Development of a Surgical Simulator to training Laparoscopic procedures

Christian A. Diaz, Daniel Posada, Helmuth Trefftz and Jorge Bernal

Abstract — The training process for laparoscopic surgeons is currently based on interacting with experienced surgeons during procedures in a surgical room. During this interaction, the expert surgeon provides feedback based on qualitative appreciations about the performance to the trainee, and based on this evaluation, the expert surgeon determines the level competence of the trainee to carry out the surgical procedure. The development of specific skills involved in laparoscopic surgery, however, claims for new training methods and tools, as well as for means for quantitative evaluation of the surgeon's performance.

In this context, the virtual surgical simulator arise as a flexible tool to compensate for some deficiencies of the present training methodology. In the virtual surgical simulators the surgeon can train without time constraints and can polish or practice new interventional methods and techniques. Moreover, the simulator can provide feedback to the surgeon about his/her performance as the training protocol advances, without the need for an expert surgeon to supervise the process. The virtual surgical simulators have two different components: the physical interface and the virtual interface. Developing the physical user interface requires the study of the mechanical movements and forces involved in the interaction between surgeon and laparoscopic instruments. The virtual interface, on the other hand, builds on computer graphics and physical simulation in order to simulate a surgical task in an interactive and realistic way.

In the work describe in this paper we focus on the process of development of a physical interface and virtual interface. Specifically, regarding the physical interface we describe: (i)a mechanism that simulates the same degrees of freedom of the laparoscopic surgical tools with (ii)additional devices to acquire digital information from the real environment, used to construct the virtual surgical environment. This information represents laparoscopic instrumental position and its state, which may be open or closed. Regarding the virtual environment we describe the development of a training scenario, including a scenario that simulates a real laparoscopic procedure.

The paper also reports preliminary results on a study designed to evaluate the utility of the physical and virtual interface, comparing it with a real training device. The results obtained indicate that there is no significant difference between users who trained using the physical device and user who trained using the virtual training device.

Keywords— Minimally invasive surgery, surgical simulation, surgical training

I. INTRODUCTION

The current model of learning and training in laparoscopic surgery is based on observation and participation of new surgeons during procedures, taking active roles depending on their experience [1]. Unlike open surgery, Minimally Invasive Surgery (MIS) requires developing different skills due to the lack of haptic and visual feedback [2]. This makes necessary to develop new specialized ways of MIS training.

The advances of new technologies in fields such as modeling biomechanics of living tissues and virtual environments have created the conditions for virtual surgical training devices to meet all key elements required to obtain an efficient outcome [3]-[4]. The virtual laparoscopic simulators have no limitations of time, or risk unlike conventional methods of training, which could further jeopardize the health and even the lives of patients. Moreover, the evaluation of the surgeon' skills can be carried out in a more quantitative manner [5]. The present project is intended to abolish limitations faced by surgeons in laparoscopic procedures, to practice their techniques in order to improve and enhance their skills.

This aims at using virtual reality for providing a more flexible tool for training and evaluation. In this work we describe the development of the physical interface and the different scenarios of the virtual environment, including the development of scenario that simulates real anatomic structures with physical behavior.

Finally, in order to evaluate the performance of the physical interface and the virtual environment developed, we describe an experimental test and report the results.

II. RELATED WORK

Several physical interfaces and virtual interfaces have been developed in the medical field with applications as navigation attendance in biopsy [6], a surgical simulator to hysteroscopy [7], a catheterization simulator [8], angioplasty intervention [9], and Treating acrophobia [10], among others.

Some progress in virtual simulation surgery has been achieved by using certain devices in a physical interface that are used to track instruments position and some provide tactile feedback [11] to the user. Progress has also been attained by augmenting the fidelity a realism of the simulation, improving the algorithms that we have implemented to the simulation of the tissue and organs deformation [12], and procedures as cutting [13] and suturing [14].

However, not many projects related to physical interfaces and its integration with a virtual environment for training in laparoscopic surgery have been published [15]. Immersion Corporation was the first to develop an intuitive device which allowed a user to interact with a virtual environment in order to simulate a surgical procedure [16]. Recently, new interfaces have been created based on devices that allow the user to receive haptic feedback.

Other device developed to applications of laparoscopic surgery is The HIT Force Feedback Device. This haptic device provides five degrees of freedom and has been designed by Hauptabteilung Ingenieurtechnik. This has 3 degrees of freedom in its haptic feedback and has been integrated to the surgical simulation system KISMET [17].

In this paper, we describe the development of a physical interface and a corresponding virtual environment for surgical simulation. This environment is based on three training scenarios; two scenarios train simple laparoscopic task like transport objects with the instruments and the third scenario train a complex procedure, that is, a real procedure. We also report the results of a study designed for corroborating the effectiveness of the device for training purposes, when compared to a traditional physical device.

III. DESCRIPTION OF THE PHYSICAL INTERFACE

In this section, both the hardware and the software of the simulator that we have constructed are described.

A. Movement Analysis

The analysis of mechanics in the virtual surgical simulators represents an important field of study in the process of design and construction of the physical interface.

In real laparoscopic procedures, instruments have five degrees of freedom. The five degrees of freedom, or DOF for its acronym in English, are described in detail below:

Pitch: This degree of freedom allows tilting the instrument on a horizontal plane. Its measurement is done in degrees, looking at the instrument from top (Fig. 1), the movement that originates is a turning inward of the sheet, either clockwise or anti clockwise.
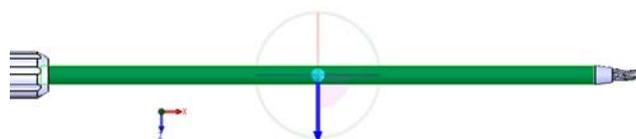
Fig. 1 Inclination (Pitch)

Yaw: This degree of freedom allows rotating the instrument on a vertical plane. Its measurement is done in degrees. Fig. 2 shows the side view of an instrument, turning on this occasion is done around the green axis.

Insertion: This degree of freedom allows the instrument to

Fig. 2 Rotation against a vertical Plane (Yaw)
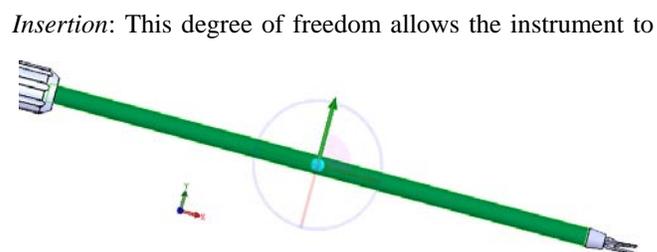
move lengthwise into the belly of the patient. Its measurement is made in millimeters. Fig. 3 shows the longitudinal displacement; this is parallel to the axis of the instrument.
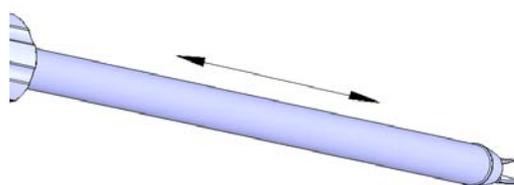
Fig. 3 Shaft displacement of the instrument (Insertion).

Rotation: This degree of freedom allows the instrument to rotate on its own axis in order to give a specific position at the instrument. Fig. 4 shows a side view of the instrument.
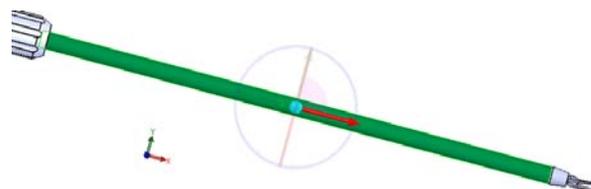
Fig. 4 Rotation on the shaft of the instrument (Rotation)

Handle: This degree of freedom allows the tip of the instrument, to open or to close. Fig. 5 shows the movement

generated.

B. Design and Development
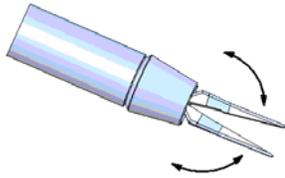
Fig. 5 Open or close the instrument (Rotation)

When designing a mechanism to satisfy laparoscopic surgery movements, it is important to consider the classification of kinematic pairs; this can be done by three different criteria [18]:

- The number of degrees of freedom in the bar connected by the pair.
- The type of contact between cells.
- The manner in which the elements remain in contact.

The classification of kinematics pairs in terms of DOF number and relative motion between the elements of peer kinematics according to the degrees of freedom in this classification, there are two conditions that impose an upper and lower limit to the DOF number, these conditions are:

- The kinematic pair must allow relative movement between the elements. Therefore, there must be at least one degree of freedom in the relative motion.
- The elements linked together by the pair, must remain in contact. Hence, there should be more than five degrees of freedom in the relative motion between the links.

Once the upper and lower limits on the number of degrees of freedom of movement to allowed kinematics in a pair have been determined, it is possible to classify them in a comprehensive manner.
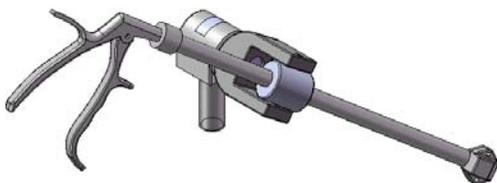
Fig. 6 Preview design of the user interface

The pursuit of the pair to comply with the DOF design requirements for the physical user interface concludes finding a pair of class IV type cylinder field Ec.

C. Acquisition System

The operation of the virtual interface requires information such as the instrument's spatial location manipulated by the user and its state, which can be opened or closed, as mentioned in the previous section. The instrument state is reproduced in virtual surgical environment, in order to provide more realistic laparoscopic procedures simulations.

The devices that need to be integrated into the user interface physics, in order to obtain the relevant information in the reconstruction of the virtual interface, are described next.

Magnetic Position Trackers

Electromagnetic trackers provide 6 degrees of freedom. They identify the position as coordinates (x, y, z), and the amount of rotation in each axis, the later are known as yaw, pitch and roll, respectively. In hardware terms, a source is needed to generate signal, a sensor that receives signals and a control component that processes the signals and can communicate with the computer. Depending on technology to be applied, one of two, sensor or source can be anchored to a body, serving as a reference.

Some trackers are electromagnetic, they use a radiation source and a magnetic sensor that calculates the position and orientation with respect to the source of radiation. There are devices that provide systems with multiple sources and their associated sensors that track the position up to a frequency of 100 Hz at ranges from one to six meters, providing a fairly high accuracy. A drawback of these devices is the fact that metal objects may distort the magnetic field, providing erroneous readings [19].

Virtual laparoscopic simulators implement five DOF in its physical interface, such as the one produced by Immersion Corporation. The magnetic tracking devices allow position digitalization in real-time up to four of the five degrees of freedom that conventional laparoscopic devices provide; this represents an 80% of movement in the user interface.

This project uses a magnetic position tracker supplied by Polhemus patriot, this has been integrated to the user interface anchoring the tracker source to the chassis and using two sensors on the mechanisms that simulate laparoscopy forceps. This makes possible to measure motions of the instruments relative to a reference point.

Analog to Digital Converters

The angular separation between a handles pair, can be read as a signal with a maximum amplitude when the handles separation is maximum, and minimum amplitude, when

separation between the handles is too small or zero. For acquisition and digitalization of this information in the user interface, a microcontroller is used, in addition to an analog-to-digital converter (A/D).

The most common A/D converters can work with an 8 or 10 bit resolution, using as a higher value the decimal number corresponding to 11111111_2. For instance, if using an 8 bits A/D converter, where V = +5 V and Vref = 0V, resolution is 5V / 255, when the analog signal is 0V has a digital number equal to 00000000 and when the signal is 5 V has a digital number equal to 11111111_2.

The microcontroller must meet the requirements of transferred amount of data and how to transfer it. The main conditions for microcontroller are:

- Minimum two-channel ADC
- USB communication
- High speed communication, between 20 and 48 MHz

The selected microcontroller for the project, which complies with the features mentioned above, is a microchip 18F4455. This includes up to seven A/D ports and USB communication.

D. Integrating the Interface to Virtual Environment

In laparoscopic surgery, the surgical instruments are the interface between surgeon and patient. It is very important to realize that a first-level interface reflects the physical qualities of the two interaction sides. The instrument is made of a solid material and has some restrictions on its movement; on the other hand, to interact with the surgeon it is located at an appropriate altitude. This is a very important idea in the design that can be described in two concepts [20]:

- *Visibility*: to be able to perform an action on an object the device must be visible.
- *Intuitive*: understanding or being clear on the part of the object that is going to take an action and how to do it.

Only if these concepts are met by the user interface, there is a successful interaction with the virtual one, which is built using the information captured from real environment, using devices like the position trackers and the analog to digital converter mentioned before; using mathematical models to recreate the mechanical human organs behavior, reproduce their deformities upon the effect of efforts. Next we describe the components and the development of the virtual interface.

IV. DESCRIPTION OF THE VIRTUAL INTERFACE

The virtual interface developed is composed for three training scenarios. Two of the scenarios visualize and simulate the physical events of the simple objects, like a cube, and there is third scenario that simulates the behavior and the interaction with a real organ..

A. Geometrical model

In the context of surgical simulation it is necessary to simulate the physical behavior of the human tissues and organs. The first step to is the creation a tridimensional model of human anatomy. In this case, the simulated procedure is a cholecistectomy. For this procedure we have to create a tridimensional model of the liver, gall bladder and associated structures.

To generate the tridimensional model, we use the images provided by the visible human project [21]. From these images we carry out a process to get the contour of the anatomical structure and later applied an algorithm to create a tridimensional model from this contours. Fig. 7 shows the process follow to carry out the reconstruction of the anatomical structures.

In order to extract the contour of the anatomical structure from the picture, we follow a methodology described in [22].
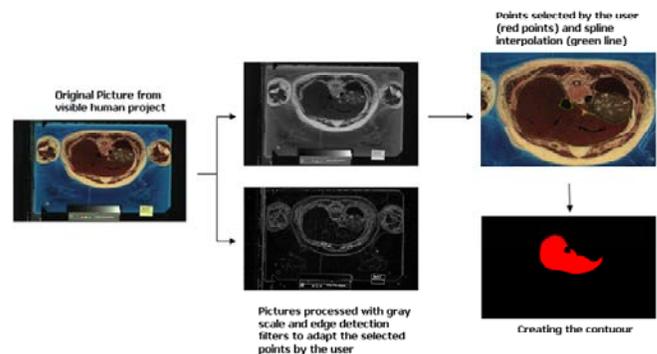
Fig. 7 Process to extract the contour of the anatomical structure from the picture.

This methodology was basically semiautomatic and a long time is required in order to complete the process. However it conserves the anatomical morphology of the organ contour. The process consists in the follow steps:

- The user clicks some control points in the contour of the anatomical structure on a sequence of images.

- The points selected by the user are adapted to the contour of the anatomical structure using an algorithm for edge detection.

- Interpolation of the points selected by the user using a spline cubic method.

- Smoothness of the abrupt changes using segmented spline.

In order to extract the contour of the organ or tissue from a picture, we developed an application in C++ language. This application was used on images from the visible human project.

After carrying out the above procedure, we applied an algorithm to create a tridimensional mesh from the two-dimensional point that define the contour of the organ in every image. The algorithm used to the tridimensional reconstruction is called Marching Cubes [23].

To implement a tridimensional reconstruction process we developed in order to to define the contours of the anatomical structures. To apply the marching cubes algorithm we use the VTK (Visualization Toolkit) library, which is a group of algorithms to handle tridimensional meshes. Due to the huge amount of points and primitives that compose the mesh after the marching cubes algorithm, we performed a decimation algorithm in order to decrease the amount of points and primitives of the mesh. Moreover, to improve the quality of the mesh we implement additional algorithms to smooth the mesh. Fig. 8 shows the tridimensional mesh of the liver created using the process described before.

B. Collision detection.

After creating the tridimensional mesh of the tissue and organs and the instruments involved in the surgical procedure, we implemented a collision detection module to query the interactions between the objects present in the virtual environment. In the surgical simulator three different interactions [24] are possible:

- Rigid Object – Rigid Object.

- Rigid Object – Deformable Object.

- Deformable Object – Deformable Object.

In this work we addressed only the first and second interactions mentioned before. Next we describe the implementation of two interactions.

Rigid Object – Rigid Object Interaction

In general the collision detection between rigid objects is a simple task. This kind of collision detection is necessary in the surgical simulator to development of the basic training tasks, which do not correspond to a complete surgical procedure as the cholecistectomy. This task will be described in the

experimental setup section. The process is simple and can be resuming in the next steps:

- Create a bounding volume of the object.

- Carry out a intersection test between bounding volumes of the objects in the scene.

In our case the bounding volume used to cover the rigid objects was spheres. The center and radio of the sphere were calculated using the size and position of the object; specifically we use the Ritter algorithm [25]. This algorithm allows for a good fitting of the bounding volume to the geometry of the object.

Interaction Rigid Object – Deformable Object

Fast detection of collision between a rigid object and a
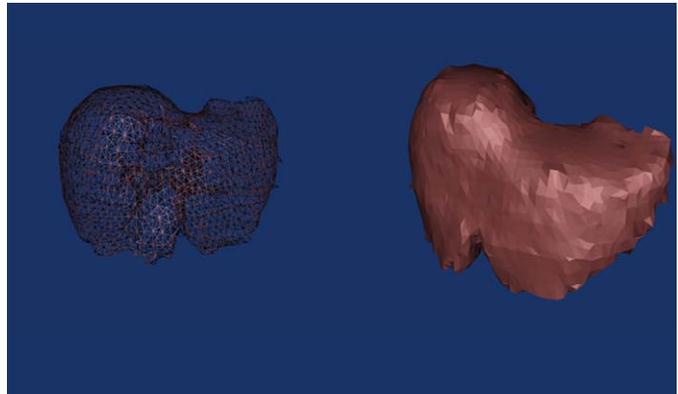
Fig. 8 Tridimensional mesh of the human liver. Right Wireframe visualization and left flat visualization.

deformable object can be implemented of several ways, for example calculating the distance between the objects applying space breakdown using voxels, and other methods. However, one of the methods currently used in surgical simulation is the use of hierarchy of bounding volumes of different types, for example of spheres [26], AABB's (Aligned Axis Bounding Box) [27], OBB's (Oriented Bounding box) [28], among others, useful for determining collision in real time among geometric models composed of many primitives, a critical issue in surgical simulation.

The hierarchy of bounding volumes consists basically in creating a hierarchy of several levels of bounding volumes that cover the object, in our case the liver or the gall bladder. The first step consists in creating a coarse bounding volume that contains all the organ, next other two sublevels (in the case of a binary hierarchy) each one of which would contain half of the organ and so on, until arriving at level n in which the bounding volumes contain the minimum primitive of the mesh, in our case a triangle.

The precision depends of the type of bounding volume used, the better adaptation to the object`s shape by the bounding volume, the higher computational cost the test done to investigate the collision. At Fig. 9 can observe the adaptation that offer the different bounding volumes. However, as a better adaptation is obtained, a higher computational cost is payed .
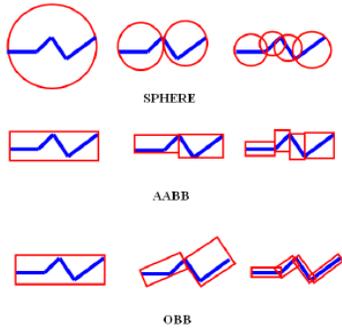
Fig. 9 Different bounding volumes used to collision detection with hierarchies.

C. Physical Model.

In order to discover the interactions among objects in the virtual environment, an algorithm that takes into account deformable objects is necessary. To accomplish with this objective we implemented a physical model based on mass-spring method. The next explanation is based on the work published by Brown et al. in [24]. This model represent the deformable object by a tridimensional mesh M , of n nodes $N_i(i = 1,...,n)$ connected by links L_{ij}; i, j, $\in (1,...,n)$, $i \neq j$. Each node maps to a specific point of the object, so that the displacements of the nodes characterize the deformation of the object. The nodes and links on the object's surface can be triangles or tetrahedral, in our case, the surface is triangulated. Fig. 10 shows an example of a deformation achieve implementing this model.

The mechanical properties (viscoelasticity) of the object are described by constants stored in the nodes and links of M . A mass m_i and a damping coefficient c_i are associated with each node N_i, and a stiffness k_{ij} is associated with each link L_{ij} . The internal force between two nodes N_i y N_j is shows in Eq. (1)

$$\vec{F}_{ij} = -k_{ij}\left(\Delta_{ij}\right)\vec{u}_{ij} \quad (1)$$

where,

$$\Delta_{ij} = l_{ij} - rl_{ij} \qquad (2)$$
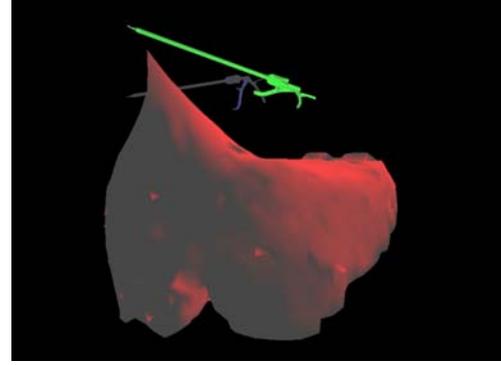
Fig. 10 Deformation of the liver when it interact with a surgical instrument.

Δ_{ij} is the current length of the link minus its resting link, and $\vec{u}_{ij}$ is the unit vector pointing from N_i toward N_j. The stiffness k_{ij} may be constant or a function of Δ_{ij} . In either case, $\vec{F}_{ij}$ is a function of the vectors coordinates x_i and x_j of N_i and N_j. This representation can describe objects that are nonlinear, non-homogeneous, and anisotropic.

At any time t , the deformation and motion of M is described by a system of n differential equations, each expressing the motion of a node N_i:

$$m_i\,\vec{a}_i + c_i\,\vec{v}_i + \sum_{j\in\sigma(i)} \vec{F}_{ij}\left(\vec{x}_i, \vec{x}_j\right) = m_i g + \vec{F}_i^{\,ext} \quad (3)$$

where $\vec{x}_i$ is the coordinate vector of N_i; $\vec{v}_i$ and $\vec{a}_i$ are its velocity and acceleration vectors, respectively, $m_i g$ is the gravitational force, and $\vec{F}_i^{\,ext}$ it the total external force applied to N_i. $\sigma(i)$ Denotes the set of indices of the nodes adjacent to N_i in M .

In order to resolve the set of differential equations presented before we applied the Runge-Kutta method of fourth order [24].

The mass-spring format was chosen for the follow reasons:

• The mass-spring is the simplest model of the physically based models.

- This model can be implemented as a volumetrically or superficial model and as a static or dynamic model.

- Due to the simplicity and fast implementation, the mass-spring model has been implemented in several surgical simulators.

- With this model is possible to achieve a real time simulation with a limited computation capability.

V.   EXPERIMENTAL SETUP

The proposed hypothesis to be proven through the virtual environment and physical interface is to determine whether or not if a user that trains with a virtual environment, he or she obtains the same skill level as when training with a real environment; that is, conventional tool using in a normal curriculum. With the aim to prove our hypothesis, an experimental test was developed. Two groups of subjects who did not have previous knowledge or experience on minimally invasive surgical procedures and open surgical procedures were used during the trial. The first group, called control group, had 7 subjects and the training session was done by a conventional tool. The second group also had 7 subjects and the training session was done using the virtual environment. Both groups had to take a pre-test to determine their skill level before the training session, and after the session they had to take a post-test to determine the skill level reached after the training session. The defined task to execute during the training session to both groups was to grasp and transport some objects to a specific target. Each subject, weather in the control group or the experimental group, did ten repetitions of the task to acquire the necessary skills to do that task.

The conventional device used by the control group is a set of mirrors, which are useful to change the pint of view of the zone where do the task, this to simulate the effect generated by the point of view of the camera in a laparoscopic procedure. Additionally, the device has two supports for the surgical devices and allows the degrees of freedom of the movement in agreement to the real surgery devices.

The virtual environment used for the experimental test consisted of three cubes on a surface, which ought to be grasped with the surgical devices by the user and then transported into a clear area. In order for the virtual environment to achieve a larger realism, simulated physical characteristics of the cube movement, such as free fall were added. Fig. 11 shows the virtual environment of the experience. The simulator have another implemented scenario very similar that it describes previously, the only difference is that the task executed by the user is not transport a cubes to a specific area, but transport each cube to a area with color equal to color cube. This last scenario described and the surgical simulation scenario were not used during the experimental test.

VI.   DISCUSSION AND RESULTS

As mentioned before, subjects in the control group and subjects in the experimental group, perform a pretest and posttest, in which they completed the task as training. Their performance was assessed by measuring the time to complete the task. The pretest and the posttest of both groups were made in the conventional tool, in a real environment. The
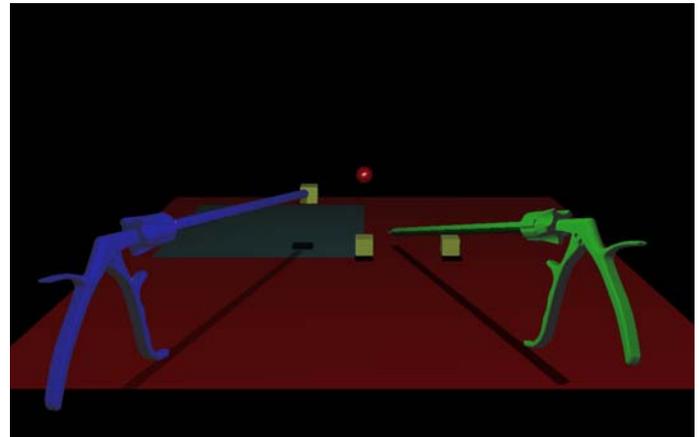
Fig. 11 Virtual Environment developed to experimental task.

results obtained in the pretest and the posttests to both groups are described in Table I and Table II. Tables I and II also show the difference of the time between the pretest and the posttest for each subject, and the percentage of performance improvement.

Using these two variables a t-student test was conducted to reject the null hypothesis, which was: Both groups had a similar improvement, both in absolute time difference as well as in relative (percentage measured) difference. The meaningful statistical parameter was $P<0.05$ and StatGraphics was used to do the data analysis.

The t-Student test shows that is not possible to reject the null hypothesis, leading us to conclude that the absolute and relative time improvements are similar for the control and the experimental groups.

Moreover, during the repetitions of the task in the training sessions to both groups, measuring the time to complete the task, it is possible to observe the advance of the learning curve for each subject. In figures 12 and 13, is possible to observe

TABLE II
RESULTS OF THE CONTROL GROUP
Real Environment

Subject	Initial Time (s)	Final Time (s)	Time Delta	Improvement Porcentaje (%)
Subject 1	28,1	16,9	11,2	39,85
Subject 2	27,9	17,8	10,1	36,20
Subject 3	33,8	14,1	19,7	58,28
Subject 4	65,3	30,9	34,4	52,67
Subject 5	22,7	12,3	10,4	45,81
Subject 6	19,7	9,7	10	50,76
Subject 7	40,2	10,4	29,8	74,12

the learning curve of each person, of the experimental groups and of the control group respectively. Is shows how time to complete the task for all subjects tends to converge to a similar value after the training session.

Similarly, during the repetitions of the task in the training
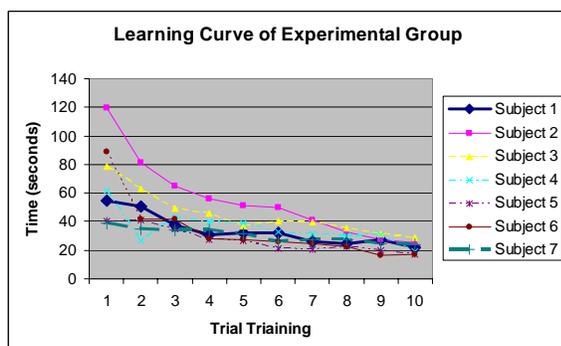
Fig. 12 Learning curve of the experimental group.

sessions of the experimental group we measured the magnitude of the trajectory of the instruments. Fig. 14 shows how the magnitude (total length) of trajectory decreases as the training advances.

After the session, the subjects of the experimental group answered a questionnaire about the virtual environment, physical interface and about their impact in the skill training of the task performed. Several subjects agreed that the use of virtual environment and physical interface were intuitive and the movements of the instruments in the virtual environment and real environment were similar.

VII. CONCLUSION

Based on these results we can conclude that the performance of the experimental and control group are similar, demonstrating the potential of the virtual environment and physical interface to transfer the acquired skills to the real

environment.
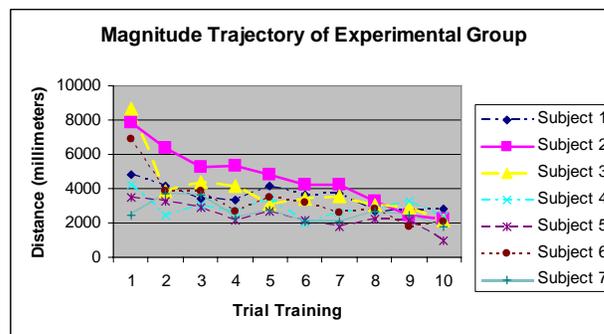
Fig. 14 Magnitude trajectory of the experimental group.

Moreover, the description of the surgical simulation scenario will allow for the evaluation a set of skills with higher complexity as the ones evaluated in the experiments described in this paper.

Following the physical interface and virtual environment developed we propose to add a force feedback to the physical interface in order to allow the surgeon to practice simple tasks On the other side, we will also add more complex tasks to the virtual environment, like cut, suturing and manipulating deformable objects.

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TABLE I
RESULTS OF THE EXPERIMENTAL GROUP
Virtual Environment

Subject	Initial Time (s)	Final Time (s)	Time Delta	Improvement Porcentaje (%)
Subject 1	25,6	16,2	9,4	36,71
Subject 2	23,1	15,3	7,8	33,76
Subject 3	59,1	28,3	30,8	52,11
Subject 4	51,7	34,7	17	32,88
Subject 5	77,9	43,9	34	43,64
Subject 6	95	37,9	57,1	60,10
Subject 7	55,8	21,9	33,9	60,75

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