

**Improvement of Psychomotor Skill Development for Veress Needle Insertion
with Haptics and Virtual Reality**

BY

CHIARA DI VECE

B.S, Politecnico di Milano, Milan, Italy, July 2017

THESIS

Submitted as partial fulfillment of the requirements
for the degree of Master of Science in BioEngineering
in the Graduate College of the
University of Illinois at Chicago, 2019

Chicago, Illinois

Defense Committee:

Cristian Luciano, Chair and Advisor

Craig Niederberger

Elena De Momi, Politecnico di Milano

To my family, for always being my greatest supporters and motivators and for giving me the opportunity to live this wonderful journey.

ACKNOWLEDGMENTS

First, I would like to thank my thesis advisor, Dr. Cristian Luciano, for his constant support even while ill, dedication, and patience during the entire realization of this experience. It has been a privilege to work with him during these months.

I would like to express my sincere and deep gratitude to the UR* Lab for having introduced me to their amazing interdisciplinary group meeting, where different departments and fields are combined giving life to stunning projects.

A special thanks to all my friends here in Chicago for becoming my family throughout these months, sharing so many happy moments that I will forever have in my heart. I feel so lucky to have you in my life. To Giulia and Claudio the best "Sistas" I could have ever asked for; thanks for always being by my side during these months, during happy and sad moments. To my Tipsy Chicago friends for have shared with me the best memories of this adventure.

A deep thank you Marco, for the love and the constant support, for continuing to believe in me even when I did not.

Finally, I would like to thank my family for having made me feel so close to them while being so far from home, for the constant love and support in every day of my life. To my mum, my point of reference, now more than ever. Thanks for all the experiences that you let me do. I owe you everything for that. To my dad, who has always supported me and pushed me to improve myself. To my sister Camilla, whom I love much more than I am able to show her.

CDV

TABLE OF CONTENTS

<u>CHAPTER</u>		<u>PAGE</u>
1	INTRODUCTION AND MOTIVATION	1
1.1	Skill Set	2
1.2	Skill Assessment	2
1.3	Simulation	3
1.3.1	Physical Simulation	3
1.3.2	Computer-based simulation: VRE	4
1.3.2.1	Surgical Simulators and Validation	7
1.3.3	Importance of Haptic Feedback in Simulators	9
1.3.3.1	Haptic devices	10
1.3.3.2	Haptic Feedback in Needle Insertion Training	11
1.4	Thesis Goal	13
1.4.1	High-level Specifications	17
1.5	Outline	18
2	BACKGROUND	19
2.1	Laparoscopic Surgery	19
2.2	Veress Needle Placement	20
2.2.1	History	21
2.2.2	Veress Needle Structure	21
2.2.3	Anatomy of the Abdominal Cavity	22
2.2.4	Site of Veress Needle Entry	23
2.2.5	Veress Needle Placement	23
2.2.6	Indicator of safe Veress needle insertion	29
2.2.7	Physiologic effects of pneumoperitoneum	30
2.2.8	Number of insertion attempts	31
3	RELATED WORKS	32
3.1	Simulators in Minimally Invasive Surgery	33
3.1.1	Simulators for Veress Needle Placement	36
3.2	Simulators in Endourology	37
3.2.1	Disadvantages and Advantages of Current Solutions	38
3.3	Summary	40
4	MATERIALS AND METHODS	41
4.1	3D Models Creation	41
4.2	Software Development	42
4.2.1	LACE Library	43

TABLE OF CONTENTS (continued)

<u>CHAPTER</u>		<u>PAGE</u>
	4.2.2 Hardware components	50
	4.2.3 Data	50
	4.2.4 Processes	51
	4.3 Experimental protocol	52
5	IMPLEMENTATION	53
	5.1 Image Segmentation	53
	5.2 3D Models Post-processing	57
	5.3 Implementation Details	63
	5.4 Software Development	65
	5.4.1 Graphics Rendering	65
	5.4.2 Haptics Rendering	69
	5.4.2.1 Shape-related Haptic Effects	70
	5.4.2.2 Event-related Haptic Effects	71
	5.4.3 Graphical User Interface	74
	5.5 Performance Evaluation	75
6	DISCUSSION	77
7	CONCLUSIONS AND FUTURE WORKS	79
	CITED LITERATURE	81
	APPENDICES	88
	Appendix A	89
	Appendix B	91
	Appendix C	93
	Appendix D	100
	VITA	104

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
I	CLASSIFICATION OF FAILURE CAUSES INTO FIVE DIFFERENT CATEGORIES.	12
II	COMPARISON OF AVAILABLE ALTERNATIVES FOR SURGICAL SIMULATION.	13
III	RESULTS OF THE TUNING OF STIFFNESS AND BREAK FORCE MADE BY TWENTY-TWO EXPERT SURGEONS.	37
IV	3D SYSTEMS® (ROCK HILL, SC, USA) TECHNICAL SPECIFICATIONS.	43
V	FEATURES OF THE EXPERIMENTAL SETUP.	52
VI	INITIAL VALUES OF THE HAPTIC PROPERTIES SET FOR THE 3D MODELS.	71

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
1	Example of a Phantom-based model.	5
2	Examples of a Veress needle insertions.	15
3	Injury proportions resulting from improper placement of the Veress needle.	16
4	Example of Veress needles used in laparoscopic surgery.	22
5	View of abdominal wall musculature.	22
6	Example of umbilicus immobilization.	24
7	Points of needle insertion.	26
8	Veress needle placement through the fascia of the linea alba.	28
9	Most used surgical simulators in laparoscopy.	35
10	Most used surgical simulators in endourology.	39
11	Touch TM 3D Stylus.	42
12	Logic and interaction among the four distinct software/hardware environments in <i>LACE Library</i>	45
13	Organization in four different groups of the classes in <i>LACE Library</i> . .	48
14	Communication in LACE_Object class.	49
15	General workflow of the application.	52
16	Example of automatic and manual segmentation performed with itk-SNAP TM	56
17	3D volume obtained with manual an automatic segmentation in itk-SNAP TM using a separate label for each organ.	56
18	Models obtained for the graphics rendering after the post-processing phase using ZBrush [®] and 3ds Max [®]	59
19	Three different models used for the different phases of the simulation.	60

LIST OF FIGURES (continued)

<u>FIGURE</u>		<u>PAGE</u>
20	Model with separation of rectus abdominis and linea alba from peritoneum.	61
21	Addition of clamps to help the immobilization of the umbilicus.	62
22	Model of the Veress needle created in Autodesk® Fusion 360™.	63
23	Schematic representation of the implementation details.	64
24	Starting scene showing the patient in horizontal position and the touchable buttons.	66
25	Example of rotation and translation of the models within the virtual environment.	67
26	Example of use of the cutting plane and frozen Veress needle.	68
27	Haptic fulcrum point effect.	72

LIST OF ABBREVIATIONS

API	Application Programming Interface
AR	Augmented Reality
AS	Ascension 3D Guidance
CT	Computerized Tomography
DICOM	Digital Imaging and COmmunication in Medicine
DoF	Degrees of freedom
MIS	Minimally Invasive Surgery
OR	Operating Room
QH	QuickHaptics
ROI	Region of Interest
VN	Veress Needle
VL	Visualization Library
VR	Virtual Reality
VRE	Virtual Real Environment
VRE	Wikoby Library

LIST OF ABBREVIATIONS (continued)

2D 2-dimensional

3D 3-dimensional

SUMMARY

Nowadays, cognitive checklists and description of different steps are the main tool used to learn cognitive aspects of surgical procedures in terms of sequence of steps to be taken during the surgery. The link between cognitive functions and physical movement is represented by psychomotor learning, which emerges with physical skills such as movement, coordination, manipulation, strength, speed and actions like the use of precision tools or instruments. However, the previously mentioned tools might be ineffective to help develop the necessary psychomotor skills needed to get familiar with the steps themselves, from a practical point of view. In fact, their main problem is that they do not allow trainees to fully understand and be prepared to the three main aspects of the surgical procedure: first of all the tactile sensation that they will feel in a real surgical operation, secondly the real anatomical response of organs and tissues in terms, for instance, of deformation, and lastly the different nuances of the surgical procedures.

At present, the available simulator machines for the development of psychomotor skills do not fully exploit the haptic feedback, lacking a precise feeling of tissue resistance to instrumentation. In addition, another drawback is the impossibility of simulators to fully emulate real-life situations and another point to take into account is cost constraints. However, a surgical simulator has many pros such as the possibility to give to users a realistic rendering of tissues and deformation characteristics, to capture objective measurements of skill performance, and to have a tactile feedback from the instrument.

SUMMARY (continued)

The ultimate goal of this project is to find an objective way to prove or confute that the hypothesis regarding the shortcomings of cognitive check lists in the context of urological surgical education. This could be done developing a haptic and virtual reality platform exploiting an interactive 3-dimensional manipulation of surgical anatomy from medical imagery; in this way it would be possible to compare training outcomes between current cognitive-only training protocols and combined cognitive and psychomotor training platforms. In particular, the attention will be focused on the first step of laparoscopic procedures: the Veress needle insertion. The insertion of a Veress needle, that allows the surgeon to create the pneumoperitoneum, is never perfectly safe [1], and almost every kind of intra-abdominal organ injury due to these insertions has been reported worldwide, most notably vascular and bowel injuries.

The proposed approach aims at evaluating the use of haptic feedback in the training of skills. By using haptics technology and virtual reality, this surgical simulator could allow the trainees to learn how correctly puncture the abdominal wall at the umbilicus level in the Veress needle placement technique. The trainees are allowed to explore a 3-dimensional virtual human body and experience real tactile sensations through a virtual needle.

The validation of the simulator will be conducted as a continuation of this project, first by finding the optimal haptic training parameters, then by conducting the actual study of skill learning measuring both the execution time and the obtained accuracy. Moreover, some consideration about future developments of this project will be proposed.

CHAPTER 1

INTRODUCTION AND MOTIVATION

When considering surgery, psychomotor skills are difficult to be developed as these technical movements require to be performed in a restricted work space, such as during minimally invasive surgery (MIS) procedures. The traditional surgical training phase has been based on the Halstedian model of "see one, do one, teach one"; this model has been used as the basis for the surgical residency that is still known today [2]. According to it, a trainee should be able to perform the procedure and then to teach to another trainee how to perform it, after the observation of the procedure itself. However, the characteristics of the training environment, such as the resident duty hour restrictions and patient safety concerns regarding the connection among human error and patient mortality, have made this model inadequate. As a consequence, the public scrutiny of trainee participation has increased over the past years. In addition, the advancements in novel technologies, in particular in the urological field, require that also the more expert trainees are in need of acquiring new technical skills [3]. In fact, according to many medical education experts, this method has been considered obsolete [4], [5], [6] since students are not able to conduct the medical procedure after one observation and, as a consequence, they put at risk patient safety. However, even though it has been discovered that seeing an expert that performs a certain procedure, such as through videotapes [7], sets a standard that can be useful to compare the students' performance, studies have pointed out that the actual key to

acquire psychomotor skills is practice [8] so that the trainees can be involved both physically and mentally in the learning process [9], [10], [11].

1.1 Skill Set

When the trainees have to execute laparoscopic procedures, there is a series of ability and skills that they should have. These skills can be grouped in three main categories on the basis of the performance level of the surgeon, depending on his/her instruction level and technical proficiency [12]:

- **Basic skills.** Examples are spatial-visual orientation and ability to explore, perceptive abilities, two-handed movements, hand-eye alignment, skills in relocate objects;
- **Intermediate skills.** Knowledge and proper use of laparoscopic surgical instruments for specific cases and the ability to perform the surgery correctly;
- **Advanced skills.** Ability to perform laparoscopic procedures, as well as skills like manual dexterity and precise control.

1.2 Skill Assessment

Currently, the assessment of students' skills is carried out by experienced surgeons, and this makes the assessment process expensive and subjective. However, the problem of subjectivity and risk connected to human error is reduced with computer-based systems that support the evaluation of the skills. The evaluation of the surgical skills is based on two main concepts: *validity* and *reliability*.

1.3 Simulation

Surgeons have to perform complex technical and cognitive tasks with little or no margin for error that can lead to unpredictable and serious problems. Over the last decade, simulation, in particular, has enabled students to experience a broad spectrum of scenarios and situations with high risk of errors and to speculate on performance without compromising their patient safety, while offering a supervised environment in which severe skill evaluations and feedback help students in developing their clinical skills [13]. In fact, even though clinicians gain most of their competencies in situational events, the use of a simulator can accelerate training, diminishing time associated with learning procedure and thus potentially reducing the risk for patients undergoing the surgery as trainees start operating. In fact, simulation represents a potential solution to the challenge of providing appropriate training in a reduced time [13], [14] and it is considered a useful proxy measure for experts surgical performance [15].

Generally speaking, it is possible to distinguish among two different classes of simulation, that are physical simulation and computer-bases simulation; the latter is also known as virtual reality environments (VREs).

1.3.1 Physical Simulation

In the context of physical simulation, cadavers or animal models are used in wet and dry laboratories. In particular, the first ones are mainly fresh-frozen and Thiel embalmed cadavers and they are referred to as the gold standard. They allow for a high fidelity both in terms of anatomy and tissues even though the technology advancements give a detailed rendering of human anatomy. The Thiel embalmed cadavers present many pros, such as the retention

of flexibility and permeability of fresh tissues, long-term stability, minimal toxicity and low infectious risk [16]. Of course, there are also problems connected to the use of cadavers, such as the high cost, the limited availability and space requirements as well as the variability between them; in fact, even though this aspect could be considered positive for teaching, it has to be said that it causes a lack of "standardization" between the subjects. When considering animal models, they are used for surgeons' training in urological MISs, including laparoscopy and endourology approaches. The main advantages of using animal models are the possibility to perform full procedures with high tissue and physiological fidelity, moderate affective and anatomic fidelity. However, the cons are related to the significant facility and personnel costs that are required to support live animal labs as well as inherent ethical concerns. Another type of physical simulation is represented by phantom-based models shown in Figure 1 that allow trainees to practice with realistic-pulsatile-bleeding tissues; moreover they are able to teach them how to behave when stressful and emergency situations occur [17]. The main problem related to them is that they can be considered to as static, i.e., they are not able to change according to the advancements in users' performance or ability [18].

1.3.2 Computer-based simulation: VRE

Virtual reality (VR) is defined as "a realistic and immersive simulation of a 3-dimensional (3D) environment, created using interactive software and hardware, and experienced or controlled by movement of the body" [19] or as "an artificial environment which is experienced through sensory stimuli (as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment" [20]. David Gaba is considered



Figure 1: Example of a Phantom-based model.

the pioneer of medical simulation; he has divided the simulation into five different categories [21]:

- **Verbal simulation.** Trainees can become aware of their role in a variety of real-life and intra-operational situations by playing a role-playing game;
- **Standardized patients.** These pre-formed actors have actually the aim of helping the trainees to develop their communication skills, as well as to carry out an exhaustive physical examination;
- **Pre-task trainers.** These constitute a modeling of the anatomy in normal conditions or in case of pathological disease processes;
- **Computer patients.** The doctor-patient interaction is trained with patients created in a virtual way;

- **Electronic patients.** The aim of this kind of simulation is to improve the teamwork development.

The currently used and more sophisticated VR simulators are based on these levels.

The VR simulators represent a pre-operative exercise that exploits 3D computed tomography scans of the patient who will undergo surgery [22], allowing for the overcoming of some limitations characterizing the physical simulation. The main advantages are the possibility to provide trainees both with different scenarios in terms of complexity and real time feedback; moreover they allow for the measurements of trainees' performances [22], [23], [24]. Computer-based, VR platforms offer the possibility to overcome limitations due to learning-by-opportunity and reproduction of human anatomy. The flexibility of the VR simulator and its development could easily lead to patient-focused surgery preparation, targeted to a preliminary evaluation of possible drawbacks during the operation. Additionally, thanks to the advancements in computer and graphic technology, today VR is able to render realistic tissue appearances and deformation characteristics, as well as to provide tactile instrument feedback. However, the efficiency of computer-based training has not been fully demonstrated yet since both the implementation of the procedures and the fidelity of the scene represent open problems that are complex to be solved [23], [24]. In addition to that, the use of whether VR or augmented reality (AR) systems in the context of MIS, implies a significant decrease in surgeon' direct interaction with the tissue with respect to open surgery; nevertheless, the limited residual haptic input from the instrument is still indispensable. In the past few years, a number of training systems has been proposed: VR simulators can help the residents to train on simple (basic psychomotor skills)

or complex (skills on entire procedure) tasks in order to let them fully understand the needed gestures and practice them [17].

1.3.2.1 Surgical Simulators and Validation

The lives of real people are often at risk when considering the medical sphere and, therefore, the training of a person could be well complemented by the use of simulators [25]. In particular, surgical simulators allows the trainees to practice outside of the operating room (OR) ensuring patient safety and to overcome the drawbacks of the traditional surgical teaching; moreover, they have the potential to both develop new skills and maintain the already acquired ones [26]. Another advantage is the opportunity to have a very detailed feedback and measurement of a trainees performance [27]. Four main parameters are used to evaluate simulators that train and assess urological skills: fidelity, validity, reliability and cost.

Fidelity

Fidelity refers to the likeness to an intended construct; it includes four main types of fidelity:

- **Anatomic fidelity** refers to how well the simulator is able to replicate the human body in terms of organs, supportive structures and tissue planes;
- **Physiological fidelity** describes the realism and the complexity of the model representing the physiological state or process;
- **Tissue fidelity** is how close the model materials are to the physical properties of the actual human tissue [28];
- **Affective fidelity** relates the elicited emotional engagement and response of the trainee [29].

Validity

Validity is defined as “the degree to which evidence and theory support the interpretation of simulator data/scores for measuring a certain construct”, where a construct is “the concepts or characteristics that a simulator is designed to measure” [3].

According to the new 2014 guidelines the main categories of evidence that can be aggregated for the simulator validity are the following:

- **Response process evidence (prior Face validity).** This is a subjective collected metric that ensures subject evaluators agree on how the construct is defined and how they are being evaluated;
- **Content evidence (prior Content validity).** It describes how appropriate the learning objectives, instructions, questions are to the construct being examined;
- **Relations with other variables (prior Criterion validity).** It is a statistically measurable category of evidence that compares scores obtained on the tested simulator on existing or previously validated models; the results of the test should allow for a distinction among an expert and a novice surgeon;
- **Internal structure evidence (prior Concurrent validity).** It relates to the reliability and appropriateness of items, factors and scores used with the intended construct; so, by comparing the results of the test for a certain skill, they should be equivalent to the ones obtained with other similar tests;

- **Consequences evidence (prior Predictive validity).** It take into account the impact of the simulator assessments on the learner or on society, whether intended, unintended, positive or negative [30]. So, this category of evidence ensures similar surgeon's performance when considering the test and the real environment.

Reliability

Reliability refers to the preciseness or reproducibility of simulator effects. It is considered part of the "internal structure" aspects that contribute to a defined construct. This parameter is expressed with an r-value correlation coefficient included between 0 and 1. A reliability ≥ 0.8 is considered reasonable. Reliability of simulators effects on subjects can be expressed as a test-retest reliability, whereas reliability of observers can be express as either intra-observer or inter-observer reliability [30].

Cost

This aspect always represents a focal point when choosing a training model. It should include the cost of the time requirement for trainers to be physically present for certain components of the training curriculum and to complete assessments.

1.3.3 Importance of Haptic Feedback in Simulators

Touch is considered as the most proficient among all the human senses because of its unique ability of simultaneous perception of inputs and outputs [31]. In fact, when considering medical procedures, the sensation of touch is one of the most important physical sense; it can be related to the direct tissues manipulation of to the handle of a surgical instrument. Hence,

the combination of VR and haptic technology could be fundamental for the trainees; in fact, it could have a key role in the development of psychomotor skills needed for the first step of laparoscopic procedures by using a virtual Veress needle (VN) and allowing for the interactions with different parts of the 3D virtual human body. In the recent years, haptic devices have been applied to medical simulators becoming a valid alternative for training. The main reason for that is their possibility to convey the sense of touch to the trainee in a VRE. Thanks to this combined use of VR and haptics, a significant increase of realism in simulation procedures has been obtained and, as a consequence, there has been an increase also in the quality of training when making a comparison to the standard learning environments of medical schools.

1.3.3.1 Haptic devices

Haptic devices are electro-mechanical instruments that are able to provide add tactile feedback within VREs; this can be done with different degrees of freedom (DoF) according to the allowed users' movements in the space; at this moment, haptics-based simulators include haptic devices with three or six degrees of freedom. In general, there are two different ways to control the interaction between the virtual scene and the haptic devices, that are admittance or impedance control. Taking into account the first one, the force applied by the user to the haptic device is translated into a relative distance that is then used to compute the proportional force feedback. Their complexity is translated into an enlargement of the device itself, which prevent them to be widely spread in the medical simulation field. In case of the impedance control, the movements imposed to the haptic device are coded and transmitted to the computer; the generation and monitor of the feedbacks is up to the application itself. This kind of apparatuses

are smaller and easy to connect and integrate into a work station, such as Phantom Geomagic [32]. Moreover, the training simulators for the insertion of the virtual needle have proven the efficacy of commercial haptic devices [33].

1.3.3.2 Haptic Feedback in Needle Insertion Training

In particular, needle insertion is considered as the most basic skill in medical care; the haptic feedback is the main stimulus that novices have to be trained in, as it plays a major role in the current practices of healthcare such as needle biopsies, laparoscopy with Veress needle placement, local anesthesia, injections, angiography, endoscopy, brachytherapy cancer treatment, spine and neurosurgery. All these procedure have three parameters to be determined in common: point of insertion, needle orientation, and movement within the soft tissues [34].

The haptics-based trainings represent a valid alternative to the traditional cadavers, porcine, bovine samples or anesthetized animals since they partially avoid the difference among cadavers' tissues and live patients' ones. A recent study has shown that even the well-trained physicians can have high failure rate when performing needle procedures [12]: the results of the survey on Acute Pains performed at the University of Washington Medical Center regarding the failure rates of thoracic needle procedures (32%) and lumbar epidural anesthesia procedures (27%) are shown in Table I along with the classification in different categories of these failure rates.

For these reasons medical simulations are spreading more and more, allowing for trainings that ensure patients' safety and a great variability of scenarios as it is possible to easily change tissues properties. When considering procedures involving needle insertion, visual and haptic feedback are relied upon by physicians. The former, in particular, allows the surgeon to

TABLE I: CLASSIFICATION OF FAILURE CAUSES INTO FIVE DIFFERENT CATEGORIES.

	Failure Rate [%]
Dislodged catheter	17
Not in epidural space	11
One-sided block	7
Develop a leak	7
Uncertain cause	58

determine the position of the tip of the needle and is obtained by the segment of the needle that remains external to the body. On the other hand, since the insertion forces are different according to the type of tissue that the needle penetrates through and the depth of this penetration, the haptic feedback results of great importance. In particular, the needle location and the detection of underneath structures is possible by detecting the changes in the tissue properties at various depths. However, the needle location inside the body can be predicted only through in-vivo experiments; this represents a huge challenge for the novice and it is the main reason behind the substantial increased need for training including force feedback. In fact, the tactile feedback is considered a fundamental factor when developing needle simulators [34] and in particular simulators for VN placement.

Table II, Appendix B, summarizes the advantages and disadvantages of the previously mentioned alternatives for surgical simulation.

TABLE II: COMPARISON OF AVAILABLE ALTERNATIVES FOR SURGICAL SIMULATION. Table adopted from [4]. The permission to reprint this copyrighted material is in Appendix B.

Category	Example	Advantages	Disadvantages	Cost	Uses
<i>Low fidelity</i>	Peg boards, synthetic suturing mats	Widely available, reusable, may use actual instruments	No procedural training	+	Basic task training for novices
<i>High fidelity</i>					
Biological	Live animals, dissected animal tissues, human cadavers	Whole procedure simulation, dynamic anatomy in live animals, realistic haptics	Anatomical differences (animals), poor tissue compliance (human cadaver), ethical considerations, not reusable	++	Whole procedural training (i.e. laparoscopic nephrectomy /cystectomy)
Nonbiological	High fidelity bench models	Reusable, allow use of actual instruments	Not proven to be more effective than low fidelity models for basic skills training, less realistic tissue haptics than biological models	++	Basic skills training, procedural training (especially endourological procedures)
Virtual reality	LapSim, Per Mentor, etc.	Reusable, instant performance feedback, may simulate basic tasks or whole procedures	Maintenance, costly, unreliable haptics	+++	Basic skills or procedural training, simulators available for endourological, laparoscopic and percutaneous renal procedures

1.4 Thesis Goal

It is traditional for surgical skills to be acquired through a long-term training with with expert surgeons; the main problem is that this method implies a very long learning curves. Nevertheless, in the present financial situation in the major part of the countries, it is becoming more and more difficult for institutions to have the possibility to invest time, effort and money in these long trainings. Moreover, in the present world, since responsibilities and performance are of such importance, simulators could represent the key to progress.

Patients are no more regarded as simple "training objects" and, as explained in previous sections, the Halsted's learning model of "seeing one, doing one, teaching one" is no more appropriate. In fact, each situation is quite unique and a surgeon may only have one shot at being successful at the given time. During the very early years of their surgical careers, simulators would shorten the learning curve by allowing for repetition and revision; in this way the trainee would be able to cope better and with less stress the intra-operative situations of real life. The main positive aspects of this training is the good, gradual control allowed and a great margin for adaptation according to the needs of the individual trainee. In addition, the training carried out through simulators reduces operating time and the possibility of complications in a significant way. Urology is best suited to take advantage of simulation technology among of all surgical subjects, as most surgeries are laparoscopic and endourological for which the perfecting of competences requires a great number of hours spent in specialized formation resulting in a quite steep learning curve [4].

For the aforementioned reasons, the aim of this work is to analyze and try assessing the possible benefits of a haptic and VR platform exploiting an interactive 3D manipulation of surgical anatomy from medical imagery, that would allow for the comparison of training outcomes between current cognitive-only training protocols and combined cognitive and psychomotor training platforms. A VRE is easily modifiable and it is not affected by degradation, delivering a durable device. In fact, tasks in VR simulators can be indeterminately repeated, with settings of increasing difficulty.

After literature review and analysis of the State of the Art, it has been identified the need for an easily accessible, anatomically precise training model for the urologists desiring to improve skills development in a particular step of Laparoscopic procedures: the VN insertion; this step allows the subject to create the pneumoperitoneum, that is an abnormal presence of air or other gas in the peritoneal cavity, a potential space within the abdominal cavity.

The VN placement could result in risk of complications like injuries to bower, arteries and veins and extra-peritoneal emphysema caused by an improper needle placement as shown in Figure 2, Appendix C; for this reason, even though the VN insertion has many advantages over the now less popular open techniques, the blind insertion of the VN makes this procedure risky for non-trained surgeons.



Figure 2: Examples of a Veress needle insertions. Image adopted from [35]. The permission to reprint this copyrighted material is in Appendix C.

However, the VN insertion could be accurately simulated by the haptic technology, providing trainees with accurate anatomical orientation and step-by-step tactile feedback ideal for the puncture skills acquisition.

A study has demonstrated that the mortality rate resulting from the previously mentioned injuries is in the range between 8% and 17%. [36]. In particular, analyzing data coming from 696,502 laparoscopic procedures carried out with the use of a VN, 1575 lesions (0.23%) have been caused. Among these, 126 (8%) were related to hollow viscera and blood vessels; among these 126 cases, 25 are regarded as major injuries. More detailed injury proportions resulting from improper placement of the VN [37] in the considered 696,502 laparoscopic procedures are shown in Figure 3.

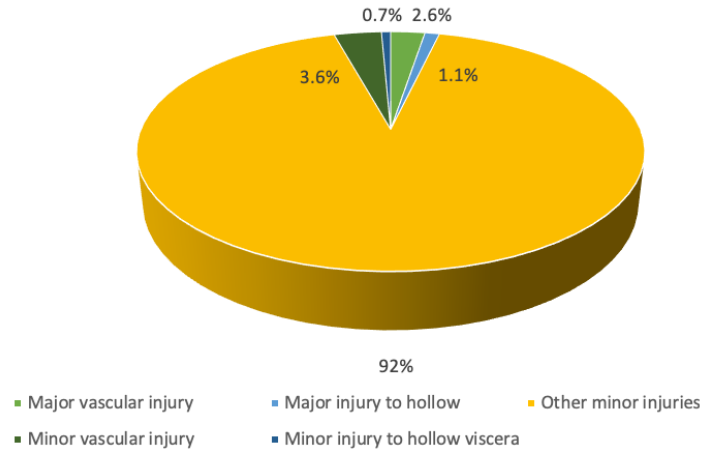


Figure 3: Injury proportions resulting from improper placement of the Veress needle.

1.4.1 High-level Specifications

The aim of the realized simulator is to meet all the disadvantages of current training models; for this reason it should ensure the following specifications in order to be attractive and address the physicians' needs:

- **Anatomical accuracy.** It should present an acceptable graphics rendering of tissue characteristics to users in order to be as close as possible to the physical simulators in terms of realism. Fidelity of the human anatomy could be preserved as the models of organs and tissues are extracted from a real patients volumetric dataset;
- **Realistic and real time haptic feedback.** The haptic feedback is extremely important in order to give the proper tactile sensation to trainees while performing the procedure;
- **Intuitive use for trainees.** It should allow for an easy skill improvement;
- **Accurate measurements of training outcomes.** This aspect is fundamental in order to objectively measure and compare the outcomes between current cognitive-only training protocols and combined cognitive and psychomotor training platforms;
- **Reproducible results;**
- **Non-invasiveness.** This feature allows the user to perform the training in a risk-free environment, outside the ORs;
- **Commercial viability and relevancy.** This tool should be economically accessible for medical schools and convey the visual and the tactile stimuli of a real operation to the

trainees, enhancing the realism and accuracy of the training environment and shortening the learning curve of the procedure. Aiming at the cost containment of the overall simulator, in the development of the platform a bunch of pre-existing software could be comprised, to obtain good performances in term of haptics and graphics rendering. The application could run on a standard computer, so that the only additional component needed could be a 3-DOF haptic device, which is now commercially available at a reasonable price.

1.5 Outline

Going next, Chapter 2 will give some useful knowledge to the reader about the case study and techniques used for the Veress Needle Insertion; Chapter 3 will discuss the State of the Art of the current simulators; continuing in Chapter 4, the details about the choices made for the simulator realization will be presented; then Chapter 5 will depict the details of the single stages of the creation of the models and of the application; Chapter 6, then, will present a discussion of the obtained results. Finally, Chapter 7 will draw the conclusions and possible future works starting from the achieved results.

CHAPTER 2

BACKGROUND

This Chapter presents to the reader some theoretical pillars in order to facilitate the understanding of the faced problems and the proposed solutions.

2.1 Laparoscopic Surgery

Laparoscopic surgery has experienced a tremendous expansion since the mid-1980s, when a merge between the laparoscope and the video camera took place. Since then, laparoscopic equipment and instruments have been refined along with surgical capabilities, allowing surgeons to perform a variety of laparoscopic procedures safely. This type of surgery is technically demanding and, in general, requires well-trained surgical teams; the latter is the key element that could allow to have a safe, efficient operations and not long, difficult ones that increase the risk of complications in both pre- and post-operative phases [38].

The general strengths of laparoscopy compared to the open techniques are [39]:

- Use of tiny incisions;
- Reduction of pain to the minimum possible;
- Attenuation of stress response;
- Earlier return to ambulation;
- Reduction in hospital stay;
- Reduction of postoperative pain;

- Reduction in the recovery time;
- Reduction in postoperative complications, e.g., wound infection, incisional hernia.

Before any laparoscopic procedure can be initiated, the pneumoperitoneum must be established by entering the peritoneal cavity and positioning the ports for the laparoscope and various laparoscopic instruments. Access to the abdomen is the cause of unique complications. In particular, potential life-threatening complications, such as involuntary bowel lesions or severe vascular lesions, may arise during this initial access [40], [41], [42], [43], [44].

Altogether, there are three different general approaches to laparoscopic access; however, the attention will be focused on the earliest and most traditional: the Veress needle technique.

2.2 Veress Needle Placement

The VN technique is defined as a closed method; during this procedure the abdominal wall is punctured by the means of a VN. Once the special needle is in the correct position, it is possible to insufflate the abdomen. After this step, the tracer/port is positioned in place of the previously inserted VN. This is considered one of the most arduous step during the laparoscopy. In fact, since the haptic feedback is relied upon by surgeons when inserting the VN through the different layers of the abdominal wall, this technique becomes difficult to teach. For novice trainees in particular can be challenging to acquire the knowledge of this delicate phase of laparoscopy without having the opportunity to practice in an environment that does not present a risk of injury to patients.

2.2.1 History

This tool was originally developed in 1932 in Hungary by an internist, Janos Veress, who was working with tuberculosis patients. It was used to create iatrogenic pneumothorax in patients with tuberculosis, without damaging the underlying pulmonary hooligan. Nevertheless, it became widely known starting from 1938, when the invention was first published in German literature. One of the pillars of this early version of the technique was to collapse an infected lung and allow the lesions to heal [19].

2.2.2 Veress Needle Structure

The VN is a special needle used to create a pneumoperitoneum that perforates the layers of the abdominal wall. It is equipped with a protective spring loaded shutter that rewinds to recover the end of the needle, allowing it to enter a body cavity without overwhelming the underneath organs. Currently, the needles have an outer diameter of 2 mm and are 12 to 15 mm long. The outer cannula is made up of a beveled tip to cut abdominal wall tissue and an inner spring loaded stylet positioned inside the outer cannula. This thinner stylet has a dull tip to prevent any viscera from being injured by the pointed outer cannula. The direct pressure of the tip, as when it penetrates the tissue, pushes the opaque stylet into the stem of the outer cannula. An example of VN is shown in Figure 4.

There are now available single-use and re-usable (non-disposable) Veress needles. The first is a single piece of plastic 70 or 120 mm long, 14 gauge and 2 mm diameter; the second is made of metal and can be disassembled.

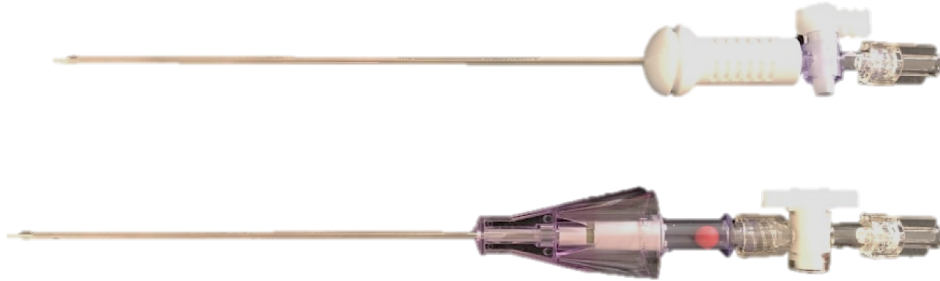


Figure 4: Example of Veress needles used in laparoscopic surgery.

2.2.3 Anatomy of the Abdominal Cavity

Knowing the anatomy of the abdominal wall, shown in Figure 5, is essential for the safe placement of laparoscopic access devices. In fact, these devices pass through the skin, subcutaneous fat, variable myofascial layers, preperitoneal fat and parietal peritoneum.

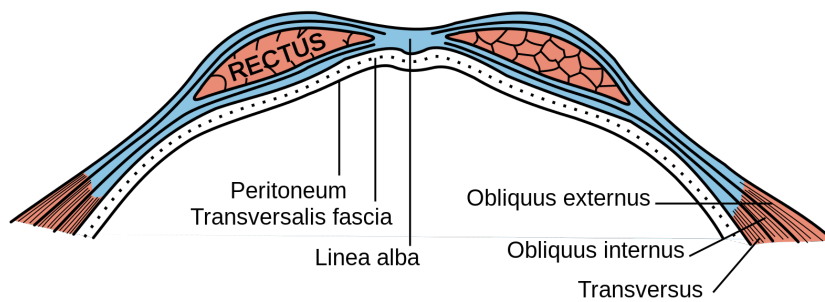


Figure 5: View of abdominal wall musculature.

2.2.4 Site of Veress Needle Entry

The initial entry for abdominal insufflation is most frequently carried out at the umbilicus. The umbilicus is a fusion of fascial layers and is free of subcutaneous fat; it is favored for its central position and its ability to hide the scar. The mid-line abdominal wall has no important vessels or nerves and is the preferred initial access site. The layers include the skin, subcutaneous fat and a fascial layer, also known as the linea alba. Particularly, the upper or lower crease of the umbilicus are used in non-obese patients, whereas in other cases the access to transumbilicus is preferred; the first one is the case of obese patients and the second is when the laparoscopic procedures for diagnosis purposes are carried out during local anesthesia. Alternative sites include the lateral edge of the rectus muscle 3 cm below the left costal margin, i.e., Palmer's point, and the lateral edge of the rectus muscle at the level of the iliac crest. Along the medial costal margin, the layers of the abdominal wall comprise the skin, subcutaneous fat, anterior rectal fascia, rectal muscle, posterior rectal fascia, transverse fascia, transverse abdominal muscle, pre-peritoneal fat and parietal peritoneum [45].

2.2.5 Veress Needle Placement

As previously mentioned, the peritoneal cavity must be reached before any laparoscopic procedure can be initiated; the first aim of this step is the establishment of the pneumoperitoneum and the second one is to then position the laparoscope and add the placement of additional ports for various laparoscopic instruments. In general, initial access is preferred in sites that have not been previously instrumented.

Stabilization of umbilicus

The first step is the stabilization of the umbilicus by means of two forceps, followed by the making of an smiling incision on the lower crease of the umbilicus. However, there are various ways to stabilize the umbilicus and provide needle resistance. As shown in Figure 6, Appendix D, pinching the upper margin of the umbilicus with the thumb and the forefinger of the non-dominant hand represents another way to immobilize the lower crease of the umbilicus; this upper margin must then be rolled in the cephalic direction.

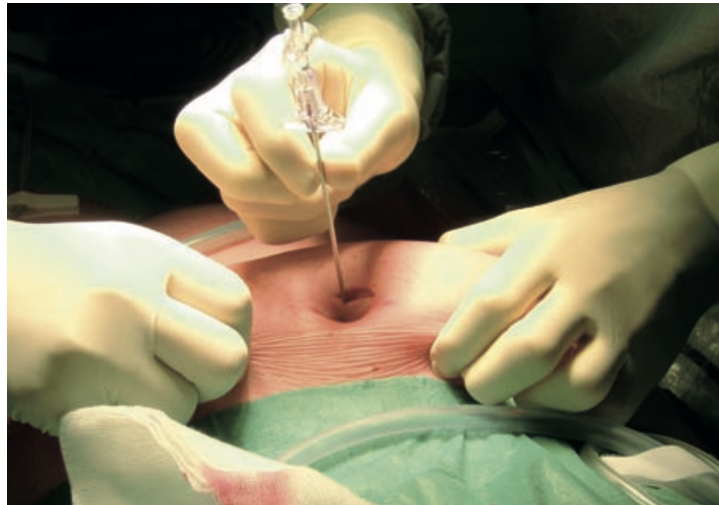


Figure 6: Example of umbilicus immobilization. Image adopted from [46]. The permission to reprint this copyrighted material is in Appendix D.

In case of anesthetized patients, the upper crease of the umbilicus can be secured by applying one small clip on both sides; this method allows the surgeons to lift upwards the the lower margin.

Many surgeons have used the forceps to lift the abdominal wall for years. The Johns Hopkins University first supported this technique for abdominal wall lifting; then it became clear that in this way the increase of the distance between the skin and the underlying tissues was bigger than the one between the abdominal wall and the viscera. In fact, it is necessary to hold the abdominal wall by means of four fingers, hypothenar and thenar.

Incision

As stated before, the VN is more frequently inserted into the umbilicus because there is no fat or muscle in between the skin and the peritoneum. Considering that the distance between the base of the umbilical stem and the aorta is generally less than 4 cm and only 2 cm in thin individuals, a vertical or horizontal cutaneous incision of 1 cm is made; the umbilicus represents a point of minimum distance between the skin and the peritoneum but also between the peritoneum and all the other sites of the abdominal wall [47]. The patient should be placed supine, upside down 10-20 degrees. If there are no scars on the abdomen, the entry side can be either the upper or lower edge of the umbilical ring, as shown in Figure 7.

Positioning of the Veress Needle

At the beginning, a 5-mm incision of skin and subcutaneous tissues should be given with blade no. 11 in order to estimate the length of the VN needed to reach the peritoneal cavity. The needle is subsequently positioned through the incision to the level of the fascia, the depth

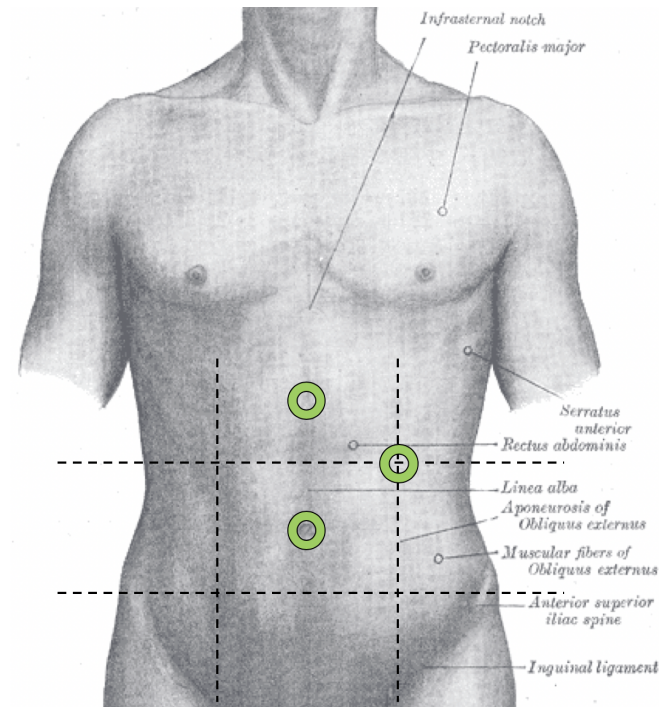


Figure 7: Points of needle insertion.

of the needle is marked and then it is removed. This stab incision is made in the midline of the upper or lower umbilical margin. Evidently, if the incision is made at the level of the umbilicus just the skin will be incised since no fat is present in that point of the abdomen. The skin and the fascia are grasped manually or with a Kocher clamp in order to elevate the abdominal wall. Using the dominant hand, the shaft of the VN is held like a dart and the needle is delicately passed through the incision with an elevation angle of 45 degrees (mildly obese subjects) or orthogonal to the abdomen (90-degree angle) in the severely obese patient. The elevation angle is the caudal angle between the instrument and the abdominal wall. Note that to achieve a

45-degree elevation angle, the tip of the Veress needle should be pointing at the anus. Surgeons should pay attention to insert the VN away from fixed viscera and so that it cannot deviate laterally.

It is necessary to prevent the creation of pre-peritoneal slip of the VN tip and this must be done by perpendicularly placing the VN to the abdominal wall. The main problem is that in this way there may be a permanent fear of injury of great vessels or bowel. For the sake of avoiding both situations, the inferior portion of the abdominal wall must be raised so that it creates a 90-degree angle with the VN, but the latter must be pointed towards anus at an angle of 45 degree in relation to the body of patient. Additionally, the abdominal wall lifting should aim be adjusted so that the distance of abdominal wall elevation phase should aim at increasing the distance between the first and the underlying viscera. In summary, it is fundamental that the elevation of the abdominal wall ensures that the VN and the abdominal wall create a 90-degree caudal angle, whereas the one formed by the first and the patient's body is 45 degrees. Once the abdominal wall has been lifted, the fascia

As shown in Figure 8, the blunt tip recoils exposing its sharp edge as it encounters the fascia of the linea alba. As the sharp edge of the needle crosses the fascia, the blunt tip springs forward into the preperitoneal space. With the needle tip entering a space such as the peritoneal cavity, the opaque inner stylet lifts forward so that the blunt tip is used to prevent damage to the abdominal structures.

When the needle is introduced, the crucial step is the sensation of two distinct "pops": they signal that the tip is passing through the layers of the abdominal wall, made up of the external

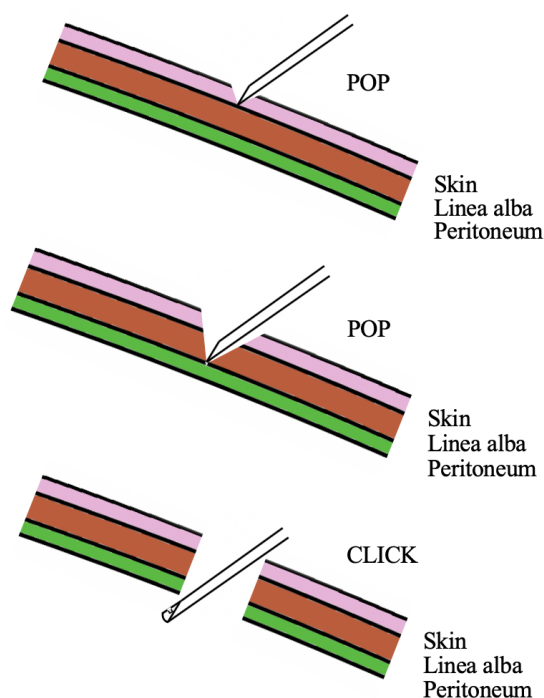


Figure 8: Veress needle placement through the fascia of the linea alba.

oblique/rectus fascia and then by the transversalis fascia and parietal peritoneum [38]. Since at the level of the umbilicus the anterior and the posterior rectus constitute a single piece, known as linea alba, the surgeon will feel only one click when traversing the rectus. As the needle enters the peritoneal space, the shifted hub of the needle will "click" when the protective sheath recoils to cover the extremity of the needle. An intra-abdominal wall also moves more freely than a needle within the abdominal wall. In these passages before feeling a give, there will be an initial sensation of resistance from the tissues.

2.2.6 Indicator of safe Veress needle insertion

There are mainly four methods to confirm the VN placement:

1. **Needle movement.** As soon as the VN is inside the abdominal cavity, the VN tip is free and when the surgeon gently moves it, he should not feel any resistance. It has to be remembered that it is necessary to not move away through the abdominal cavity the VN, as this may result in laceration of the bowel if punctured.
2. **Saline aspiration and injection.** The hub of the VN is connected to a 10-mL syringe containing 4 mL of normal saline; the surgeon should be able to inject at least 5 mL through the VN so that the syringe is used for aspiration. If no content is returned, the tip is assumed to be in an intraperitoneal position, whereas if either blood or enteric content is returned to the suction of the syringe, an involuntary vascular or visceral injury may have occurred. In this circumstance, it is essential to have the needle kept in place and to obtain abdominal access to a site to evaluate the original site for potential injuries and the initial access needle should only be removed under direct viewing. In more general terms, if the saline is injected freely without resistance, an intraperitoneal position of the tip is assumed, whereas if there is high pressure to resistance, the needle is generally still within one of the layers of the abdominal wall.
3. **Hanging drop method.** A drop of saline is injected into the VN open hub and the abdominal wall is lifted; an intra-abdominal position is suggested for the needle if the drop of water is aspirated into the needle due to the negative intra-abdominal pressure generated.

4. **Measurement of intra-peritoneal pressure.** The pressure is determined by connecting the VN to the laparoscopic insufflator. Correct positioning is recommended for intra-abdominal pressure ≤ 10 mmHg.

Once an intra-abdominal needle location is confirmed, the gas insufflation is triggered by typically using carbon dioxide (CO₂) gas.

2.2.7 Physiologic effects of pneumoperitoneum

The abdomen is usually insufflated by means of the CO₂ gas; the circulatory system quickly absorbs it through the peritoneal membrane allowing for the production of carbonic acid in the blood which, in turns, leads to the respiratory acidosis. When considering long laparoscopic procedures, body buffers absorb part of the CO₂ and become saturated so that the lungs are the new ones responsible for the absorption and the release of the gas from body buffers.

Some effects on the different organ systems are associated with the pneumoperitoneum pressure such as:

- Increase pressure in the abdomen;
- Decrease in heart rate and stroke volume;
- Decreased venous-femoral blood flow and venous return;
- Reduction of kidney perfusion and intra-operative urinary flow;
- Decrease in the respiratory compliance and increase in the pressure in the airways;
- Increase in the intra-cranial pressure.

2.2.8 Number of insertion attempts

According to some studies such as [22], the associated complications could be extra-peritoneal insufflation, omental and bowel injuries and failed laparoscopy. Moreover, the complication rates associated to the insertion of the VN into the peritoneal cavity are 0.8-16.3% on the first attempt, 16.31-37.5% in case of two attempts, 44.4-64% for three attempts and 84.6-100% when the attempts are more than three.

It is necessary that the surgeons are well-trained and experienced in performing laparoscopic procedures prior to carry out any procedure independently, including familiarity with the equipment and instruments.

CHAPTER 3

RELATED WORKS

As described in the previous chapters, the application of the haptic feedback is used in several surgical simulators. Its use has given encouraging results, even though there is not an unanimity on how much it could be really effective; it could be particularly necessary when an understanding of tissue consistency is required.

Some examples of medical practices that can be trained with haptic-based application are:

- **Stitching procedures** in which the haptic feedback is required in order to have a simulation of surgeon's hand torsion when piercing the dermis layer;
- **Palpation**, a procedure in which the physician has to digitally analyze the tissues or the organs in order to detect irregularities in their surface and in particular to individuate tumor masses linked with areas of higher stiffness;
- **Dental procedures** such as calculus and caries removal;
- **Endoscopy and laparoscopic procedures**, performed with both hands; for this reason, their simulation requires the use of two separated haptic devices in order to provide trainees with simulation for endoscopy navigation and video laparoscopic surgery;
- **Orthopedics** in which a key role is given to interaction with bones; for this reason, drilling and realistic force feedback are of main focus;

- **Biopsies** that consists in cell analysis and detection of pathologies such as cancerous regions or inflammation by sampling human tissues with a needle.

Several biomedical companies have developed different training systems based on haptic and VR: they can give the residents access to various simple (basic psychomotor skills) or complex (whole procedure skills) tasks using an off-site location available at any time, thus helping them to fully understand the necessary gestures and put them into practice [48].

This Chapter presents a review of the State of the Art of the most used surgical simulators use haptic feedback to improve psychomotor skills. The attention will be focused on the ones related to the field of urological surgical education.

Currently, different urological simulators, shown in Figure 9 and Figure 10, are commercially available. As explained in the following sections they can be divided in surgical simulators for MIS and for endourology.

3.1 Simulators in Minimally Invasive Surgery

Among the surgical simulators developed for laparoscopic procedures, one of the most relevant is the LapSim[®] developed by Surgical Since, Inc. (Sweden) [49] and shown in Figure 9a. This workstation can simulate several laparoscopic procedures such as suturing and clipping, as well as grasping organ and tissues; it uses an integration of real-time tactile feedback and visualization of the laparoscopic monitor.

Another similar example is provided by LAP MentorTM, released by Simbionix (USA) [50] and shown in Figure 9b. Also this workstation has integrated instruments capable of provid-

ing haptic feedback but just for basic laparoscopic skills modules (suturing, cutting and peg transfer); in fact, only nephrectomy modules are available. Moreover, both of them are able to provide performance feedback and trainees' evaluation with the addition of a quantitative assessment of the capabilities and improvements training after training.

The da Vinci[®] Skills Simulator (dVSS), developed by Intuitive Surgical (USA) [51] for the training of basic robotic skills is shown in Figure 9c. It is presented as a "backpack" on the actual da Vinci surgeon console. The possibility of training on the actual da Vinci hand controls and console is the key advantage of this workstation; however, the main disadvantage is that it is available for training just when the console is not in use. Moreover, this system is powered by the MSim[®], the softwares present on the dV-Trainer[®] engineered by Mimic Simulation (USA) [52] and regarded as the most studied robotic simulator for basic robotic skills like peg transfer, clutch, suturing tasks and camera.

The last example is RoSSTM (Robotic Surgical Simulator), a workstation provided by Simulated Surgical Systems (USA) [53], shown in Figure 9d; this is a standalone surgeon console pretty similar to the da Vinci one since it trains the trainees on similar robotic skills and surgical training modules that are full procedural simulations such as radical cystectomy, prostatectomy and lymph node dissection.



(a) LapSim® by Surgical Science. Image adopted from [49].



(b) LAP Mentor® by Simbionix. Image adopted from [50].



(c) daVinci Skills Simulator (dVSS) by Intuitive Surgical (USA). Image adopted from [51].



(d) RoSS™ (Robotic Surgical Simulator) by Simulated Surgical Systems (USA). Image adopted from [53].

Figure 9: Most used surgical simulators in laparoscopy.

3.1.1 Simulators for Veress Needle Placement

Veress needle placement is considered one of the most arduous step in laparoscopic procedures since an error in the insertion could be cause of significant damages to the patients. In fact, it has been estimated that one half of all complications in laparoscopic surgery can be attributed to this first step [54], [55].

A simulator with haptic feedback for the training of VN placement could be really useful; in fact, this step is particularly difficult to be taught since it is performed only once at the start of the procedure and requires a strong on tactile feeling as the VN passes across the abdominal wall layers. At present, the only available example is a haptic and VR simulator prototype for the VN placement developed by an engineering team from Quanser Consulting Inc. (Toronto, ON) in collaboration with the University Health Network (Toronto, ON) [56]. This prototype incorporates mechanical tissue parameter and it gives back to the trainee the forces computed through the haptic feedback; the latter help the user to feel the different layers of the abdominal wall. In particular, the mechanical parameters can be tuned by the user. Additionally, the prototype allows for two different kind of trainings: blind access to the abdomen or access seeing a cross-section of the layer. The former can be used for testing and practice purposes whereas the latter is more suitable for training and teaching purposes. The haptic parameters were tuned by twenty-two experienced surgeons who were in charge of adjust stiffness and break force through graphic slider bars for both layers of the abdominal wall. The aim is to have the two "pops" felt during the insertion of the VN as realistic as possible.

In Table III the results of the tuning process are shown.

However, no technical details regarding the simulator are given in the literature.

TABLE III: RESULTS OF THE TUNING OF STIFFNESS AND BREAK FORCE MADE BY TWENTY-TWO EXPERT SURGEONS.

	Mean stiffness + SD [N/mm]	Mean break force + SD [N]
<i>First Fascial Layer</i>	1.3 + 0.45	3 + 0.6
<i>Second Fascial Layer</i>	1 + 0.35	3.5 + 1.2

3.2 Simulators in Endourology

The most popular VR simulators for Endourology are PERC MentorTM and URO MentorTM, platforms developed by Simbionix [57], shown in Figure 10d; these complementary apparatuses combine digital image displays with the use of physical mannequins in order to simulate cystoscopy and flexible or semi-rigid ureteroscopy. The former, in particular, is used for the simulation of percutaneous renal access, to verify that the kidney has been correctly accessed; moreover, it provides performance measurements both from a quantitative and qualitative perspective. The main problem of these platforms is the high cost [58] and this prevents their expensive use for surgical training.

Other examples are TURP Mentor, developed by Simbionix (USA) [59], shown in Figure 10a, and UroSim by Vitamed AG (Switzerland) [60], shown in Figure 10b. The former allows

for a full procedural simulation including bleeding control and transurethral resection of bladder tumors.

Along with these VR surgical simulators, also an example of Augmented Reality system is commercially available: Maestro AR[®] System by Mimic Technologies [61], shown in Figure 10c; it uses AR for cognitive rather than technical skills training. It provides an interaction of trainees with recorded surgical videos in real time to learn procedural steps and anatomy thanks to haptic feedback; moreover, modules for partial nephrectomy and prostatectomy are available.

3.2.1 Disadvantages and Advantages of Current Solutions

The unavailability of haptic feedback or, above all, an improper use of it is one of the main drawbacks of currently commercially available simulators. Another disadvantage is the lack of resistance of the tissue to the instrumentation, as well as the fact that simulators cannot emulate real-time situations; indeed, with a simulator is not possible to simulate all the different nuances of a surgical procedure, mainly because of the unpredictability of some steps. Another downfall is the lack of simulators able to provide the user with a sensory input of pressure or texture. Furthermore, also the cost of this simulator is another factor that should be taken into account, particularly when considering less developed countries [25].

However, a surgical simulator in general, has many strengths; for instance, it provides an acceptable rendering of tissues, permits objective measurements of skill performances so that it is possible to compare training outcomes. Finally, it also would allow for tactile feedback from the instrument.



(a) TURPMentor by Simbionix (USA). Image adopted from [59].



(b) UroSim by Vitamed AG (Switzerland). Image adopted from [60]



(c) Maestro AR[®] System by Mimic Technologies. Image adopted from [61]



(d) PERC Mentor[™] by Simbionix. Image adopted from [57]

Figure 10: Most used surgical simulators in endourology.

3.3 Summary

Even though the early prototype of the haptic VN insertion simulator developed by [56] appeared and felt pretty realistic, no technical details were given by the authors regarding the realization. Moreover, other parameters such as the correct orientation and position of the tip of the VN should be included in order to have a proper role for teaching and assessment purposes. For this reason, the aim of this study is the creation of a more advanced and complete simulator for VN placement to analyze and try to evaluate the possibility of the benefits of haptic feedback in psychomotor skills development and its relevance in surgical training.

Therefore, this work is going to show the experimental setup created to conduct the study necessary to find out whether or not the use of this feedback can improve the training outcomes. In the next chapters, the application used to optimally tune haptic feedback is explained in detail, then some final considerations about the setup are presented, introducing which will be the further steps in order to answer our question: can haptic feedback improve learning of psychomotor skills considering a particular step of laparoscopic procedures such as the VN placement?

CHAPTER 4

MATERIALS AND METHODS

This Chapter gives a detailed description of the experimental setup that takes into account both graphics and haptic elements, since the requirements include the integration of a highly-defined graphics rendering and haptics rendering through a haptic device. Moreover, a stereoscopic view of the scene will be implemented in order to convey to the user a proper perception of depth.

4.1 3D Models Creation

In order to achieve a correct and precise mimic of the procedure, it is necessary to include in the virtual environment the 3D models of the structures of interest. Since one the main requirements of the simulator was an acceptable graphics rendering of organs and structures with which the user is be given the possibility to interact while training on the procedure, not only the organs of interest for the procedure itself have been included. In fact, besides bowel, linea alba, peritoneum, rectus abdominis, skin and subcutaneous fat, the 3D scene also include 3D models of aorta, arteries and veins, bladder, colon, gallbladder, heart, inferior vena cava, kidneys, lateral abdomen, liver, pancreas, portal vein, spine, spleen and stomach. The simulator provides visual and haptic feedback to the trainee like in the ORs; for this reason, the 3D models have tactile properties that is perceived by the trainee through a haptic device.

For these reasons, the steps for the application development required a first phase of segmentation of the image and extraction of two different sets of 3D models from CT images. The second set of meshes has been then processed to make them computationally lighter as to comply to the specifications of the virtual environment, that is requested to comprise both a visual and a haptic representation of the models. The details of these processes will be explained in details in Chapter 5.

4.2 Software Development

The used haptic device is a TouchTM 3D Stylus [62], shown in Figure 11; it is provided by 3D Systems[®] (Rock Hill, SC, USA) and its technical characteristics are summarized in Table IV. TouchTM 3D Stylus is an impedance control device so that, as explained in Chapter 1, it performs a measure on position and apply a proportional force.



Figure 11: TouchTM 3D Stylus. Image adopted from [62].

TABLE IV: 3D SYSTEMS[®] (ROCK HILL, SC, USA) TECHNICAL SPECIFICATIONS.

Type	Touch 3D Stylus
Positional Sensing DoF	6
Force Feedback DoF	6
Force Feedback Workspace (WxHxD)	~6.4 x 4.8 x 2.8
Maximum Force	0.75 lbf/3.3 N
Nominal Position Resolution	~0.055 mm

The user interface of the haptic device is handled by QuickHaptics[™] Micro Application Programming Interface (API) [63]; this library allows the user to create basic haptics-based applications. However, the built-in graphics rendering of QuickHaptics[™] is limited in graphic rendering as it only display items that are either meshes or geometric primitives. In order to face the limitation introduces by QuickHaptics[™], a graphic library based on C++ coding language has been used to supply this lack: *LACE Library*, developed by previous students for their Master’s thesis in the Mixed Reality Laboratory, in the Department of Bioengineering at the University [64], [65], [66], [67]. This unique platform allows for good real-time performance in terms of haptics and graphic rendering.

4.2.1 LACE Library

This external library has been chosen in order to gain a robust graphics interface and haptics renderings. *LACE library* combines and handles interactions between four distinct software/hardware environments that can be used by the developers to create their applications:

- **Visualization Library (VL).** It is an open-source library based on OpenGL for 2-dimensional (2D) and 3D graphics applications. The library preserves the characteristics

of the flexible and high performant OpenGL API, with its user-friendly and intuitive classes and functions; it takes care of the graphics rendering of the virtual scene in use;

- **QuickHaptics (QH)**. It is a haptics library developed in C++ that is built on the foundation of Geomagic OpenHaptics, the software development toolkit for 3D Systems haptic devices. This library is used for managing the force feedback;
- **Wykobi Library (WK)** [68]. It is a library for 2D-3D computational geometry implemented in C++ that allows for fast mathematical calculations;
- **Ascension 3D Guidance (AS)** [69]. It is a 3D electromagnetic tracking system; with this system it is possible to have an easy communication with a tracking unit through the 3D Guidance API.

In Figure 12 it is possible to observe how these four different environments communicate and function.

This library works as two different threads on a Windows platform that run simultaneously: the rendering rate for the graphical display is 60 Hz, whereas the one for the haptic servo loop is 1000 Hz. In particular, considering the former, it has to be said that the rendering rate becomes 30 Hz for each eye view when the stereoscopic modality is enabled. This particular application does not take advantage of WL and AS; for this reason, a more detailed explanation of the VL and QH only will be presented in the remaining of this Section.

In *LACE library* all the processes related to the graphical visualization are managed through the VL functionalities. Additionally, this library allows the programmer to adjust the visual characteristics of the scene objects and allows the users to interact with the elements present

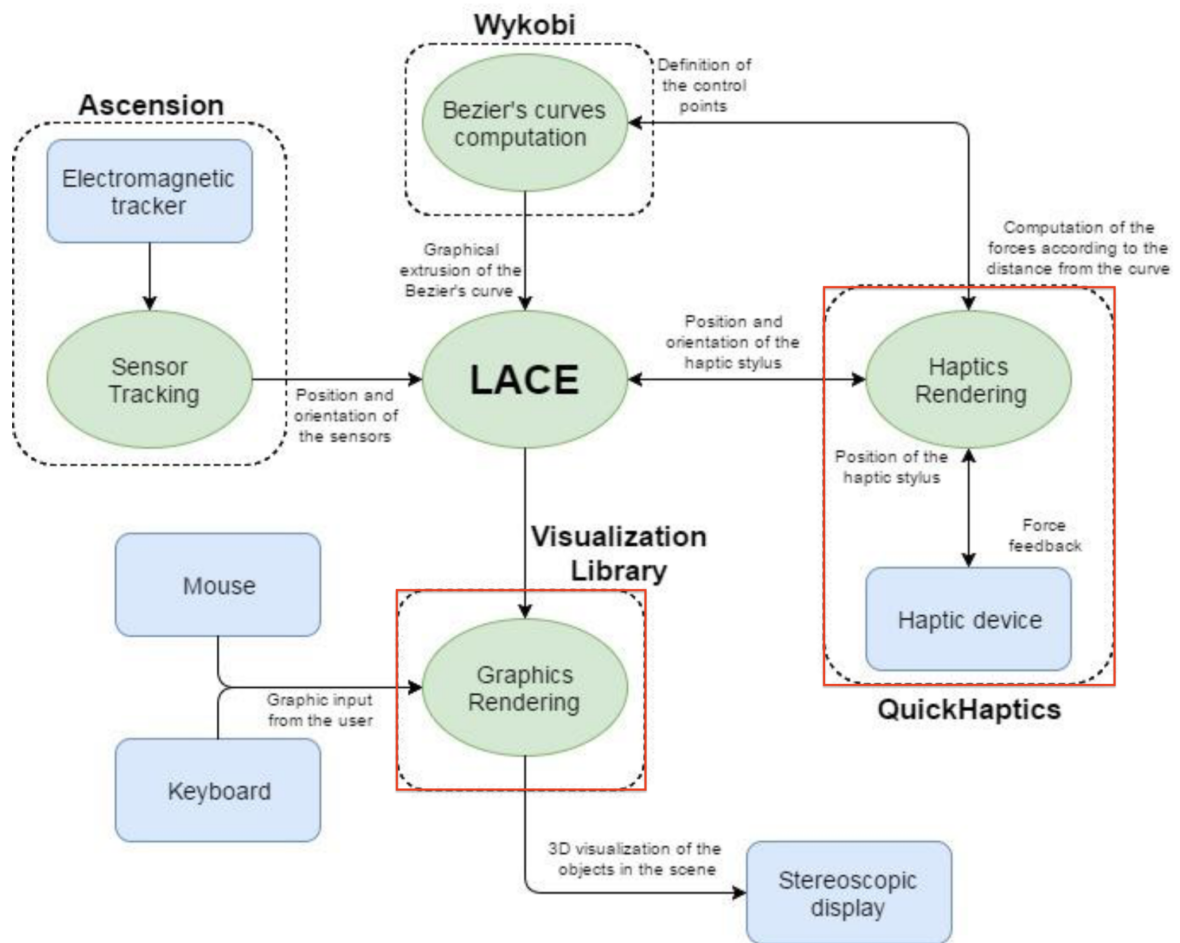


Figure 12: Logic and interaction among the four distinct software/hardware environments in *LACE Library*.

in the scene through the use of the keyboard and the mouse; this last function is provided by customized callback functions. On the other hand, the haptics rendering is managed by the QH library. Two different alternatives can be chosen by the programmer: he/she can use the pre-made features of this library, or he can decide to create his/her own algorithms. The two previously mentioned libraries communicate through the *LACE Library* and in particular through the base class `LACE_Object` in such a way that a correct mapping and display in the graphic environment of all the objects in the scene and the haptic device is possible.

In *LACE Library* the available classes can be divided in four distinct groups:

- **Renderable Objects:** in this group all the classes used for graphics and haptics rendering based on the `LACE_Object` class are included. These classes are used for the creation of the meshes representing the organs, the tissues and the instruments used for the simulation along with basic geometric primitives;
- **Tracking System:** the classes belonging to this group manages the communication with the AS library;
- **Special Force:** the two main classes of this group are `LACE_VolumeForce` and `LACE_ForceField` used for the definition of the rendered force field coming from the interaction between the VN and the other objects present in the scene;
- **Rendering Classes:** each `LACE_Rendering` class instance allows for a different rendering in the scene regarding the objects, the camera and the viewport.

A useful class included in this group is the `LACE_CuttingPlane` that allows the trainee to cut one or more `LACE_Object` instances. This class could be useful for the VN placement simulator; in fact, once the trainee repotes that the VN is placed in the correct position, he/she can use the cutting plane to explore the anatomy as a self-evaluation.

The most important class in the *LACE Library* is the `LACE_Class`; this special class controls the processes of initialization and updating, and it contains many functions to customize the executable. Each program based on *LACE Library* must contain the definition of this singleton class since inside it the pointers to all the used classed are memorized. The organization in the four distinct groups of *LACE Library* classes in shown in Figure 13.

As stated before, the VL and QH libraries can communicate through the base class that is common to all the objects that are present in the scene.

The creation of the objects that have to be included in the scene will be explained in details in Chapter 5. Once they have been created, all these meshes must be added to the main rendering in order to be displayed inside the scene. For this simulator two different set of meshes have been created: the first set of haptically inactive meshes with a higher number of triangles for the graphics rendering and the second one of graphically invisible meshes with a lower number of triangles for the haptics rendering.

By using the classes `VL_Tranform` and `QH_Tranform` the exchange of information between the corresponding classes in made possible as shown in Figure 14.

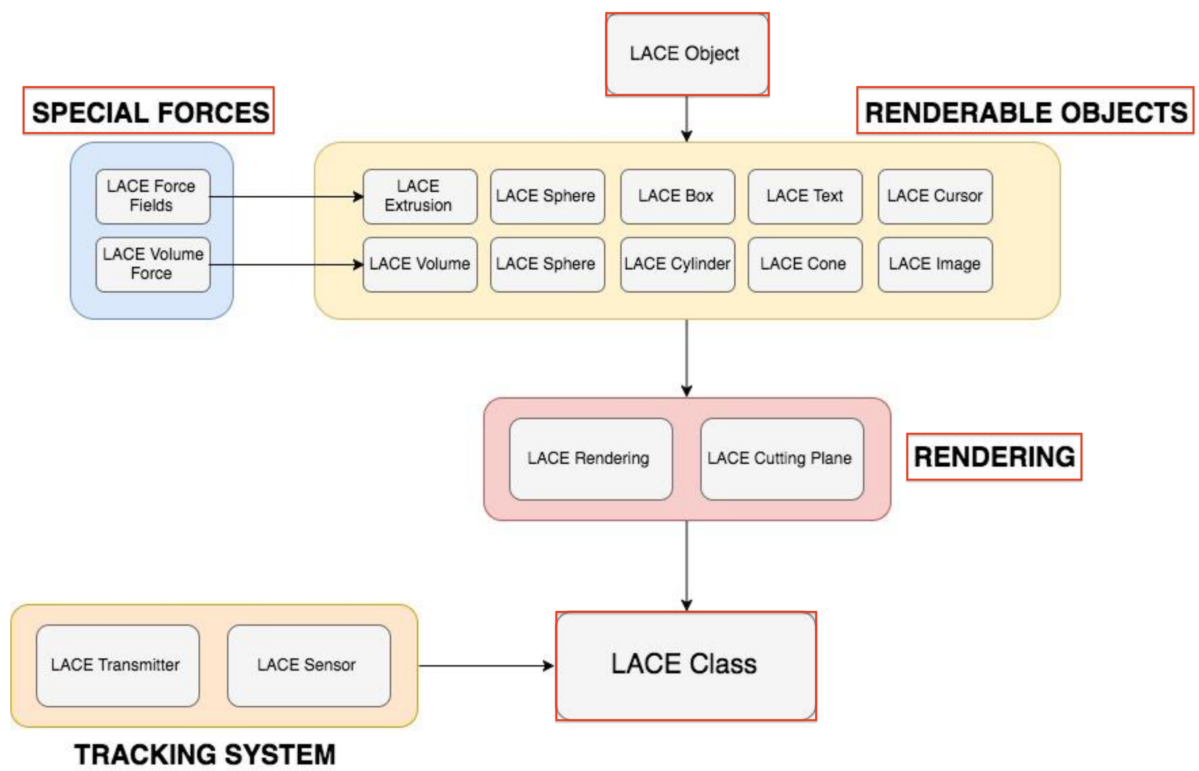


Figure 13: Organization in four different groups of the classes in *LACE Library*.

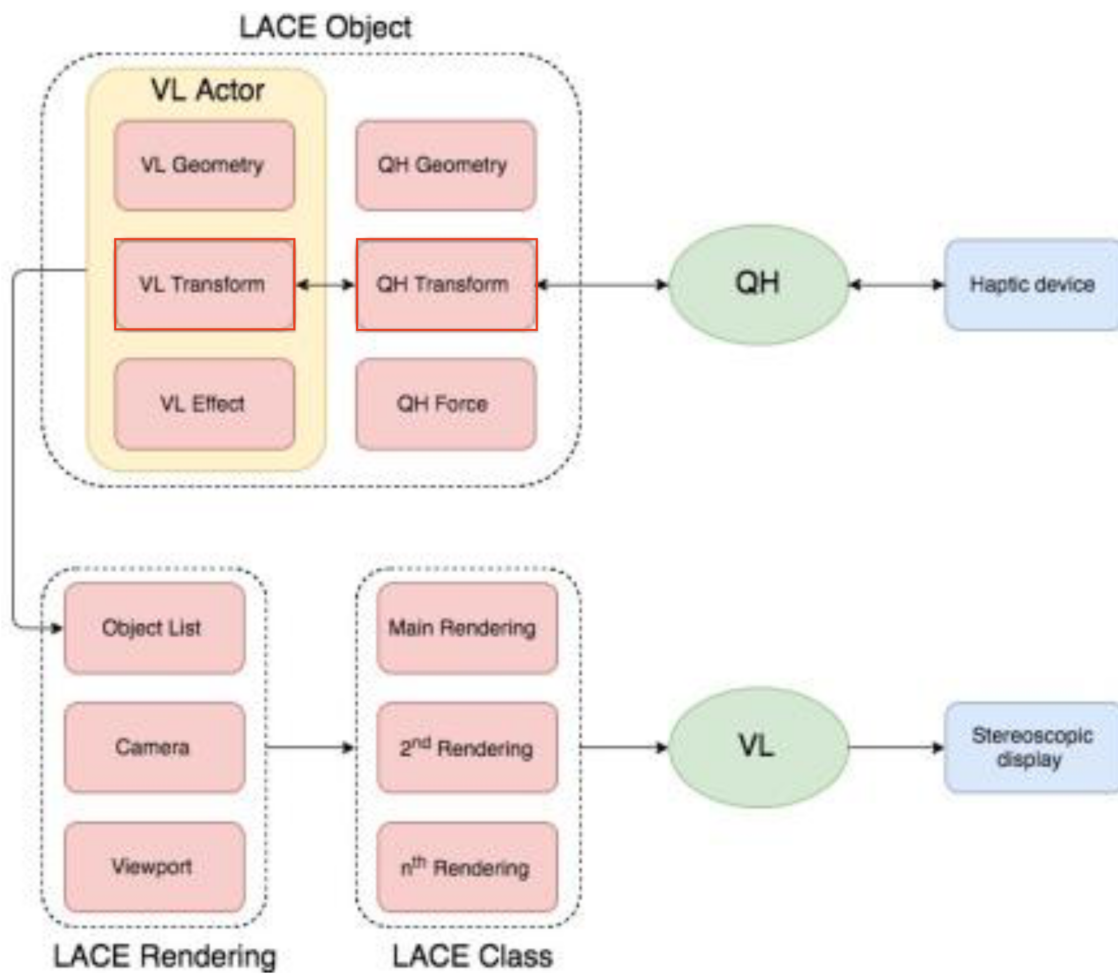


Figure 14: Communication in LACE_Object class.

4.2.2 Hardware components

The hardware components used for the development of this simulator are the following:

- **Haptic devices.** It is the one presented in Figure 11 and it is used to convey the sense of touch of the VE to the user;
- **Stereoscopic display.** This element is fundamental in order to provide to the user a depth perception to better emulate the procedure and the environment of the OR; in fact, the stereoscopic view compensate for the loss of depth perception occurring when 3D shapes are rendered on a 2D computer screen. The 3D monitor must support the side-by-side mode and the trainee must then run the application with proper 3D glasses.
- **Keyboard and mouse.** The first is used to make the GUI visible or invisible through the pressing of the space key; the second is used to select the model of interest and modify its parameters through scrollbars.

4.2.3 Data

Various type of data are used in simulator implementation:

- **Computerized Tomography images.** As previously mentioned in this chapter, the virtual models have been extracted from a volumetric image; in particular CT images taken from an open-source repository have been used. Further details will be given in Chapter 5;

- **Virtual models.** The two previously mentioned set of models have been extracted and segmented from the CT image according to a procedure that will be explained in details in next Chapter;
- **Virtual needle.** The model of the Veress needle has been created by using Autodesk® Fusion 360™ [70], imported in 3ds Max® [71] in order to assign the correct position and orientation within the virtual scene in which it has been imported as a .3DS file.
- **Text files.** They contain the initial values of the haptic and graphic features of the virtual models (transparency, stiffness, damping, friction and pop-through).

4.2.4 Processes

The simulation is handled by two key processes: the graphics and the haptics rendering.

- **Graphics rendering.** This process takes into account all the steps that are related to graphical aspects of the simulator by handling the reading of the data for the visualization of the virtual models. This thread is totally supported by the VL;
- **Haptics rendering.** This process mainly include the tracking of the haptic device in the space in order to detect the collisions and compute forces. This thread in handled by QH.

Both processes will be further explained in the next chapter.

Figure 15 shows the general workflow of the application; in particular this graphical representation pays attention to the interaction between hardware components and data coming from the model and the user.

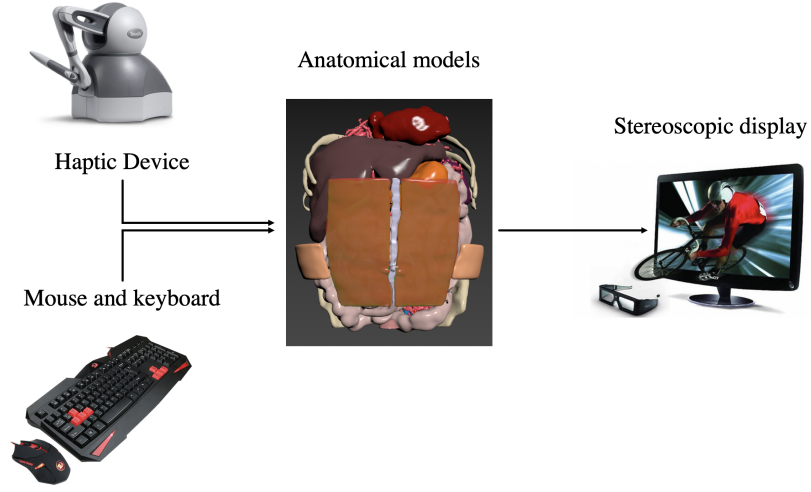


Figure 15: General workflow of the application.

4.3 Experimental protocol

The application present in this work has been developed on a workstation available at the University of Illinois at Chicago. The main features of the system are reported in Table V.

TABLE V: FEATURES OF THE EXPERIMENTAL SETUP.

Processor	RAM	GPU	Stereoscopic display	Haptic device
Intel Core i5 2500K CPU 3.3 GHz	8 GB	NVIDIA Quadro K6000	Yes	3D System Touch™ 3D Stylus

CHAPTER 5

IMPLEMENTATION

The aim of this work is to analyze and assess possible benefits of a haptic and VR platform exploiting an interactive 3D manipulation of surgical anatomy from medical imagery. It would allow for the comparison of training outcomes between current cognitive-only training protocols and combined cognitive and psychomotor training platforms. The attention will be focused on a particular and risky step of laparoscopic procedures: VN placement.

Within this Chapter the implementation details of the VN placement simulator will be presented. It will first cover the preliminary phase of image segmentation, the refinement of the extracted 3D models, the software development and the implementation details of the simulator.

5.1 Image Segmentation

A dataset of medical images from a CT have been first pre-processed in order to eliminate all the artifacts due to low contrast and noise that are typical of this type of images; then the segmentation has been applied in order to obtain the 3D models that will be included in the virtual scene.

Image segmentation is the process by which an image is subdivided in homogeneous regions where all the voxels related to a certain anatomical structure are grouped together. This grouping is based on a homogeneity criterion that allows for the distinction between one area

and another one. The segmentation can be performed either automatically or manually. In particular, the former allows the user to obtain a fast segmentation but not so precise when considering contours extraction and, as a consequence, it may lead to extraction of unwanted areas. The latter is accurate but, instead, on the other hand, extremely time-consuming; in fact, the user has to contour manually the region of interest (ROI) in each slice of the medical image dataset.

In this work, the automatic segmentation based on Thresholding method has been first used in order to define, in a more gross way, the various anatomical regions of interest; then, the manual segmentation has been performed in order to refine and improve the contours extraction.

Thresholding is a region-based segmentation method in which the different areas are chosen according to the similarity of gray levels that are associated to the voxels. When considering anatomical images generated by a CT scanner, this kind of segmentation is a good option since each region has usually a gray level that is different from the surrounding ones.

In particular, the contrast is adjusted according to the necessity of the highlighted ROI and the smoothing factor is increased to gain noise reduction; in this way, the signal is filtered and the image is more clear. All these steps are necessary before proceeding to the automatic segmentation in order to use itk-SNAPTM, a software for image segmentation.

itk-SNAPTM [72], [73] is an open-source software used for the segmentation of 3D medical images. In this application, the loaded dataset is shown on the home screen both in a sagittal, frontal and transverse view. By moving the cursor the user is given the possibility to scroll the slices and to see all the different layers of the anatomy. According to the desired ROI, the user

can change the contrast through the graphical user interface. In this software, the automatic segmentation can be performed according to the Threshold method by setting the threshold value manually. By manipulating the spectrum of gray levels and adjusting the smoothing factor, the user is allowed to differentiate the parts of the image that will be segmented (shown in white) from the ones that should be discarded (shown in blue). The segmentation is performed by positioning bubbles of different sizes in the white areas that will expand until the user determines that the result is satisfactory.

The volume used to segment the models was taken from the DICOM Library [74], “a free online medical Digital Imaging and Communications in Medicine (DICOM) image or video file sharing service for educational and scientific purposes”. The important aspect is that all the information related to both patient and doctor are not revealed since all the datasets available on the site are made anonymous before their upload.

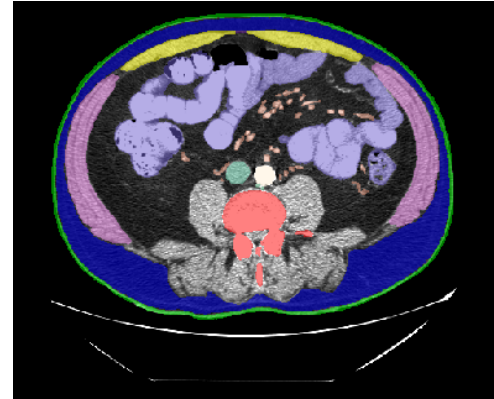
When the manual segmentation is performed, the user has the possibility to manually adjust the contours of the considered areas. In order to be as precise as possible, a WACOM Intuos Pro creative pen tablet [75] has been used. An example of segmentation of different organs associated with labels of different colors is shown in Figure 16.

The final result of the volume obtained through both segmentations in itk-SNAPTM is shown in Figure 17.

After automatic and manual segmentations have been performed, itk-SNAPTM finally allows the user to export the segmented images into a mesh in .STL file format. A .STL (“StereoLi-

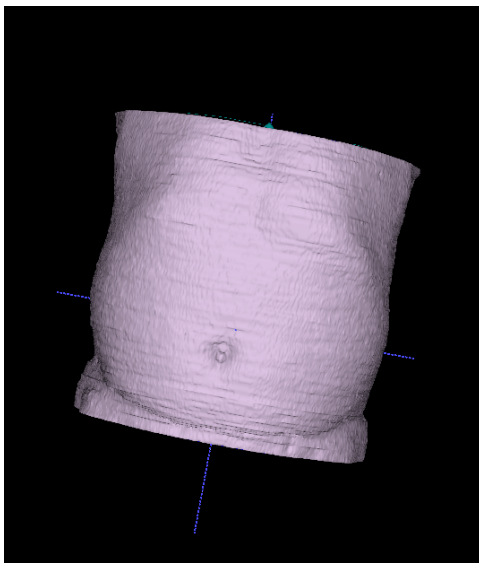


(a) Example of a CT slice.

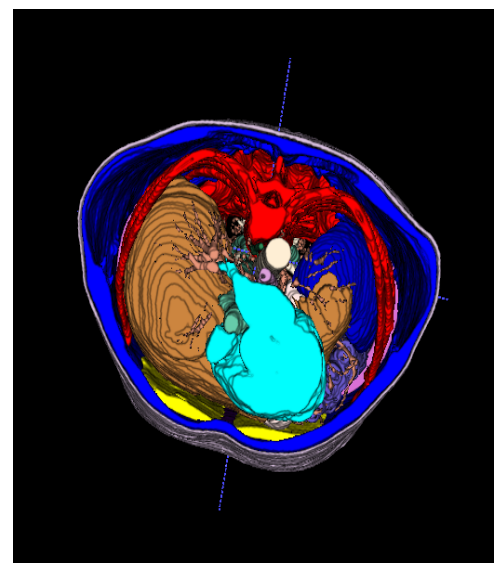


(b) Same slice after the application of automatic and manual segmentation.

Figure 16: Example of automatic and manual segmentation performed with itk-SNAPTM.



(a) Front view of the obtained 3D volume.



(b) View from above of the obtained 3D volume.

Figure 17: 3D volume obtained with manual and automatic segmentation in itk-SNAPTM using a separate label for each organ.

tography”) file describes and represents a three-dimensional surface through its discretization with a series of interconnected triangles.

Mesh exportation represents a crucial step since the 3D models need to be processed before being added to the VRE.

5.2 3D Models Post-processing

The main problem of the previously extracted 3D models is the high surface roughness; the main cause is the similar X-ray absorbance level of many organs and tissues in the human body. Due to this, in CT images the elements that are close to each other can have similar levels of gray leading to a difficult identification of specific structures.

As stated before, in order to have a more accurate representation of the anatomical structures, two different sets of meshes have been created. The first one is used for the graphics rendering of the anatomy and is haptically inactive in the virtual scene, whereas the second one is used for the haptic rendering and is graphically invisible.

Then, it is necessary to carefully decimate the meshes obtained from the segmentation in order to both preserve the anatomical topology of the surface and to maintain a proper number of polygons so that the haptic libraries can perform in an adequate way at the frame rate described in the previous chapter. In this way, it is possible to increase the real-time performance of graphics rendering.

Both sets need to be decimated but in a different way; in fact, the first set will contain a higher number of polygons to maintain a better resolution with respect to the second one. In order to perform smoothing and decimation, three different applications were used: ZBrush[®],

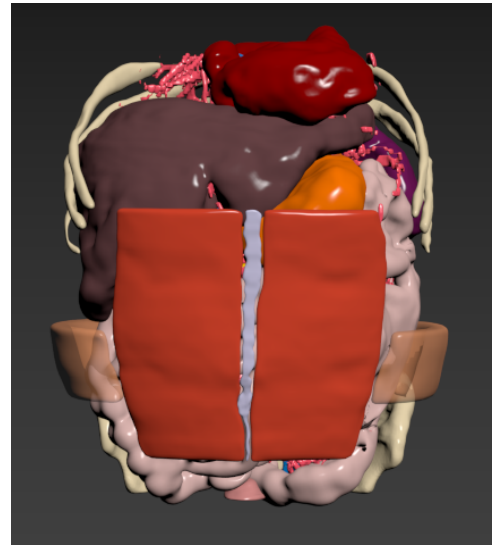
ParaViewTM and 3ds Max[®]. The first one [76] is “an advanced software that enables the user to use customizable brushes to shape, texture and paint virtual clay in a real-time environment that provides instant feedback”. It has been used for the post-processing of the 3D models used for graphics rendering in order to obtain better results in smoothing and decimation. The second one [77] is “an open-source, multi-platform data analysis and visualization application”, which supports a wide variety of visualizations algorithms including advanced modeling techniques such as contouring, polygon reduction and mesh smoothing. This software has been used to process the haptic models that have been further decimated in 3ds Max[®] [71], an open-source (in its student edition) 3D software for modeling, animation, and rendering. Both graphic and haptic 3D models have been then imported in 3ds Max[®] in order to obtain a correct and coherent positioning within the scene and to apply the materials to all of them. In Figure 18 the 3D models used for the graphics rendering after smoothing, decimation, positioning and material application are shown.

As previously explained in Chapter 2, there are different steps that have to be carried out for a proper VN placement. The first one is the stabilization of the umbilicus, that is made through the application of two clamps. The next step is the creation of an incision of the skin along the inferior crease of the umbilicus where the VN will then be placed.

Buttons in the virtual scene with which the trainee can interact through the haptic device, allow for a switch between the different steps of the procedures. In order to make the trainee visually perceive these steps, three different models of skin, shown in Figure 19, have been created; the first one represents the start of the procedure, when the patient first enters the



(a) Model of the inner anatomy of the human body.



(b) Addition of the rectus abdominis and linea alba.



(c) Addition of subcutaneous fat.



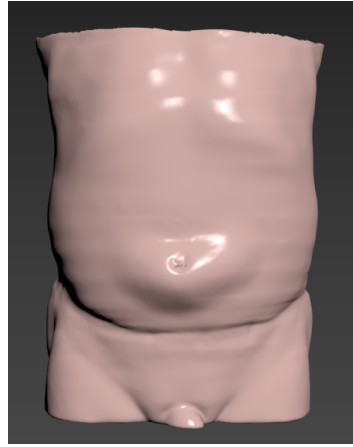
(d) Final model of the anatomy used for graphics rendering.

Figure 18: Models obtained for the graphics rendering after the post-processing phase using ZBrush[®] and 3ds Max[®].

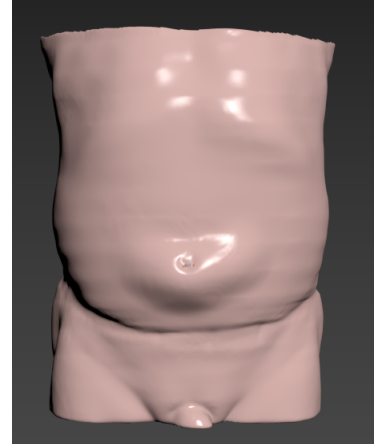
OR; the second one shows the stabilization of the umbilicus by the mean of two clamps whereas the third one models the 5-mm incision made at the umbilicus with a blade n. 11.



(a) Model used at the start of the simulation.



(b) Model for umbilicus stabilization used while performing the procedure.



(c) Model with a 5-mm incision made at the umbilicus with a blade n. 11.

Figure 19: Three different models used for the different phases of the simulation.

It is fundamental to note that the 3D models obtained from the segmentation present four different faces; in fact, due to their thickness two front faces and two back faces are perceived by the haptic device when passing through them. This represents a problem for the haptic feedback; for this reason it is necessary to cut one of the surfaces of the haptic 3D models in order to get just one front face and one back face for elements such as the rectus abdominis and the linea alba. Moreover, since the peritoneum was difficult to segment because of its

barely visible aspect in the DICOM dataset of CT images, the volumes obtained for the rectus abdominis and the linea alba have been divided into two different layers. In this way, the inner layers will be used to model the haptic peritoneum, whereas the outer ones will be used to model the rectus abdominis and the Linea Alba. This step has been performed in ZBrush® through the creation of masks on both sides of the meshes. The obtained result is shown in Figure 20.

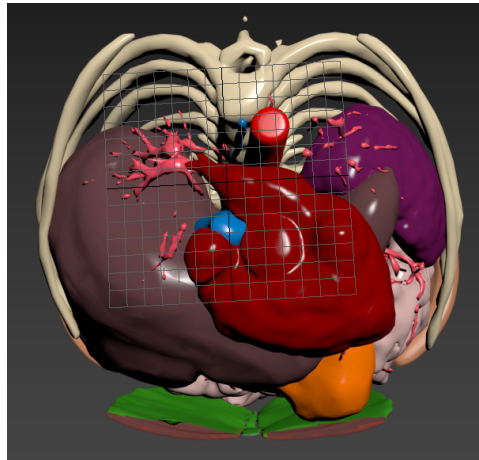


Figure 20: Model with separation of rectus abdominis and linea alba from peritoneum.

Next, also the 3D models used for the haptics rendering have been decimated using 3ds Max®.

Once all the models have been post-processed, both the graphic and haptic sets of meshes have been imported in 3ds Max®; in this way it is possible to place all the elements in the scene and above all to create a precise correspondence and overlap between the two distinct

sets. The disposition of all the elements is a key step because it will be then kept when the models are imported in the virtual scene. Moreover, the upper and lower parts of a male human body have been added to the final model in order to give to trainees a more realistic idea of the patient's orientation. Figure 21 shows the presence of two clamps the help the trainee in the umbilicus immobilization that are set graphically invisible at the beginning; in fact, their graphic visibility will be changed when the trainee decides to proceed to the second step of VN placement.



Figure 21: Addition of clamps to help the immobilization of the umbilicus.

The VN has been modeled by using Autodesk[®] Fusion 360[™] [70] and it is shown in Figure 22.

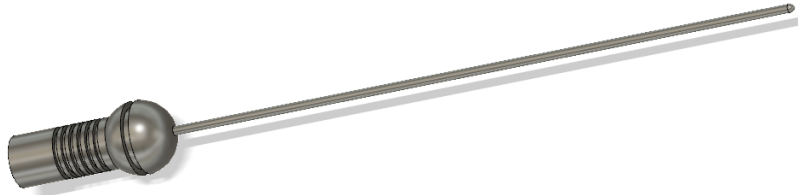


Figure 22: Model of the Veress needle created in Autodesk[®] Fusion 360[™].

The model has been saved as an .STL file and has been then imported in 3ds Max[®] to obtain a .3DS model.

5.3 Implementation Details

The scene is composed by the two previously mentioned sets of 3D models that represent the organs. The first set has its own graphic properties, whereas the models in the second set have properly set haptic properties. The user is given the possibility to modify these parameters through a graphical user interface (GUI) implemented with GLUI, a GLIT-based C++ library.

Figure 23 shows the logic that is behind the implementation and the processes occurring in the application. In particular, the circles represent the processes that occur in the simulation from the hardware components (represented by the squares) and the data (represented by the cylinders) used in the simulation. Moreover, the graphics and haptics rendering processes and represented by two different colors: the first ones are indicated in green and the second ones, in red.

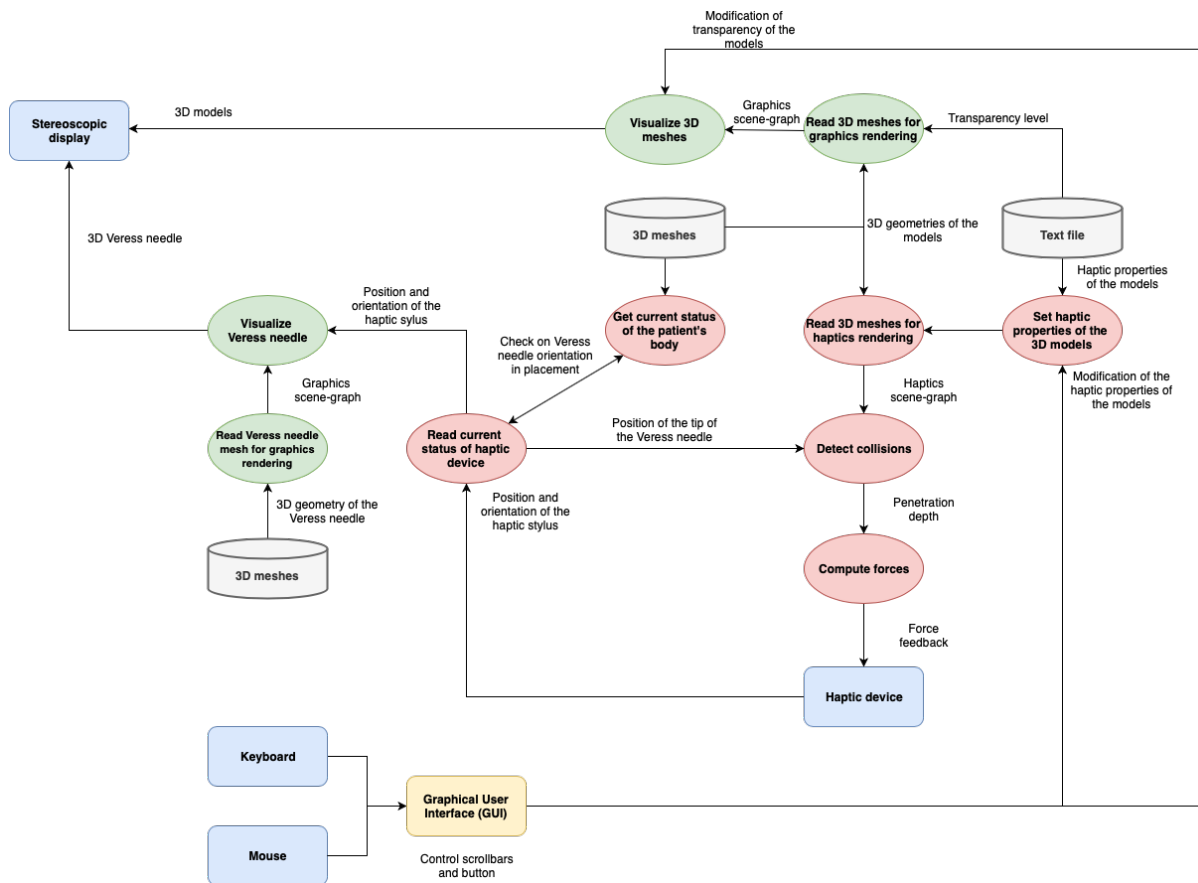


Figure 23: Schematic representation of the implementation details.

5.4 Software Development

Both graphics and haptics renderings have been taken into consideration for the implementation of the simulator.

5.4.1 Graphics Rendering

All the previously created 3D models are added to the scene as LACE_Meshes instances; this class allows the user to load 3D shapes in different formats that are supported by the VL, such as .3DS, .STL or .OBJ. All the models for this simulator have been imported as .3DS shapes. It is necessary to make sure that no material is applied to the meshes and that the polygons of which they are made are triangles before exporting them from 3ds Max[®].

Five different buttons are present in the virtual scene as LACE_Box elements as shown in Figure 24.

The first button on the left allows the user to restart the simulation and shows the scene with the patient in the horizontal position. In a real OR, the surgeon is allowed to move around the patient in order to find the most suitable position to perform the procedure. Since this is not possible in the VE, the simulator allows the trainee to move virtual patient model until he/she judges that their relative position is correct. In fact, by pressing button 1 on the haptic stylus, it is possible to rotate and translate all the objects within the virtual scene. An example is shown in Figure 25.

The second button allows the trainee to pinch the skin and the subcutaneous tissues; as explained in Chapter 2, it is necessary that the abdominal wall is lifted in such a way that it creates a 45-angle with the patient's body. Moreover, some clamps can be used in order to keep

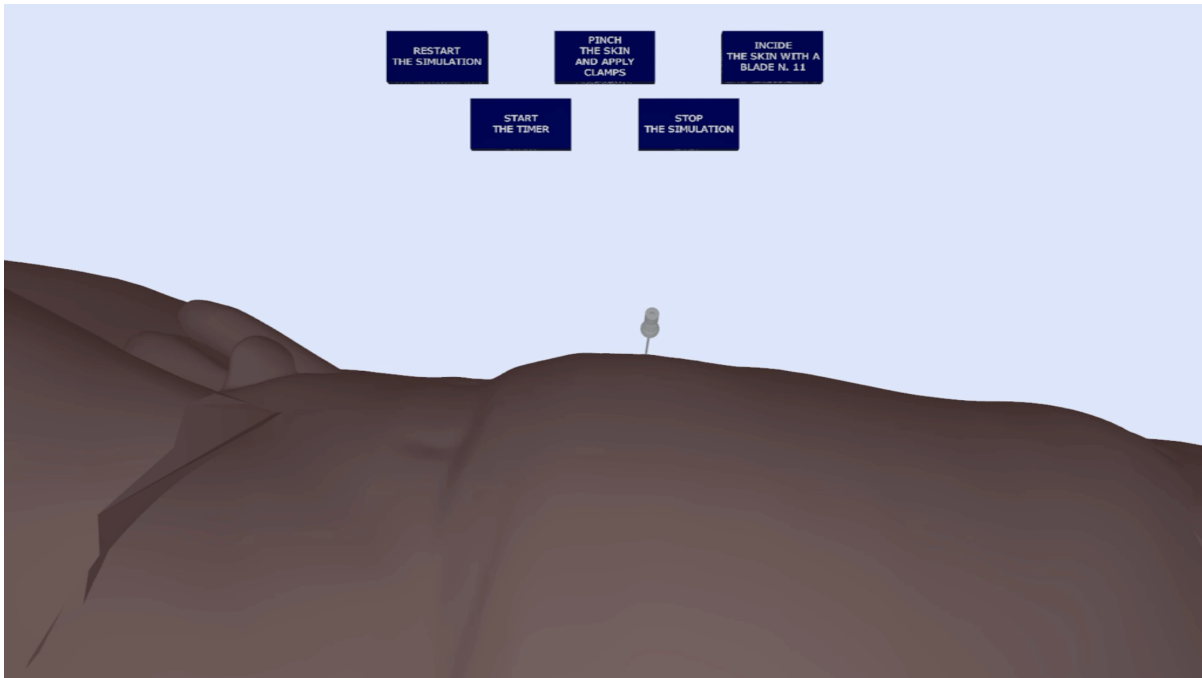


Figure 24: Starting scene showing the patient in horizontal position and the touchable buttons.

the abdominal wall lifted. By pressing this button, the trainee can see the new model for the skin in which the skin is pinched with the correct orientation and two clamps are applied in order to simulate the umbilicus immobilization. When the third button is pressed, the third model for the skin appears; it shows a 5-mm incision along the lower crease of the umbilicus in the skin and subcutaneous tissues.

Once the patient is in the correct position with the umbilicus immobilized and the incision made, the Veress needle can be inserted in the umbilicus pointing towards the anus and forming an angle of 90 degrees with the lifted abdominal wall and 45 degrees with the patient's body. When the trainee inserts the needle at the correct depth inside the patient's body, he/she can

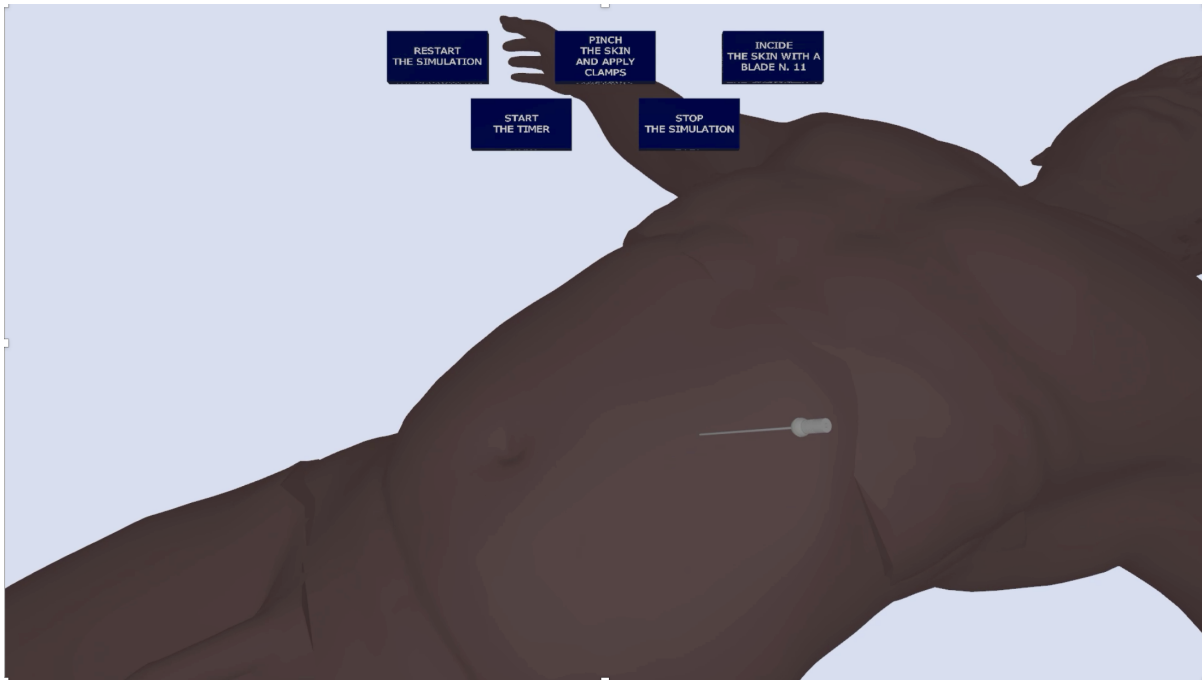


Figure 25: Example of rotation and translation of the models within the virtual environment.

press the button 2 to freeze the Veress needle in the position and the orientation of the haptic stylus when the button has been pressed and to toggle the activation of a cutting plane. When the class of *LACE Library* named *LACE.CuttingPlane* is initiated, the shapes in the scene are clipped by a plane that changes its position and orientation according to the movements of the haptic stylus that are visually reflected by the graphic cursor. In the simulator the cutting plane is activated just for the drape covering the patients, the lower and upper parts of the body, the clamps but, most importantly, for the skin, the subcutaneous fat, the rectus abdominis, the linea alba and the peritoneum. In this way, it is possible for the trainee to evaluate the Veress needle proximity to the underlying organs so that he/she not only can have

a better understanding of the inner anatomy, but also a preliminar self-evaluation. An example is showed in Figure 26.

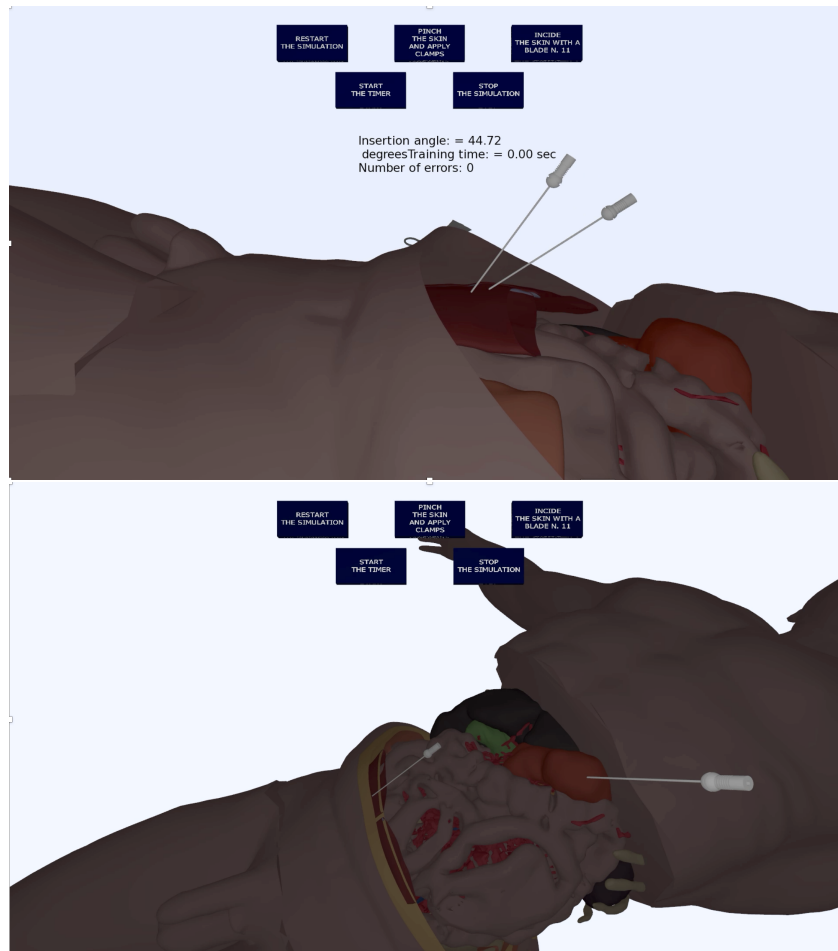


Figure 26: Example of use of the cutting plane and frozen Veress needle.

In each moment of the training the user can decide to start the timer to compute the time required to perform the procedure by pressing the fourth button from the top. Once the training is over the trainee can press the last button on the right to stop the simulation. At this point the number of mistakes is computed and showed on the screen along with the employed time. The number of mistakes is computed according to the number of times in which an organ or a tissue not directly involved in the procedure is touched and showed as a LACE_Text in the virtual scene.

Additionally, the GUI allows the user to select a particular shape in the virtual scene and to modify its transparency through a scrollbar. In this way, the trainee is provided with the possibility to further explore the anatomical structures of the body in a first phase of the training. The transparency value is an absolute number between 0 and 1.

5.4.2 Haptics Rendering

All the haptic effects that are present in the application can be divided in two main categories: shape-related and event-related.

The first group of effects is related to the material properties that are assigned to the different elements present in the scene, whereas the second group is related to the activations of the previously mentioned buttons to switch between the different phases of the simulation. Moreover, they are activated when the haptic stylus enters the skin and the underlying tissues. In fact, the tip of the haptic device is used to detect the collisions with the virtual models present in the scene. The *LACE Library* uses a collision detection algorithm that is proxy-based, based on a spring-damper model. According to this collision detection algorithm, a

reaction force proportional to the penetration depth is applied to the tip of the haptic device.

The penetration depth is computed with the following formula:

$$PenetrationDepth = HapticDevicePosition - ProxyPosition \quad (5.1)$$

The proxy is represented by a point that closely follows the position of the haptic stylus since its position is continuously updated by the haptics rendering engines. When a collision is detected and the tip of the haptic stylus is inside a model, the proxy is constrained on the exterior surface of the touchable shape.

5.4.2.1 Shape-related Haptic Effects

Each of the 3D models belonging to the second set of meshes has specific haptic properties: stiffness, damping, static and dynamic friction and pop through. When a collision is detected, the proxy algorithm computes the forces that must be sent to the haptic device according to the haptic properties of the object involved in the collision and the penetration depth.

Also for the haptic models the GUI allows the user to select a particular shape in the virtual scene and to tune this values through some scrollbars. This will be useful for the validation part of the simulator in order to define the most suitable values to properly set the properties of the different organs. All the values are numbers between 0 and 1. The initial values of the haptic properties set for the second set of 3D models are reported in Table VI.

TABLE VI: INITIAL VALUES OF THE HAPTIC PROPERTIES SET FOR THE 3D MODELS.

Model	Stiffness	Damping	Friction	Pop Through
Bowel	0.02	0	0	0.01
Linea Alba	0.5	0.1	0.1	0.02
Pancreas	0.1	0	0	0.05
Peritoneum	0.2	0.05	0.35	0.05
Skin	0.4	0.1	0	0.05
Subcutaneous fat	0	0	0	0
Vasculature	0.2	0	0	0.2

5.4.2.2 Event-related Haptic Effects

The occurrence of certain events in the VE activates the haptic effects belonging to this second class. Each time that a collision takes place between the tip of the needle and front surface of the haptic models with a force that is greater than the set pop through value for the shape, the instrument enters the object triggering a series of tactile stimuli. For instance, when the considered object is the skin, a constant damping effects is perceived by the user and the so called haptic fulcrum effect is generated.

The haptic fulcrum effect simulates the sensation that is experienced by the surgeon when he/she penetrates a tissue with a pointed instrument; the surgeon is free to move the Veress needle in the direction of the needle, back and forth, but not to move it laterally without feeling the constraint given by the tissues around the incision. When the force applied to the skin exceeds its resistance, the proxy position of the tip of the Veress needle is stored as the location of the fulcrum point \mathbf{f} . In the servo-loop thread, the position and the orientation of the

haptic device are computed at each frame and the line \mathbf{l} passing by the fulcrum point with the same orientation of the stylus is generated. By considering the projection of the current stylus position \mathbf{p} onto the fulcrum line, the desired stylus position \mathbf{p}' is then computed. The force perceived through the haptic device is computed as the distance between \mathbf{p} and \mathbf{p}' multiplied by a gain, pre-set to 0.3.

A visual representation of the haptic fulcrum point effect computation is showed in Figure 27.

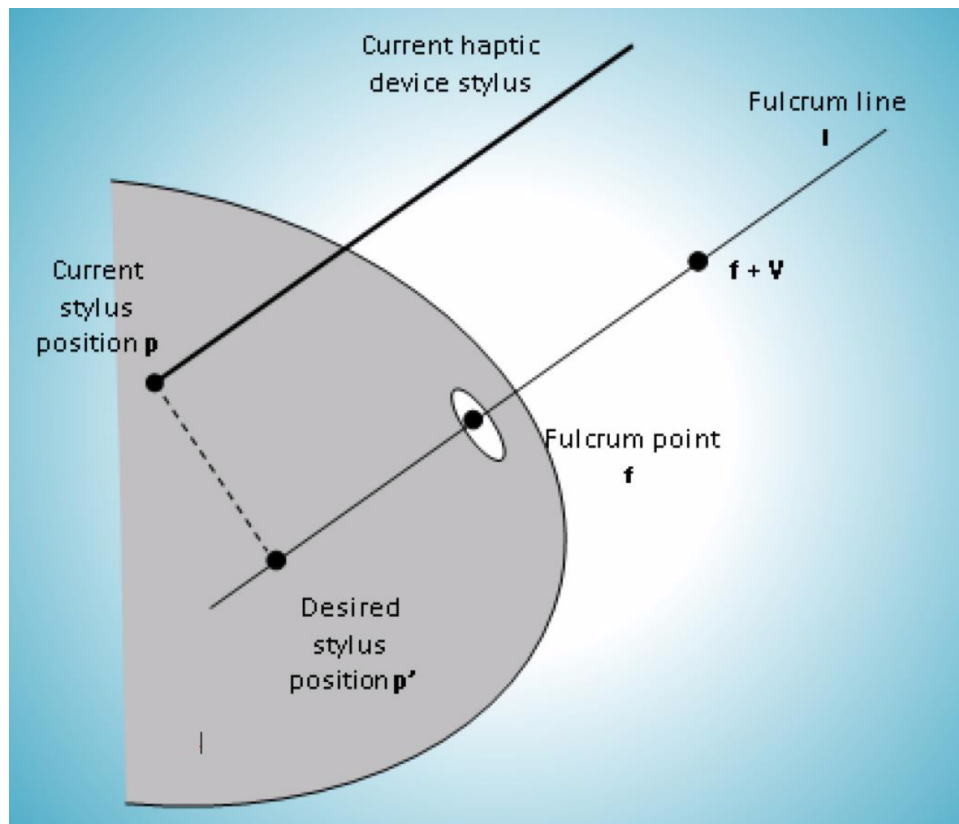


Figure 27: Haptic fulcrum point effect. Image adapted from the slides of the Haptics course of University of Illinois at Chicago.

As soon as the Veress needle soaks into the surface of the underlying tissues, such as the linea alba and the peritoneum, a constant friction and an increased damping stimulus are added to the fulcrum point effect until the user can feel the sensation of a give both between the linea alba and the peritoneum and when reaching the peritoneal cavity in order to simulate the two "pops".

When the needle is then taken out of the object with an applied force greater than the pop through value set for the back surfaces of the objects, these haptic effects are disabled. Note that in order to feel the same sensation when popping through in and out it is necessary to set a lower value for the back face with respect to the front one. In this simulator this value is set at half of the value chosen for the front face.

Also in this case the user is allowed to modify the value of the gain through the GUI in order to make the perceived constraint as similar as possible to the sensation of tissue perforation.

Once the pop through in the skin is detected, it is necessary to check that the Veress needle has a proper orientation. In fact, in order to reduce the risk of damaging the organs not involved in the procedure, the caudal angle between the patient's body and the Veress needle must be 45 degrees. A lower and upper threshold have been defined in order to consider the needle properly placed if the created angle is included between 40 and 50 degrees.

As previously mentioned, the position and the orientation of the haptic stylus are computed at each frame in the servo-loop thread; the orientation, in particular, is defined as an `hduQuaternion`. Once the popthorough is detected, two `hduMatrix` (`oriS` and `oriVN`) are defined; the inverse of the `hduMatrix` for the skin is computed and multiplied by the `hduMatrix` of the

cursor. Through the function *getRotationMatrix()* all the information are saved in another hduMatrix (relmat2) from which it is possible to extract relative angle through the function *toEulerAngle()*. The code is shown Appendix A.

The lower and the upper thresholds for the angle are set to 40 and 50 degrees, respectively; however, it is necessary to convert their values from degrees to radians in order to compare them with the angles between the skin and the VN. At each placement performed with the wrong orientation a counted created on purpose is incremented.

5.4.3 Graphical User Interface

The GUI has been implemented in order to have the possibility to manage the graphic and haptic effects of the object in the scene for the successive validation phase. Properties such as transparency and haptic material properties can be easily modified in real time. Since *LACE Library* is a C++ middleware relying on GLUT to handle all the system-dependent issues, the GLUT User Interface Library has been chosen. It provides controls to OpenGL applications to make the user able to interact with the program. The available tools in the GLUT are sliders, scrollbars, buttons and checkboxes. The developed graphic interface allows the user to set the transparency for the graphic models and stiffness, damping, friction and pop through values for the haptic models through sliders. Moreover, it has also two buttons to reset the simulation and to quit the application. In the case of a new user, the default parameters are given to the scene at the beginning of the application: once he/she modifies the graphic and haptic properties of the objects, the new values are stored into a text file, as they could be reset instead of the standard ones when the same person will run the application the next time.

5.5 Performance Evaluation

The main advantages of VR-based simulators is the possibility to obtain a performance report at the completion or during the tasks. Besides a qualitative assessment, the simulator should be able to offer a quantitative measurements of the users' skills in order to assess the improvement over time and state the effectiveness of the tool itself.

As previously mentioned a first self-evaluation can be made by the trainee by freezing the needle at the completion of the VN placement. By pressing the button 2 on the haptic device he/she is allowed to visually explore the anatomy and the location of the VN needle with respect to the inner organs; additionally, the user can get some quantitative feedbacks on the completed task. The success of the VN placement step is the insertion of the needle without touching the organs that are below the peritoneum; for this reason it is imperative to insert the needle with a certain orientation with respect to the patient's body. For this reason a counter for all the haptic models that are not involved in the procedure such as the arteries and veins, the bowel and the colon, the pancreas and the lateral peritoneum have been implemented. At the end of the simulation, when the user touches the button on the screen, the total number of errors is showed along with the total time. At the end of the task, all the quantitative data elaborated from the simulator are saved in a text file that is accessible from the apprentice and from the supervisor of the training. The process is completely automatized and allows the user to keep a track of the improvements in the task performing time after time. For the VN placement the saved performance indicators are the following:

- **Duration of the task.** This time interval expressed in seconds includes the moment in which the user touches the button to start the timer and the one in which he/she presses the button to stop the simulation;
- **Orientation of the VN.** The relative orientation of the skin and the VN is computed as previously explained. It is necessary to make sure that the orientation of the needle is correct in order to reduce the risk of injury to the nearest organs;
- **Number of mistakes.** The total number of mistakes made during the training is computed at the end of the training by summing up the number of undesired contact with arteries and veins, colon, pancreas and lateral peritoneum plus the number of times in which a placement has been performed with the wrong orientation; this is intended as the number of times in which the virtual VN collided with the haptic virtual models in the scene.

CHAPTER 6

DISCUSSION

The aim of this work was the development of a simulator based on haptics and virtual reality for training in Veress needle placement. It is addressed to urologists that routinely insert the VN as it is the starting step for all laparoscopic procedures. It represents a very risky step since is a blind insertion and the surgeon mainly relies on touch sensation when traversing the various layers of the abdomen. Furthermore this step is linked to a steep learning curve since it is performed only once at the beginning of laparoscopic procedures; for this reason the trainees are prevented from gaining experience and confidence in the surgery by only attending the operative room. In fact, most of the competencies obtained are due to situational events and thus the use of the simulator can accelerate the training phase reducing the learning time; moreover, it can potentially reduce the risks connected to this step for patients undergoing laparoscopic procedures as surgeons start operating. The developed simulator aims at overcoming the drawbacks of currently available solutions.

Unlike the animal models, it is anatomically accurate since the 3D models are segmented and extracted from real patient's CT images; another positive aspect is the avoiding of all the ethical concerns connected to the use of animals. Another strength of the application is the possibility to perform the task a potentially infinite number of times without redefining the experimental set-up, saving resources in terms of costs of the materials and effort in the continuous reset of the model. On the contrary this is no more true when it comes both to

animal models and non-biological prototypes. Furthermore, the trainee has the possibility to practice in a safe environment, outside the operating room and to acquire the necessary skills in correctly placing the Veress needle at the same time.

Even though the early prototype of the haptic VN insertion simulator described in Chapter 3 appeared and felt pretty realistic, no technical details were given by the authors regarding the realization other than the chosen values for stiffness and break force for the two different fascial layers. Moreover it has not been validated or ready for commercialization.

The simulator realized for this work was implemented with a reasonably low-cost hardware, the TouchTM 3D Stylus, while the software is composed by four C++ libraries; other tools are:

- The workstation constituted by a haptic device;
- A computer running with a Windows operating system;
- A 3D monitor to exploit the stereoscopic visualization.

The efficiency of *LACE Library* allows for a stable haptic effect despite the high computational load due to the heavy dataset and the well-defined 3D models in the graphic rendering. However, there are perceivable delays between the actual movement of the haptic stylus and the displacement of the needle on the screen. The application has not been assessed yet by experienced urologists as the validation step will take place in further studies.

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

This work describes the implementation of a simulator for Veress needle placement based on haptics and virtual reality. The application is built upon the *LACE Library*, a C++ based software developed by previous students from the Department of Bioengineering of University of Illinois at Chicago.

The achieved simulator integrated both visual and haptic information on a patient's 3D models of aorta, arteries and veins, bladder, colon, gallbladder, heart, inferior vena cava, kidneys, lateral abdomen, linea alba, liver, pancreas, portal vein, rectus abdominis, skin, spine, spleen, stomach and subcutaneous fat extracted from real volumetric dataset. It allows trainees to perform the Veress needle placement in a safe environment.

The aim of this simulator is to represent an important resource for the basic Urology training in obtaining the pneumoperitoneum. The emulation of the task with the haptics-based application may shorten the learning curve for the VN placement; in fact, it allows for repetitive skills training in a risk-free virtual environment. Practicing on this simulator is also likely to improve the necessary psychomotor skills.

Future Research and Development

For the next phase of validation, a sample of students, residents, fellows and faculty members will be recruited to perform the task with the simulator, and a survey will be conducted to

test the usefulness of the application and the realism of the simulation. This performance assessment has already been planned in the immediate future as a continuation of this work in collaboration with Politecnico di Milano.

Thanks to the implemented GUI, the subjects will be able to tune the haptic parameters in order to make the simulator as more realistic as possible. It is undeniable that a more powerful computer would allow us to obtain higher performances, both in terms of graphic and haptic accuracy.

Moreover, it could be useful to use the set of parameters saved in the text file to make some statistical considerations about them.

CITED LITERATURE

1. Cakir, T., Tüney, D., Esmailzadem, S., and Aktan, A.: Safe veress needle insertion. Journal of hepato-biliary-pancreatic surgery, 13:225–7, 02 2006.
2. Carter, B. N.: The fruition of halsted’s concept of surgical training. Surgery, 32(3):518–527, 1952.
3. Kotsis SV, C. K.: Assessment of surgical competence. Plast Reconstr Surg, 131(5):1194–201, 2013.
4. Wignall, G. R., Denstedt, J. D., Preminger, G. M., Cadeddu, J. A., Pearle, M. S., Sweet, R. M., and McDougall, E. M.: Surgical simulation: A urological perspective. The Journal of Urology, 179(5):1690–699, 2008.
5. Qayumi, K. and Vancouver: Surgical skills lab: a hub for competency training. Journal of Investigative Surgery, 23(1):48–56, 2010.
6. Vozenilek, J., Huff, J. S., Reznick, M. A., and Gordon, J. A.: See one, do one, teach one: Advanced technology in medical education. Academic emergency medicineofficial journal of the Society for Academic Emergency Medicine, 11(11):1149–1154, 2004.
7. Rohrich, R.: ”see one, do one, teach one”: An old adage with a new twist. Plastic and reconstructive surgery, 118:257–8, 08 2006.
8. Beard, J. D., Robinson, J., and Smout, J.: Problem-based learning for surgical trainees. Annals of the Royal College of Surgeons of England, 84(4):227–229, 2002.
9. Norman, G. and Schmidt, H. G.: The psychological basis of problem-based learning: A review of the evidence. Academic medicine, 67(9):557–565, 1992.
10. Beech, D. and R Damer, F.: Utility of the case-method approach for the integration of clinical and basic science in surgical education. Journal of cancer education : the official journal of the American Association for Cancer Education, 17:161–4, 02 2002.

CITED LITERATURE (continued)

11. Custers, E. J. F. M., Regehr, G., McCulloch, W., Peniston, C., and Reznick, R.: The effects of modeling on learning a simple surgical procedure: See one, do one or see many, do one? Advances in Health Sciences Education, 4(2):123–143, 1999.
12. Hamza Lup, F., Bogdan, C., Popovici, D., and Costea, O.: A survey of visuo-haptic simulation in surgical training. eLmL - International Conference on Mobile, Hybrid, and On-line Learning, pages 57–62, 01 2011.
13. Issenberg, S. B., McGaghie, W. C., Petrusa, E., Gordon, D. L., and Scalese, R. J.: Features and uses of high-fidelity medical simulations that lead to effective learning: a beme systematic review. Medical teacher, 27 1:10–28, 2005.
14. Trochim, W.: The research methods knowledge base, ed. 2. 01 2007.
15. Kirkman, M., Ahmed, M., F Albert, A., Wilson, M., Nandi, D., and Sevdalis, N.: The use of simulation in neurosurgical education and training: A systematic review. Journal of neurosurgery, 121:1–19, 06 2014.
16. Satava, R. M.: The revolution in medical education - the role of simulation. Journal of graduate medical education, 1(2):172–175, 2009.
17. Darzi, A. and Mackay, S.: Assessment of surgical competence. BMJ Quality & Safety, 10(suppl 2):ii64–ii69, 2001.
18. Wignall, G. R., Denstedt, J. D., Preminger, G. M., Cadeddu, J. A., Pearle, M. S., Sweet, R. M., and McDougall, E. M.: Surgical simulation: a urological perspective. The Journal of urology, 179(5):1690–1699, 2008.
19. J, V.: Neues instrument zur ausführung von brust-oder bauchpunktionen und pneumothoraxbehandlung. Deut Med Wochenschr, 64: 1480-1481, 1938.
20. Merriam-webster online dictionary. www.merriam-webster.com,. [Online; Accessed 2019-03-21].
21. The history of medical simulation. Journal of Critical Care, 23(2):157 – 166, 2008.
22. Richardson, R. E. and Sutton, C. J.: Complications of first entry: a pospective laparoscopy audit. Gynaecological Endoscopy, 8(6):327–334, 1999.

CITED LITERATURE (continued)

23. Richardson RF, S. C.: Complications of the first entry: a prospective laparoscopic audit. Gynaecol Endosc, 8: 327-34, 1999.
24. Liss, M. A. and McDougall, E. M.: Robotic surgical simulation. The Cancer Journal, 19(2):124–129, 2013.
25. Aggarwal, G. and Adhikary, S. D.: Simulators in the urological training armamentarium: A boon or a bane? Arab Journal of Urology, 15(2):166 – 169, 2017.
26. O'malley, M. K., Celik, O., Huegel, J. C., Byrne, M. D., Bismuth, J., Dunkin, B. J., Goh, A. C., and Miles, B. J.: Robotics as a tool for training and assessment of surgical skill. In Computational Surgery and Dual Training, pages 365–375. Springer, 2014.
27. Reznick, R. K. and MacRae, H.: Teaching surgical skills—changes in the wind. New England Journal of Medicine, 355(25):2664–2669, 2006.
28. Seymour, N. E.: Vr to or: a review of the evidence that virtual reality simulation improves operating room performance. World journal of surgery, 32(2):182–188, 2008.
29. Anderson, J. E., Chang, D. C., Parsons, J. K., and Talamini, M. A.: The first national examination of outcomes and trends in robotic surgery in the united states. Journal of the American College of Surgeons, 215(1):107–114, 2012.
30. Definition of virtual reality, vr. <https://www.dictionary.com/browse/virtual-reality>,. [Online; Accessed 2019-02-15].
31. Ready, L.: Acute pain: Lessons learned from 25,000 patients. Regional Anesthesia and Pain Medicine, 24(6):499 – 505, 1999.
32. Talbot, T. B.: Balancing physiology, anatomy and immersion: How much biological fidelity is necessary in a medical simulation? Military medicine, 178(suppl.10):28–36, 2013.
33. Coles, T. and John, N.: The effectiveness of commercial haptic devices for use in virtual needle insertion training simulations. pages 148–153, 01 2010.
34. Ravali, G. and Muniyandi, M.: Haptic feedback in needle insertion modeling and simulation: Review. IEEE Reviews in Biomedical Engineering, PP, 05 2017.

CITED LITERATURE (continued)

35. Yun, J., Kim, H. W., Kim, H.-I., and Lee, J.-H.: Electrical impedance spectroscopy on a needle for safer veress needle insertion during laparoscopic surgery. Sensors and Actuators B: Chemical, 250:453 – 460, 2017.
36. D., O.: Laparoscopic cholecystectomy. American Journal of Surgery, 161:339–344, 1991.
37. Azevedo, João Luiz Moreira Coutinho & Azevedo, e. a.: Injuries caused by veress needle insertion for creation of pneumoperitoneum: a systematic literature review. Surgical Endoscopy, 23(7):1428–1432, Jul 2009.
38. Fundamentals of Laparoscopic Surgery, pages 3–17. Berlin, Heidelberg, Springer Berlin Heidelberg, 2008.
39. Shabanzadeh, D. M. and Sørensen, L. T.: Laparoscopic surgery compared with open surgery decreases surgical site infection in obese patients: a systematic review and meta-analysis. Annals of surgery, 256(6):934–945, 2012.
40. Ahmad, G., O’Flynn, H., Duffy, J. M., Phillips, K., and Watson, A.: Laparoscopic entry techniques. Cochrane database of systematic reviews, 2012.
41. Hasson, H. M.: Open laparoscopy as a method of access in laparoscopic surgery. Gynaecological Endoscopy, 8(6):353–362, 1999.
42. Molloy, D., Kaloo, P. D., Cooper, M., and Nguyen, T. V.: Laparoscopic entry: a literature review and analysis of techniques and complications of primary port entry. Australian and New Zealand journal of obstetrics and gynaecology, 42(3):246–254, 2002.
43. Jansen, F. W., Kolkman, W., Bakkum, E. A., de Kroon, C. D., Trimbos-Kemper, T. C., and Trimbos, J. B.: Complications of laparoscopy: an inquiry about closed versus open-entry technique. American journal of obstetrics and gynecology, 190(3):634–638, 2004.
44. Sharp, H. T., Dodson, M. K., Draper, M. L., Watts, D. A., Doucette, R. C., and Hurd, W. W.: Complications associated with optical-access laparoscopic trocars. Obstetrics & Gynecology, 99(4):553–555, 2002.
45. Palmer, R.: Safety in laparoscopy. Journal of Reproductive Medicine, 13(1):1–5, 1974.
46. Hibner, M & Desai, N.: Open Laparoscopy. 2008.

CITED LITERATURE (continued)

47. Soper, N. J.: Access to Abdomen, pages 16–30. New York, NY, Springer New York, 2006.
48. Liss, M. A. and McDougall, E. M.: Robotic surgical simulation. The Cancer Journal, 19(2):124–129, 2013.
49. Lapsim — surgical science, inc. <https://surgicalscience.com/systems/lapsim/>,. [Online; Accessed 2019-04-08].
50. Lap mentor — simbionix. <https://simbionix.com/simulators/lap-mentor/>,. [Online; Accessed 2019-04-08].
51. da vinci[®] skills simulator — intuitive surgical. <https://www.intuitive.com/en-us/products-and-services/da-vinci/>,. [Online; Accessed 2019-04-08].
52. dv-trainer[®] — mimic simulation. <https://mimicsimulation.com/dv-trainer/>,. [Online; Accessed 2019-04-08].
53. Ross[™] — simulated surgical systems. <http://www.simulatedsurgicals.com/ross2.html>. Accessed: 2019-04-08.
54. Jansen, F. W., Kapiteyn, K., Trimbos-Kemper, T., Hermans, J., and Trimbos, J. B.: Complications of laparoscopy: a prospective multicentre observational study. BJOG: An International Journal of Obstetrics & Gynaecology, 104(5):595–600, 1997.
55. Harkki-Sirén, P. and Kurki, T.: A nationwide analysis of laparoscopic complications. Obstetrics & Gynecology, 89(1):108 – 112, 1997.
56. Okrainec, A., Farcas, M., Henao, O., Choy, I., Green, J., Fotoohi, M., Leslie, R., Wight, D., Karam, P., Gonzalez, N., and Apkarian, J.: Development of a virtual reality haptic veress needle insertion simulator for surgical skills training. Studies in health technology and informatics, 142:233–8, 02 2009.
57. Perc mentor — simbionix. <https://simbionix.com/simulators/perc-mentor/>,. [Online; Accessed 2019-04-08].
58. Noureldin, Y. A. and Andonian, S.: Simulation for percutaneous renal access: Where are we? Journal of endourology, 2016.
59. Turp mentor — simbionix. <https://simbionix.com/simulators/turp-mentor/>,. [Online; Accessed 2019-04-08].

CITED LITERATURE (continued)

60. UrosimTM — vitamed ag. <https://www.virtamed.com/en/medical-training-simulators/uros/>,. [Online; Accessed 2019-04-08].
61. Maestro ar[®] system — mimic technologies. <https://mimicsimulation.com/maestro-ar/>,. [Online; Accessed 2019-04-08].
62. TouchTM 3d stylus— 3d systems. <https://www.3dsystems.com/haptics-devices/touch>,. [Online; Accessed 2019-04-12].
63. Openhaptic toolkit overview. <http://www.geomagic.com/it/products/open-haptics/overview>,. Online; Accessed 2019-03-17.
64. Andrea, F.: Haptic and Virtual Reality Surgical Simulator for Training in Percutaneous Renal Access. Master's thesis, University of Illinois at Chicago, Bioengineering, 2017.
65. Lorenzo, R.: Virtual Reality Navigation System for Prostate Biopsy. Master's thesis, University of Illinois at Chicago, Bioengineering, 2017.
66. Eleonora, T.: Visuo-Haptic Model of Prostate Cancer Based on Magnetic Resonance Elastography. Master's thesis, University of Illinois at Chicago, Bioengineering, 2017.
67. Cecilia, G.: Application of Haptic Virtual Fixtures in Psychomotor Skill Development for Robotic Surgical Training. Master's thesis, University of Illinois at Chicago, Bioengineering, 2017.
68. Wykobi computational geometry library. <http://www.wykobi.com/>,. [Online; Accessed 2019-04-12].
69. Ascension technology corp. <https://www.ascension-tech.com/>,. [Online; Accessed 2019-04-12].
70. Fusion 360TM — autodesk[®]. <https://www.autodesk.com/products/fusion-360/overview>,. [Online; Accessed 2019-04-19].
71. 3ds max — 3d modeling, animation and rendering software — autodesk. <http://www.autodesk.com/products/3ds-max/overview>,. [Online; Accessed 2019-03-17].

CITED LITERATURE (continued)

72. Paul A. Yushkevich, e. a.: User-guided 3d active contour segmentation of anatomical structures: Significantly improved efficiency and reliability. NeuroImage, 31(3):1116 – 1128, 2006.
73. itk-snap. <http://www.itksnap.org/pmwiki/pmwiki.php>,. [Online; Accessed 2019-03-17].
74. Dicom library. <https://www.dicomlibrary.com>,. [Online; Accessed 2019-03-17].
75. Wacom intuos pro: Creative pen tablet — wacom. <https://www.wacom.com/en-us/products/pen-tablets/wacom-intuos-pro>,. [Online; Accessed 2019-03-17].
76. Zbrush — pixologic. <http://pixologic.com/features/about-zbrush.php>,. [Online; Accessed 2019-03-17].
77. Paraview. <http://www.paraview.org/>,. [Online; Accessed 2019-03-17].
78. Williams, C. K. and Carnahan, H.: Motor learning perspectives on haptic training for the upper extremities. IEEE transactions on haptics, 7(2):240–250, 2014.
79. Volante, M., Babu, S. V., Chaturvedi, H., Newsome, N., Ebrahimi, E., Roy, T., Daily, S. B., and Fasolino, T.: Effects of virtual human appearance fidelity on emotion contagion in affective inter-personal simulations. IEEE transactions on visualization and computer graphics, 22(4):1326–1335, 2016.
80. McDougall, E. M.: Validation of surgical simulators. Journal of endourology, 21(3):244–247, 2007.
81. Uro mentor — simbionix. <https://simbionix.com/simulators/uro-mentor/>,. [Online; Accessed 2019-04-08].
82. Haptic products — geomagic. <http://www.geomagic.com/en/>,. [Online; Accessed 2019-03-17].
83. imstk — kitware. <https://www.imstk.org>,. [Online; Accessed 2019-04-21].

APPENDICES

Appendix A

ALGORITHM

This appendix includes the code for the computation of the relative angle between the skin and the Veress needle, explained in Chapter 5.

```

1 static hduMatrix oriS;
2 static hduMatrix oriVN;
3 static hduMatrix relmat;
4 static hduMatrix relmat2;
5 static hduVector3Dd axis;
6 static double x, y, z;
7
8 oriS = SkinProcedureH->QH_Geometry->getTransform();
9 oriS.getInverse();
10 oriVN = VeressNeedleFixed->QH_Geometry->getTransform();
11
12 relmat = oriS * oriVN;
13 relmat.getRotationMatrix(relmat2);
14
15 toEulerAngle(relmat2, x, y, z);
16
17 angle = VNP::pi - abs(z);
18
19 if ((abs(angle) > (anglelowerth * (pi/180))) && (abs(angle) < (angleupperth * (pi/180)))
20     )
21 {

```

Appendix A (continued)

```
21     std::cout << "correct_placement!" << (abs(angle * (180/pi))) << std::endl;
22 }
23 else
24 {
25     std::cout << "wrong_placement!" << (abs(angle * (180/pi))) << std::endl;
26     PlacementError += abs(45.00 - (angle * (180/pi)));
27 }
```

Appendix B

COPYRIGHT PERMISSION 1

This appendix includes the terms under which Table II is copyrighted.

Appendix B (continued)

RightsLink Printable License

4/23/19, 11:49 AM

ELSEVIER ORDER DETAILS

Apr 23, 2019

Order Number	501480507
Order date	Apr 23, 2019
Licensed Content Publisher	Elsevier
Licensed Content Publication	The Journal of Urology
Licensed Content Title	Surgical Simulation: A Urological Perspective
Licensed Content Author	Geoffrey R. Wignall, John D. Denstedt, Glenn M. Preminger, Jeffrey A. Cadeddu, Margaret S. Pearle, Robert M. Sweet, Elspeth M. McDougall
Licensed Content Date	May 2008
Licensed Content Volume	179
Licensed Content Issue	5
Licensed Content Pages	10
Start Page	1690
End Page	1699
Type of Use	reuse in a thesis/dissertation
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Format	electronic
Are you the author of this Elsevier article?	No
Will you be translating?	No
Original figure numbers	Appendix: Categories of Surgical Simulation
Title of your thesis/dissertation	Improvement of Psychomotor Skills Development for Veress Needle Placement with Haptics and Virtual Reality
Publisher of new work	University of Illinois at Chicago
Expected completion date	May 2019
Estimated size (number of pages)	1
Requestor Location	Mrs. Chiara Di Vece 59 east van buren street apt 303 CHICAGO, IL 60605 United States Attn: Mrs. Chiara Di Vece
Publisher Tax ID	98-0397604

Appendix C

COPYRIGHT PERMISSION 2

This appendix includes the terms under which Figure 2 is copyrighted.

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

ELSEVIER LICENSE TERMS AND CONDITIONS

Apr 23, 2019

This Agreement between Mrs. Chiara Di Vece ("You") and Elsevier ("Elsevier") consists of your license details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

License Number	4574860829772
License date	Apr 23, 2019
Licensed Content Publisher	Elsevier
Licensed Content Publication	Sensors and Actuators B: Chemical
Licensed Content Title	Electrical impedance spectroscopy on a needle for safer Veress needle insertion during laparoscopic surgery
Licensed Content Author	Joho Yun,Hyeon Woo Kim,Hyoung-Ihl Kim,Jong-Hyun Lee
Licensed Content Date	Oct 1, 2017
Licensed Content Volume	250
Licensed Content Issue	n/a
Licensed Content Pages	8
Start Page	453
End Page	460
Type of Use	reuse in a thesis/dissertation
Intended publisher of new work	other
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Format	print
Are you the author of this Elsevier article?	No
Will you be translating?	No
Original figure numbers	Figure 1: Measurement of impedance during Veress needle insertion
Title of your thesis/dissertation	Improvement of Psychomotor Skills Development for Veress Needle Placement with Haptics and Virtual Reality
Publisher of new work	University of Illinois at Chicago
Expected completion date	May 2019
Estimated size (number of pages)	1

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

Requestor Location Mrs. Chiara Di Vece
59 east van buren street
apt 303

CHICAGO, IL 60605
United States
Attn: Mrs. Chiara Di Vece

Publisher Tax ID 98-0397604

Total 0.00 USD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at <http://myaccount.copyright.com>).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.
3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:
"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."
4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.
5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier at permissions@elsevier.com). No modifications can be made to any Lancet figures/tables and they must be reproduced in full.
6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.
7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.
8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. **Translation:** This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.

16. **Posting licensed content on any Website:** The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

included to the Homepage of the journal from which you are licensing at <http://www.sciencedirect.com/science/journal/xxxxx> or the Elsevier homepage for books at <http://www.elsevier.com>; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.

Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at <http://www.elsevier.com>. All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

17. For journal authors: the following clauses are applicable in addition to the above:

Preprints:

A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).

Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).

If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.

Authors can share their accepted author manuscript:

- immediately
 - via their non-commercial person homepage or blog
 - by updating a preprint in arXiv or RePEc with the accepted manuscript
 - via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group
 - directly by providing copies to their students or to research collaborators for their personal use
 - for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement
- After the embargo period
 - via non-commercial hosting platforms such as their institutional repository
 - via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

- link to the formal publication via its DOI
- bear a CC-BY-NC-ND license - this is easy to do
- if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment. Policies for sharing publishing journal articles differ for subscription and gold open access articles:

Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.

Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a [CrossMark logo](#), the end user license, and a DOI link to the formal publication on ScienceDirect.

Please refer to Elsevier's [posting policy](#) for further information.

18. **For book authors** the following clauses are applicable in addition to the above:

Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version. **Posting to a repository:** Authors are permitted to post a summary of their chapter only in their institution's repository.

19. **Thesis/Dissertation:** If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions

You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our [open access license policy](#) for more information.

Terms & Conditions applicable to all Open Access articles published with Elsevier:

Appendix C (continued)

RightsLink Printable License

4/23/19, 11:21 AM

Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated.

The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect.

If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.

Additional Terms & Conditions applicable to each Creative Commons user license:

CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at <http://creativecommons.org/licenses/by/4.0>.

CC BY NC SA: The CC BY-NC-SA license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at <http://creativecommons.org/licenses/by-nc-sa/4.0>.

CC BY NC ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at <http://creativecommons.org/licenses/by-nc-nd/4.0>. Any commercial reuse of Open Access articles published with a CC BY NC SA or CC BY NC ND license requires permission from Elsevier and will be subject to a fee.

Commercial reuse includes:

- Associating advertising with the full text of the Article
- Charging fees for document delivery or access
- Article aggregation
- Systematic distribution via e-mail lists or share buttons

Posting or linking by commercial companies for use by customers of those companies.

20. Other Conditions:

v1.9

Questions? customer-care@copyright.com or +1-855-239-3415 (toll free in the US) or +1-978-646-2777.

Appendix D

COPYRIGHT PERMISSION 3

This appendix includes the terms under which Figure 6 is copyrighted.

Appendix D (continued)

RightsLink Printable License

4/23/19, 3:00 AM

SPRINGER NATURE LICENSE TERMS AND CONDITIONS

Apr 23, 2019

This Agreement between Mrs. Chiara Di Vece ("You") and Springer Nature ("Springer Nature") consists of your license details and the terms and conditions provided by Springer Nature and Copyright Clearance Center.

License Number	4574660938334
License date	Apr 23, 2019
Licensed Content Publisher	Springer Nature
Licensed Content Publication	Springer eBook
Licensed Content Title	Fundamentals of Laparoscopic Surgery
Licensed Content Date	Jan 1, 2008
Type of Use	Thesis/Dissertation
Requestor type	academic/university or research institute
Format	electronic
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Will you be translating?	no
Circulation/distribution	<501
Author of this Springer Nature content	no
Title	Improvement of Psychomotor Skills Development for Veress Needle Placement with Haptics and Virtual Reality
Institution name	University of Illinois at Chicago
Expected presentation date	May 2019
Order reference number	11
Portions	Figure 11 - Veress needle introduction (page 11)
Requestor Location	Mrs. Chiara Di Vece 59 east van buren street apt 303 CHICAGO, IL 60605 United States Attn: Mrs. Chiara Di Vece
Total	0.00 USD
Terms and Conditions	

Appendix D (continued)

RightsLink Printable License

4/23/19, 3:00 AM

Springer Nature Terms and Conditions for RightsLink Permissions

Springer Nature Customer Service Centre GmbH (the Licensor) hereby grants you a non-exclusive, world-wide licence to reproduce the material and for the purpose and requirements specified in the attached copy of your order form, and for no other use, subject to the conditions below:

1. The Licensor warrants that it has, to the best of its knowledge, the rights to license reuse of this material. However, you should ensure that the material you are requesting is original to the Licensor and does not carry the copyright of another entity (as credited in the published version).

If the credit line on any part of the material you have requested indicates that it was reprinted or adapted with permission from another source, then you should also seek permission from that source to reuse the material.

2. Where **print only** permission has been granted for a fee, separate permission must be obtained for any additional electronic re-use.
3. Permission granted **free of charge** for material in print is also usually granted for any electronic version of that work, provided that the material is incidental to your work as a whole and that the electronic version is essentially equivalent to, or substitutes for, the print version.
4. A licence for 'post on a website' is valid for 12 months from the licence date. This licence does not cover use of full text articles on websites.
5. Where **'reuse in a dissertation/thesis'** has been selected the following terms apply: Print rights of the final author's accepted manuscript (for clarity, NOT the published version) for up to 100 copies, electronic rights for use only on a personal website or institutional repository as defined by the Sherpa guideline (www.sherpa.ac.uk/romeo/).
6. Permission granted for books and journals is granted for the lifetime of the first edition and does not apply to second and subsequent editions (except where the first edition permission was granted free of charge or for signatories to the STM Permissions Guidelines <http://www.stm-assoc.org/copyright-legal-affairs/permissions/permissions-guidelines/>), and does not apply for editions in other languages unless additional translation rights have been granted separately in the licence.
7. Rights for additional components such as custom editions and derivatives require additional permission and may be subject to an additional fee. Please apply to Journalpermissions@springernature.com/bookpermissions@springernature.com for these rights.
8. The Licensor's permission must be acknowledged next to the licensed material in print. In electronic form, this acknowledgement must be visible at the same time as the figures/tables/illustrations or abstract, and must be hyperlinked to the journal/book's homepage. Our required acknowledgement format is in the Appendix below.
9. Use of the material for incidental promotional use, minor editing privileges (this does not include cropping, adapting, omitting material or any other changes that affect the meaning, intention or moral rights of the author) and copies for the disabled are permitted under this licence.
10. Minor adaptations of single figures (changes of format, colour and style) do not require the Licensor's approval. However, the adaptation should be credited as shown in Appendix below.

Appendix D (continued)

RightsLink Printable License

4/23/19, 3:00 AM

Appendix — Acknowledgements:

For Journal Content:

Reprinted by permission from [the Licensors]: [Journal Publisher (e.g. Nature/Springer/Palgrave)] [JOURNAL NAME] [REFERENCE CITATION (Article name, Author(s) Name), [COPYRIGHT] (year of publication)]

For Advance Online Publication papers:

Reprinted by permission from [the Licensors]: [Journal Publisher (e.g. Nature/Springer/Palgrave)] [JOURNAL NAME] [REFERENCE CITATION (Article name, Author(s) Name), [COPYRIGHT] (year of publication), advance online publication, day month year (doi: 10.1038/sj.[JOURNAL ACRONYM].)]

For Adaptations/Translations:

Adapted/Translated by permission from [the Licensors]: [Journal Publisher (e.g. Nature/Springer/Palgrave)] [JOURNAL NAME] [REFERENCE CITATION (Article name, Author(s) Name), [COPYRIGHT] (year of publication)]

Note: For any republication from the British Journal of Cancer, the following credit line style applies:

Reprinted/adapted/translated by permission from [the Licensors]: on behalf of Cancer Research UK: : [Journal Publisher (e.g. Nature/Springer/Palgrave)] [JOURNAL NAME] [REFERENCE CITATION (Article name, Author(s) Name), [COPYRIGHT] (year of publication)]

For Advance Online Publication papers:

Reprinted by permission from The [the Licensors]: on behalf of Cancer Research UK: [Journal Publisher (e.g. Nature/Springer/Palgrave)] [JOURNAL NAME] [REFERENCE CITATION (Article name, Author(s) Name), [COPYRIGHT] (year of publication), advance online publication, day month year (doi: 10.1038/sj.[JOURNAL ACRONYM].)]

For Book content:

Reprinted/adapted by permission from [the Licensors]: [Book Publisher (e.g. Palgrave Macmillan, Springer etc)] [Book Title] by [Book author(s)] [COPYRIGHT] (year of publication)]

Other Conditions:

Version 1.1

Questions? customercare@copyright.com or +1-855-239-3415 (toll free in the US) or +1-978-646-2777.

VITA

NAME	Chiara Di Vece
EDUCATION	
Spring 2018 - On date	Master of Science in BioEngineering, University of Illinois at Chicago, USA
Fall 2017 - On date	Master Degree in Biomedical Engineering - BioTechnologies for Electronics (BTE), Politecnico di Milano, Italy
Fall 2017 - On date	Alta Scuola Politecnica, joint honors program of Politecnico di Milano and Politecnico di Torino - Double Degree with Politecnico di Torino
Fall 2014 - Spring 2017	Bachelor Degree in Biomedical Engineering (BE), Jul 2016, Politecnico di Milano, Italy
LANGUAGE SKILLS	
Italian	Native speaker
English	Full working proficiency
	A.Y. 2018/19 One Year of study abroad in Chicago, Illinois
	A.Y. 2017/2019 Lessons and exams attended exclusively in English
	2017 - IELTS examination
SCHOLARSHIPS	
Spring 2019	Teaching Assistantship (TA) position (20 hours/week) with full tuition waiver plus monthly stipend
TECHNICAL SKILLS	
Languages	Programming (C, C++ (basic), Python, MATLAB, LaTeX)
Operating Systems	Mac OS X, Linux, Microsoft Windows
Softwares	Microsoft Office, SQL, SolidWorks, AutoCAD, VolView, ParaView, itk-SNAP, Photoshop, inDesign
Tools	Git, iMSTK
Good level	Problem Solving

VITA (continued)

EXPERIENCE

Spring 2019 - On date	Graduate Research Fellow, Department of Urology, University of Illinois at Chicago, USA
Spring 2019 - On date	Teaching Assistant, Department of Bioengineering, Course: BIOE 310 - Biosystems Analysis, University of Illinois at Chicago, USA
Fall 2017	Chicago Mobility Hackathon.
June 2017	Xilinx Open Hardware Contest, Finalist.
July 2016	Xilinx Pynq Hackathon.

PUBLICATIONS

Spring 2019	G. Crocioni, C. Di Vece, H. Esmailbeigi. GLOS: GLOve for Speech Recognition. <i>2019 41th International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)</i> , (pp. 4), IEEE.
Fall 2017	F. Bracco, C. Di Vece, L. Cerina, M. D. Santambrogio. BIE-PInCS: Brain Injury Evaluation with Pupillometer based on INfrared Camera System. <i>2017 IEEE 3rd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI)</i> , (pp. 5), IEEE.

AWARDS

Jan 2018	2017 Lance Stafford Larson Writing Award for undergraduate students, IEEE Computer Society.
Sept 2017	Young Professional Demo Competition Event 2017 RTSI 2017, 1st place with BIE- PInCS: Brain Injury Evaluation with Pupillometer based on INfrared Camera System.
