, Haptic Feedback, 3D Modeling and Visualization.

Abstract: The minimally invasive approach of arthroscopy means less pain and faster recovery time for patients compared to open surgery. However, it implies a high difficulty of performance. In this paper, a functional prototype of a virtual reality simulator for training wrist arthroscopic surgery is introduced. This simulator allows medical students as well as surgeons to interact with anatomical structures by modeling and operating on virtual objects displayed on the computer screen. A 3-D virtual representation of the bones constituting the wrist of a patient is shown. Also, algorithms that model objects using the convex hull approaches and simulate real time collision detection between virtual objects during the training on the operation are presented. In addition, a force feedback device is used as a haptic interface with the computer simulation system. This leads in the development of a low cost system that is used by trainees with the same benefits as professional devices. In this regard, the wrist arthroscopy can be simulated and medical students can easily acquire the system and can learn the basic skills required with safety, flexibility and less cost.

1 INTRODUCTION

Virtual Environment (VE) provides a new dimension of graphical simulation (Goebel, 1993). It is described as an application that allows users to navigate and interact with a computer-generated three dimensional (3-D) space in real time. In this context, Virtual Reality (VR) is not only a hardware system but also an emerging technology that changes the way individuals interact with computers.

Recently, medicine has entered a period of intense technological transition driven by the need to provide improved care at lower cost. Since, the outcome of surgical procedures is closely related to the skills of the surgeon, the latter should remain at a high level of technical and professional expertise. These skills are being developed over years of surgical training on animals, cadavers and patients. For surgical trainees to reach a high level, new and alternative ways of performing surgical training are required. In addition, the low availability and high cost of cadaver and animal specimens for traditional medical training and the public concern with the inhuman treatment of animals have become another impetus for surgeons and medical students to use new technology in their education and their training to gain valuable information and experience.

VR technology has opened new realms in the practice of medicine. The graphics capabilities of VR tools, particularly in modeling and displaying medical data can be of great assistance in teaching, learning, training and experimenting surgeries. Furthermore, researchers on medical education depend heavily on VR simulators that have become one of the main components of changing radically the traditional medical training and the surgical certification scenarios (Immersion Corporation). They allow the process of iterative learning through assessment, evaluation, decision making and error correction which create a much stronger learning environment.

An important application is the arthroscopic surgery simulation. In arthroscopy, the object is visualized and accessed through small portals. An optical endoscope equipped with a video camera allows the visualization of the procedure through one of the portals, while surgical probes and other instruments are inserted through additional portals.

Yaacoub F., Hamam Y. and Abche A. (2009).
A VIRTUAL REALITY SIMULATOR FOR TRAINING WRIST ARTHROSCOPIC SURGERY .
In *Proceedings of the International Conference on Health Informatics*, pages 74-81
DOI: 10.5220/0001552500740081

Arthroscopy decreases soft tissue disruption which leads to less pain and less chance for infection. However, it implies a high difficulty of performance and necessitates the surgeon to acquire psychomotor skills which are essential to become expert. On the other hand, arthroscopy is increasingly being used in the treatment of the hand. Wrist arthroscopy, in particular, has proven to be extremely valuable in both diagnosis and therapy. It is an important skill for all hand surgeons (Haisman et al., 2005), in exactly the same way as shoulder and knee arthroscopy.

The skills required for arthroscopy are taught through hands-on clinical experience. As arthroscopy becomes a more common procedure, it is now obvious that special trainings are necessary to master surgical operations and guarantee qualification of the surgeons. Different research groups have shown significant advantage of using medical simulation systems over existing conventional methods that use live patients. Hence, a VR training system to simulate wrist arthroscopic procedures in VE is proposed in this paper. Two main issues are addressed: the 3-D reconstruction process and the 3-D interaction. The proposed system provides a VE with realistic representation of the region of interest. Based on a sequence of CT images a realistic representation of the wrist joint is obtained suitable for the computer simulation. Two main components of the computer-based system interface are illustrated: the 3-D interaction to guide the surgical instruments and the user interface for haptic feedback. In this context, algorithms that model objects using the Convex Hull (CH) approaches and simulate real time exact Collision Detection (CD) between virtual objects during the training on the surgical operation are presented. Also, a force feedback device is used as a haptic interface with the computer simulation system.

The rest of the paper is structured as follows: section 2 reviews some of the previous surgical simulators. The design criteria of the proposed VR system are presented in section 3. Section 4 shows the segmentation of the CT images and the generation of the 3-D virtual wrist model. In section 5, algorithm to construct the CH is implemented, then the CD problem is formulated and a linear programming solution is obtained to test whether a collision exists or not. A force feedback device that is used as a haptic interface with the computer simulation system is presented in section 6. Section 7 shows a virtual simulation of dorsal percutaneous scaphoid fixation. Finally, conclusions are given in section 8.

2 RELATED WORK

VR Surgical simulators have been developed for a wide range of procedures. However, they are often associated with specific involvements. The VR simulators presented are classified based on their applications and their relation to the organs or areas they treat.

Many simulators are associated with laparoscopy such as LapSim (Surgical Science). The LapSim simulator focuses on implanting basic skills that would be needed by the trainee towards performing bigger procedures. The Lapmentor (Simbionix) is a force feedback enabled laparoscopic training simulator. Medical students can train on either the basic skills or perform full procedures. This system offers as well the opportunity to perform a complete surgery. Moreover, The LASSO project (G. Szekely et al., 2000) is an integrated development effort to construct a laparoscopic simulation platform. The abdominal cavity is modeled using data from the Visible Human. Organ surface features are generated using a combination of texture analysis/synthesis. In addition, MIST is an endoscopic simulator where trainees are guided through a series of exercises of progressive complexity, enabling them to develop the skills essential for good clinical practice and VIST is a simulator for catheter based procedures for angiography and interventional procedures (Mentice). With VIST, trainees are able to practice on many operations such as carotid, coronary, renal and vena cava. Furthermore, VR simulations of cystoscopy and ureteroscopy procedures are done using the UroMentor (Simbionix). The UroMentor has a mass of practice modules and patient profiles that can be used to perform safe surgical procedures. Besides, the (Simbionix) GI Mentor II simulator, associated with colonoscopy, is an interactive computerized simulator that provides hands-on training in endoscopic procedures. Also, Bro-Nielsen et al. (1999) described a PC-based bronchoscopy simulator. In addition to realistic visual effects, this system uses a haptic interface designed to provide realistic force feedback during scope insertion. The system has been expanded to include colonoscopy and flexible sigmoidoscopy.

However, most simulators described above are expensive to acquire and need maintenance. Regarding arthroscopy simulators, most developments have been for knee training (Heng et al., 2004), the second case of arthroscopy that was treated is the shoulder arthroscopy simulations (Bayonat et al. 2006) and very little work has been done for wrist arthroscopy even though the wrist is a very important joint in the body and it handles many activities. Thus, the problem of building an inexpensive and practical simulator for training medical students and treat the issue of the wrist arthroscopy remained.

3 DESIGN CRITEREA

The design of the proposed computer-based arthroscopy simulator was based on a trade-off between medical professor's needs and VR limitations. Wrist arthroscopy is selected due to several reasons:

1- Wrist arthroscopy is a frequent pathology (study of essential nature of disease) that has been less studied and practiced than knee and shoulder arthroscopy.

2- A varied type of involvements and specific surgeries can be covered by wrist arthroscopy simulation such as: dorsal percutaneous scaphoid fixation, volar percutaneous scaphoid fixation, capitolunate arthrodesis ...

Two major aims are addressed:

1- Applying VR and physical simulation techniques to generate 3-D models and to simulate operations with fidelity and realism.

2- Trying to cover different requirements for the apprentice learning process and providing the user with tools to facilitate teaching, learning and training on several experiments.

Therefore, medical images are processed to generate volumetric object models. These 3-D models are presented both visually via rendering on the computer monitor and haptically with a force feedback device. Visual parameters such as viewpoint, zooming, color and lighting effects can be interactively controlled and object models can be manipulated with force feedback to change relative probe and object positions, and to simulate many surgical procedures. The interaction between the haptic device and the computer closes the feedback loop between the user and the simulator, offering a better understanding of the anatomical structures. Figure 1 outlines the main components of the proposed VR simulation system.

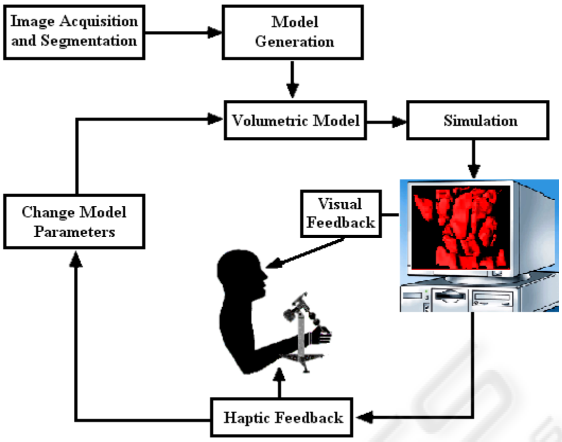

Figure 1: A Flowchart of the Simulation System.

4 3-D OBJECT GENERATION

Segmentation subdivides an image into its constituent parts. The watershed segmentation (Couprie et al., 2005) has proven to be a powerful and fast technique for both contour detection and region based segmentation. This method allows, from a gradient image, to find a thin separation between the components of a given set of points called markers. Figure 2 shows the original image and figure 3 shows the gradient with the markers.

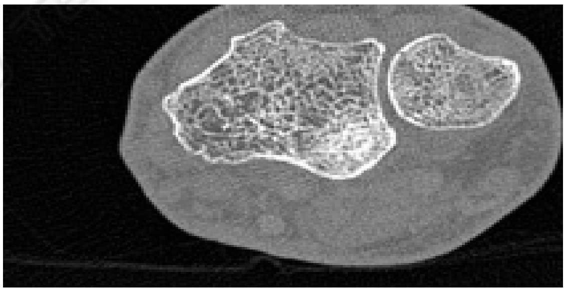

Figure 2: Original Image.

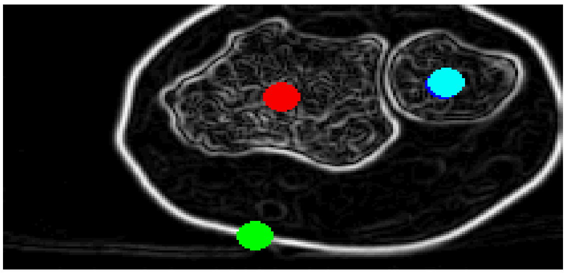

Figure 3: Gradient of Original Image with Markers.

The watershed algorithm is implemented by region growing based on the set of markers to avoid over-segmentation. At the end of the process all minima are completely separated by dams, called watershed lines. The watershed result is shown in figure 4.

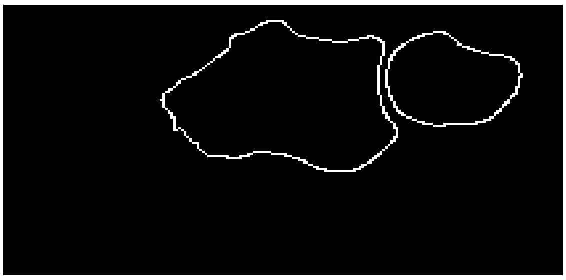

Figure 4: Watershed Result.

The final result of segmenting a set of CT images is a volumetric image that represents the labeled bones. Figure 5 shows the final 3-D image of the wrist.

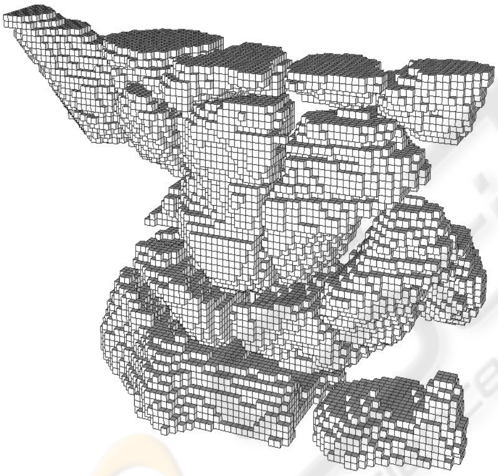

Figure 5: 3-D Image of the Wrist.

After the segmentation of the CT images, the Marching Cube algorithm is used to construct the boundary of the objects in the scene. The algorithm finds the appropriate surface patch in a look-up table and builds this patch, interpolated according to the values of the eight corners of this unit cube. The union of all these patches constitutes the approximated iso-surface and a list of facets is generated (Daragon et al., 2003). Figure 6 shows a high resolution 3-D virtual representation of the bones constituting the wrist of a patient. This representation provides the surgeon with precise and detailed information of the region of interest that he will be working on.

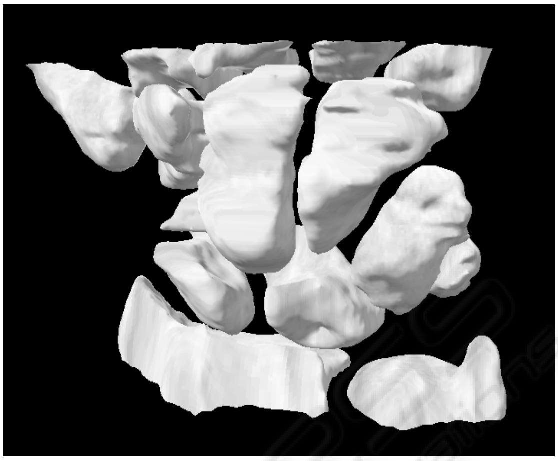

Figure 6: 3-D Virtual Model of the Wrist Bones.

5 COLLISION DETECTION

The goal of a medical simulator is to support medical students during training and practicing on surgeries with high precision. In this regard, medical objects are modeled with a tightness fit i.e. each object is modeled by its corresponding CH. This will give the simulator a high degree of precision but at the same time an increase in the cost of the complexity and the computational time for collision check. Therefore, by taking advantages of the speed and robustness of Linear Programming (LP) techniques the problem of CD is formulated and solved (Yaacoub et al, 2007). In addition, convex objects allow the LP algorithm to converge quickly and detect the collision if it exists. Thus, the CH of each object is reconstructed. Then, the CD problem is formulated as an optimization problem based on convex objects and solved using linear programming (simplex method).

5.1 Convex Hull Algorithm

Most exact collision detection systems work almost exclusively with convex objects because they allow CD algorithms to converge quickly. Moreover, convex envelopes have less contact points than real objects. This leads to a decrease in the size of the system of equations needed to calculate the collision. A new hybrid CH technique is developed to construct the convex envelope of a 3-D medical object (Yaacoub et al., 2006). The corresponding pseudo-code is shown as follow:

Algorithm 1: The Convex Hull Approach.

```
find an initial plane from the min and max abscise and
  the max distance with respect to $(x_{min}, x_{max})$
construct a polyhedron from the initial plane and the
  max distance to this plane
for each facet $F$ of the polyhedra do
  for each unassigned point $p$ do
    if $p$ is above $F$ then
      assign $p$ to $F$'s outside set
    end if
  end for
end for
Discard all points inside the polyhedron forming a new
  input set $n_{new}$
find a starting edge $(a, b)$ using the 2D Gift Wrapping
  algorithm on the $XY$ projection
for $i = 1 \ldots n_{new}$ do
  find point $p_i$ corresponding to min angle between
    plane $P$ in $XY$ containing $(a, b)$ and plane $T = (a, b, p_i)$
  replace $c \leftarrow p_i$
  save $(a, b, c)$ into $Q$
  wrap the edge $(a, c)$
  if facet has been explored then
    wrap the edge $(b, c)$
    if facet has explored then
      return
    end if
  end if
end for
```

As a result of applying the CH hybrid technique, figure 7 shows different bones constituting the 3-D wrist model: 1st Metacarpal (a), 2nd Metacarpal (b), 4th Metacarpal (c), Scaphoid (d), Capitate (e), Hamate (f), Radius (g) and Ulna (h). Each bone is covered with its corresponding convex envelope.

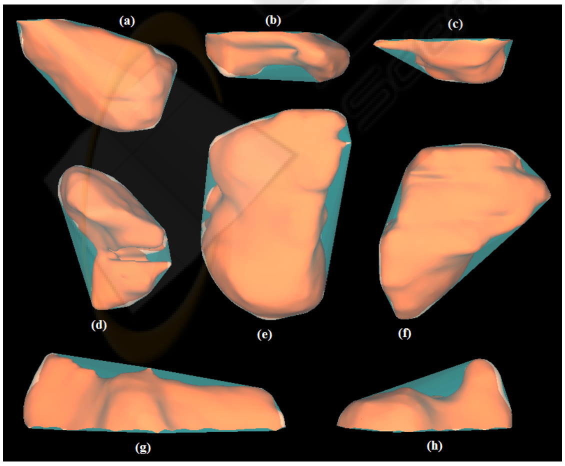

Figure 7: Bones from the 3-D wrist model enclosed by their corresponding CHs.

5.2 Linear Programming Solution

To formulate the problem, each facet i of the convex envelope is represented by the plane inequality in the form of:

$$a_i x + b_i y + c_i z \le d_i \tag{1}$$

Any point lying on the object must satisfy the inequalities of the planes constituting the object. These equations form the constraints of the collision problem and represent the facets that separate two regions in space. Therefore, if a point satisfies two sets of inequalities simultaneously, it belongs to the corresponding convex objects. Thus, a collision is detected at that point between these two objects.

The problem is reduced to maximize an objective function in the form of (x + y + z). It is formulated as follows:

$$\max \ c^T X \tag{2}$$

subject to:

$$AX \le b \tag{3}$$

$$where \ \ X = [x\, y\, z]^T$$

$$A = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \\ . & . & . \\ . & . & . \end{bmatrix} \tag{4}$$

$$b = [d_1\ d_2\ d_3 \ldots]^T, \quad c = [1\ \ 1\ \ 1]^T \tag{5}$$

The coefficients of the matrices A and b are calculated using the facets obtained from the CHs reconstructed by the approach presented in the previous subsection. Using the duality property, the problem becomes:

$$\min \ b^T \pi \tag{6}$$

subject to:

$$A^T \pi \ge c \tag{7}$$

Having formulated the problem, the dual system is solved using a linear programming algorithm. If the system is bounded, a feasible solution exists and consequently, a collision is detected. Otherwise, there is no collision.

6 HAPTIC INTERFACE

Force feedback is a very interesting technology in the context of human machine interface. It is used as a haptic interface in order to make 3-D models and simulations accessible to users and participants. In this work, a 3-DOF force feedback device is used. This will enhance the surgical performance by guiding the (surgeon, student ...) and give him a sense of touch and resistance when collision is detected.

When the user moves the haptic device, the position of the probe changes allowing dynamic interactions with the virtual environment. That is, the position of the medical probe is updated at every step and the CD is checked by applying the proposed algorithm on the updated matrices that formulate the collision problem, i.e. solving the system of equations at every step change. If collision is detected, a force is applied against the motion of the user of the haptic device. Therefore, the user can feel the resistance of the applied force against his hand's motion, i.e. against the force applied by the user to move the haptic device. This force-reflecting device enables medical students during the training to experience the real feeling of touch. Touching virtual objects rather than seeing them enhances the capability of the computer-based system and gives the user the feeling of so called "Immersion". Figure 8 shows the flowchart of the haptic feedback algorithm.

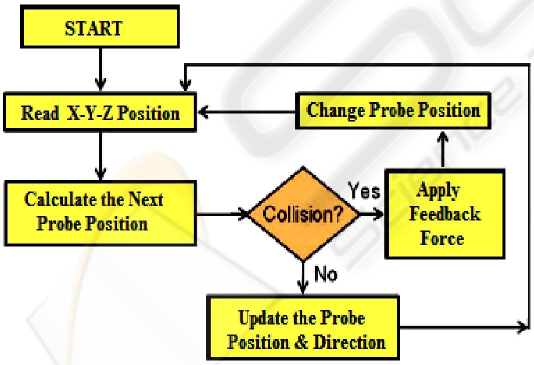

Figure 8: The Haptic Feedback Algorithm.

Figure 9 shows the haptic feedback system designed, implemented and tested with the computer-based simulation system.

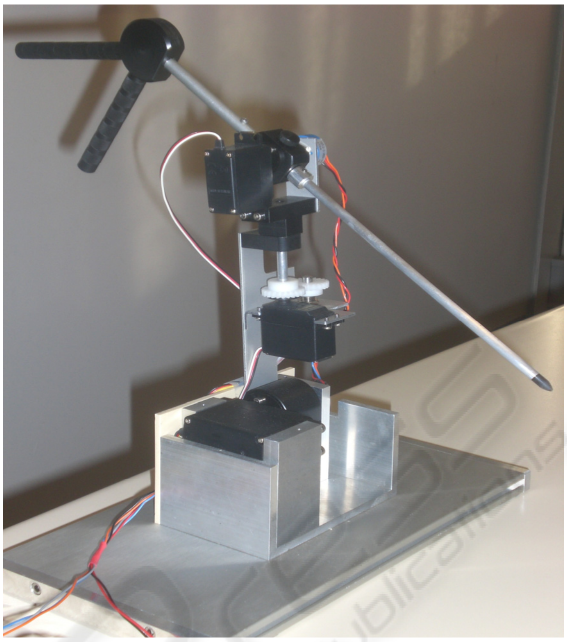

Figure 9: The Haptic Feedback System.

7 SIMULATIONS AND RESULTS

Techniques of performing wrist arthroscopy have been developed to evaluate and treat various wrist disorders, such as scaphoid fractures. For example, the dorsal percutaneous approach is a very efficient way in treating displaced proximal pole scaphoid fractures in many clinical and operating rooms. This technique allows for faster rehabilitation without restriction once CT scan confirms a solid union.

Percutaneous arthroscopically assisted internal fixation by a dorsal approach may be considered in all acute scaphoid fractures selected for surgical fixation (Rettig and Raskin, 1999). The dorsal guide wire permits dorsal and volar implantation of a cannulated screw along the central axis of the scaphoid (Wozasek and Moser, 1991). The surgical technique described in (Slade and Jaskwhich, 2001) uses the Standard Acutrak screw. This screw is a headless, cannulated, tapered screw with a graduated thread pitch to provide inter-fragmentary compression without hardware protrusion. This technique permits the percutaneous reduction and rigid internal fixation of proximal pole fractures.

First, the wrist is flexed and pronated for the scaphoid to appear as a cylinder. The center of the cylinder is the location for guide wire placement. Then, the guide wire is driven dorsal to volar through the center of the scaphoid. The wire exits at the base of the thumb. Figure 10 (a) shows the real placement of the guide wire during the surgery. Real figures of the operation are taken from a real surgery done by Dr. Joseph F. Slade and distributed by ACUMED. On the other hand, figure 10 (b) shows the same process done virtually using the proposed VR simulation system.

Figure 10 (a): Real Operation.

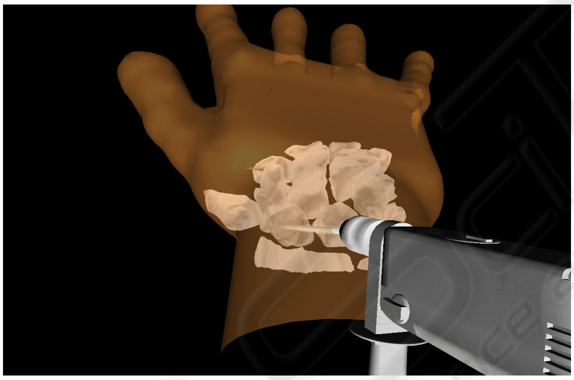

Figure 10 (b): Virtual Operation.

After this step, a hand-held cannulated reamer is placed over the guide wire and is used to prepare the scaphoid. The scaphoid is reamed to fit the length of the screw. Then the screw is selected and is advanced with a cannulated driver to the level of the reamed scaphoid. Figure 11 (a) shows the real insertion of the screw in the scaphoid while figure 11 (b) shows the virtual operation of the same process.

Figure 11 (a): Real Operation.

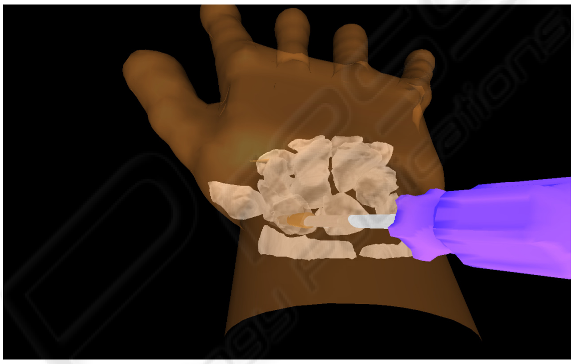

Figure 11 (b): Virtual Operation.

8 CONCLUSIONS

VR surgical simulators play a very important role in the practice of surgery for medical education and training. An innovative application is the hand surgery, especially wrist arthroscopy, which has proven to be an extremely valuable tool in both diagnosis and therapy. This paper presents a functional prototype of a VR training system for simulating wrist arthroscopy. Segmentation of CT images and 3-D virtual model of the wrist of a patient are shown. Algorithms that model objects using the CH approaches and simulate real time exact CD for solid objects are presented. Also, a force feedback device coupled with a haptic simulation algorithm is incorporated with the system. Finally, a virtual simulation of dorsal percutaneous scaphoid fixation is shown. This leads in the development of a system that is used to simulate wrist arthroscopic surgery procedures in a VE. Medical students can learn the required basic skills and then perform the training procedure on real patients. This low cost system is safe, flexible and can provide the students with precise and detailed information for training and educational purposes with the same benefits as professional devices.

ACKNOWLEDGEMENTS

This research is funded by a grant from the Lebanese National Council of Scientific Research (CNRS-L).

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