Surgical Virtual Reality-Highlights in Developing a Surgical Haptic Device

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Abstract

Just like simulators are a standard in aviation and aerospace sciences, we expect for surgical simulators to soon become a standard in medical applications. These will correctly instruct future doctors in surgical techniques without there being a need for hands on patient instruction. Using virtual reality by digitally transposing surgical procedures changes surgery in a revolutionary manner by offering possibilities for implementing new, much more efficient, learning methods, by allowing the practice of new surgical techniques and by improving surgeon abilities and skills. Perfecting haptic devices has opened the door to a series of opportunities in the fields of research, industry, nuclear science and medicine. Concepts purely theoretical at first, such as *telerobotics, telepresence* or *telerepresentation,* have become a practical reality as calculus techniques, telecommunications and haptic devices evolved, virtual reality taking a new leap. In the field of surgery barriers and controversies still remain, regarding implementation and generalization of surgical virtual simulators. These obstacles remain connected to the high costs of this yet fully sufficiently developed technology, especially in the domain of haptic devices.

Keywords: surgical virtual reality; haptic device; virtual surgical training; surgical simulator

Introduction

Traditionally, applying a surgical technique involves an interaction of the surgeon with the patient, with his/her tissues (the barrier among surgeon and patients being at most represented by the surgical instrument kit), and dexterity can be increased only by amplifying perceptions (optical devices). The fusion among calculus technique, robotics, haptic devices, telecommunications and virtual reality (VR) make possible the situation in which a surgical intervention can be "mimicked" in real time, with the surgeon having the possibility to study various operative variants, to redo certain operative stages or to complete his/her surgical training. Also, the "distant (tele)" surgery and programming of the main surgeon's robotic aids for a certain type of operation on a patient are accessible.

The first steps towards this direction have already been made, meaning that surgical interventions have been performed outside the operating theatre, from another hospital or from another continent even [1]. Using virtual reality by digitally transposing surgical procedures changes surgery in a revolutionary manner, by offering possibilities for implementing new, much more efficient, learning methods, by allowing the practice of new surgical techniques and by improving surgeon abilities and skills.

In the last decade, we observed an increased interest towards developing haptic devices. In an attempt to better understand and use the abilities of these devices (both human and non-human) research activity in fields such as robotics and telerobotics, computational geometry and computer graphics, psychophysiology, cognitive sciences and neurosciences has been largely supported [2].

A Brief History

The term *haptics* was introduced at the beginning of the 20^{th} century, in the 1920s, by researchers in the fields of experimental psychology, making reference to the active touch of real objects by people. It is derived from the Greek word "*haptesthai*" (tactile sense) and scientifically refers to both sense of touch and tactile handling [3]. In other words, a haptic device is one ensuring "physical contact" between the virtual space and the user. By using a haptic device the user not only has the possibility of transmitting information to the computer, but also of receiving information back, as sensations.

Developing these technologies ultimately allows the separation, in time and space, of the surgeon from the patient: be it a virtual

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or real patient [4]. Based on the ideas of the first simulator built by Morton Heilig in 1960, Robert Mann proposed the first medical system in VR, in 1965. The system allowed the operator to take different approaches on a given orthopaedic problem. Thus, the surgeon could choose the optimal solution for the real surgery. Despite its simplicity, the system proved 3 major benefits: it could be customized for students and residents, it could enact a variety of cases (significantly larger in comparison to real situations presented during the internship period), and residents could train for the more difficult operative stages, whenever the situation required it. A highly efficient training instrument in surgical techniques was foreseeable, useful also in objectively evaluating user knowledge and dexterity [1]. The only and most important impediments against this idea for many years remained the high costs of the systems and their performance limitations [4].

Between the years 1970 and 1980, research conducted in a completely separate domain, robotics began focusing on tactile perception. In an initial attempt to build autonomous robots, researchers discovered the fact that a functional robotic hand is a far more complex process than initially hoped for. At the end of the 1980s, the term was redefined to include all aspects connected to tactile sense and tactile interaction between man and machine [5,6].

Even if from a technological point of view it can be said that huge steps have been made, the schooling method and surgical training have remained, practically, the same: young surgeons are instructed by specialized literature reading, through lectures, by viewing surgical interventions and finally by performing the surgical intervention under careful supervision. Interactive haptic devices with kinaesthetic or tactile force-feedback function have become indispensable for the current tendency of improving the sensation of immersing into a virtual system [1,4,5,6].

The Haptic System

At present, the term has brought together various disciplines (biomechanics, psychology, neurophysiology, engineering, and informatics) which use this term to refer to the study of human tactile perception and force-feedback with the outer environment. "Touching" of certain objects can be accomplished by people (*human haptics*), by machines (*machine haptics*) or by a combination of the two (*computer haptics or haptic rendering*), and the environment can be real, virtual, or a combination of the two. Also, the interaction can or cannot be accompanied by other sensorial perceptions such as sight or hearing (*multimedia haptics*: *Haptic-Audio-Visual Multimedia System*) [4,5].

Human haptics

A human haptic device refers to the study of the method of detection and handling of objects through tactile and kinaesthetic sensations [4]. There are four types of sensors at the level of the hand's tegument mediating the sense of touch (Meissner and Pacini corpuscles, Merkel disks and Ruffini terminations). These receptors' rate of adapting to stimuli, their location within the tegument, their area of receptiveness, their response frequency rate and maximum sensitivity rate are, at least partially, understood. Their response time varies between 50-500 msec. The quality of tactile perception is determined by the combination of sensations at different type of receptors' level. This "teamwork" leads to a gradual perception of vibrations, 0.04 to over 500 Hz [7] and decreases with the shortening of the time length of action against these receptors. It allows bidirectional energy flow with information exchange between the real or virtual environment and the final user (person), when it comes to active touch (Figure 1).

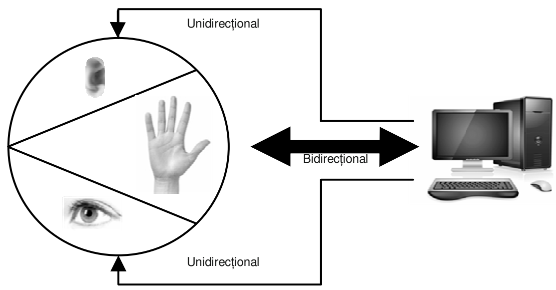

Figura 1. The distinctive characteristic of haptic devices: bidirectional information flow (2)

These details are reference points in the conception and evaluation of haptic devices (the stimulus' area of action, duration, and signal frequency) [8].

The experiments aimed at detecting the threshold for perceiving tension at finger pulp level [7] determined that this liminal threshold is strictly dependent on movement at tegument contact level (velocity, direction, rotation), viscosity and temperature. Thus, in order to feel the shape of an object, the subject must touch the entire surface of the aforementioned object, to handle it, in order to build a mental image of it. This co-dependence between tactile senses and handling is part of understanding the way in which people can interact in such a complex and deft manner with the physical world [2].

Machine haptics

Given the physiological limits of human tactile sense one proceeded to designing, building and developing mechanical systems which replace or augment this perception. This device, also known as *haptic interface* is set in direct contact with the human body in order to mediate information exchange with the central nervous system.

Haptic interfaces have two main functions: first of all they inform one of the position and/or orientation in space, of the contact forces from any side of the human body, and secondly, they generate information at tactile impulses determined by a virtual object in the script, such as rigidity, rugosity, friction etc. The devices can generate vibrations, temperature, pressure at the level of the human tegument.

This mechanical stimulation can be used to create virtual objects, to control and improve distant control of machines or mechanical devices [2]. Force feed-back is the component of a haptic device (software and hardware) which interacts with the muscular and osteotendinous systems, determining the human sensation of an opposing force applied and stimulating the sensation of touch, vibration and temperature (forces opposing to the user, corresponding to the virtual environment described: temperature, pressure, texture) [1,9]. It is the device which indicates when the user is or is not in contact with the virtual object. Force feed-back is archived as opposing forces against the user in the 3 spatial axes x, y and z.

Haptic systems with force feed-back function have known a considerably faster evolution compared to the display component [1]. In case of handling an object in the 3 axes (left/right, up/down, rotation and/or near/far) a haptic system must be capable of running a command by gradually exerting forces against the virtual object. These are highly dependent on the type of movement performed by the user. In other words, we can say that the movement recommended in a certain circumstance will be dependent on the forces exerted by the user, meaning on his/her dexterity. The manner in which the object “responds” to this manipulation is generally dependent on the laws of physics. This signal will trigger a response from the haptic system, which will be transmitted to the user, thus guiding future handlings of the object. The main components of the application are (figure 2):

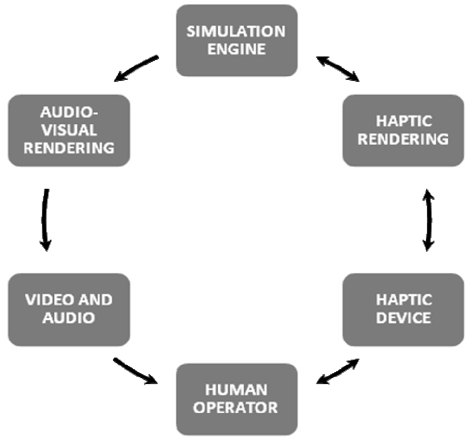

Figure 2. Haptic Interface Components

a) the simulation engine responsible for the behaviour of the virtual environment;
b) the haptic rendering algorithms, representing graphical, audio and video calculations, as well as calculations of the forces responding to the user’s manoeuvres;
c) transducers converting the signals arising from the rendering algorithms into a form in which the user can perceive them [6].

An ideal haptic device requires a sufficiently large movement field, low inertia, solidity, decreased friction forces, control in a large broadband etc. However, it is practically impossible to build a haptic device which will meet all of these requirements [10].

Computer haptics

This field is connected to designing and developing specific algorithms and software, which compose the interaction forces and physically simulate the properties of the objects touched (detecting possible collisions with the algorithms of forces involved in various actions). In essence, it deals with modelling reactions and rendering in real time of virtual object reactions to handling (haptic rendering analogue with graphic rendering). We anticipate a fast development of this field, as computers reach new levels of performance, and increasingly sophisticated software programming instruments become more accessible [11]. Therefore, computer haptics offer software architecture for haptic interactions and synchronising with display methods [5] (Figure 3).

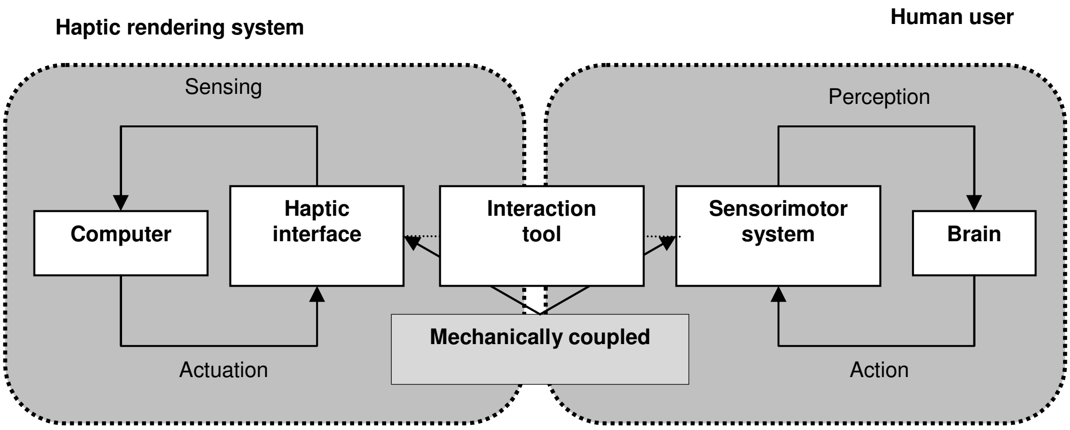

Figure 3. Computer haptic – the general scheme (5)

Multimedia haptics

The field defines the haptic device as a media channel in a system. The technologies used in developing haptic devices, including of conventional multimedia devices, have the potential to evolve into a **haptic-audio-visual multimedia system** which can offer more interactive and captivating experiences in the virtual environment [2].

How a Haptic System Operates

From what has been said we can state with certainty that a haptic system is comprised of two components: the human part and the machine part – practically being a new "man-machine" concept.

In Figure 4, the human part (left) senses (by means of receptors) and controls (cerebrally) the position and motor activity of the hand, and the machine part (right) exerts forces at the level of the hand in order to simulate contact with virtual objects [5].

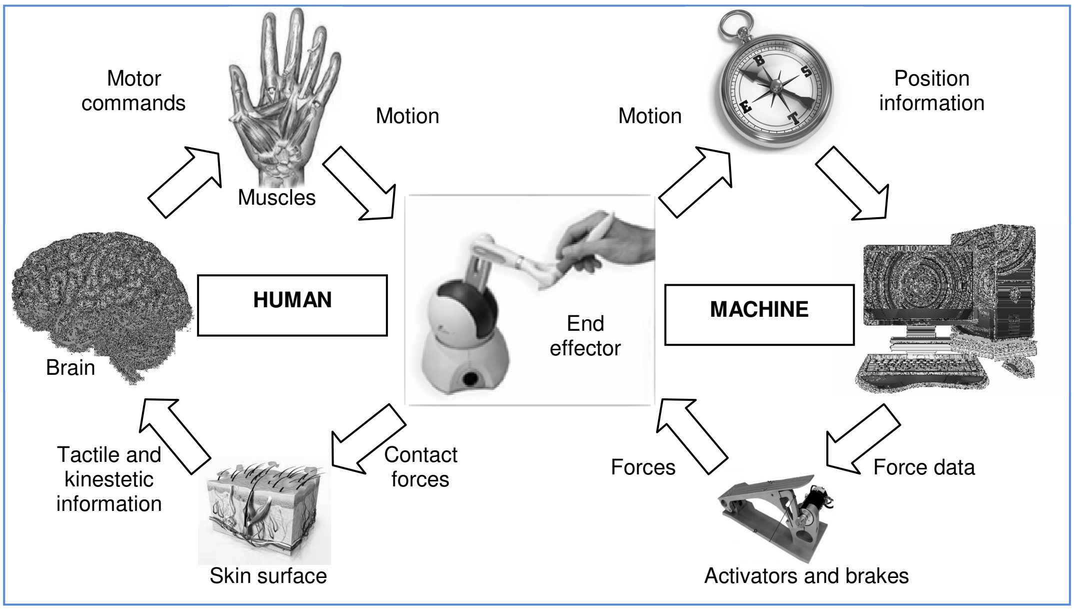

Figure 4. Man-machine concept (5)

Also, both systems are provided with sensors, processors and action mechanisms. In the case of the human system, the receptor nervous terminations and the central nervous system determine the emergence of perception to stimuli, and the muscular system acts, while the above mentioned functions at the level of the machine part are generated by the computer, software and micro-engines.

Nowadays it is impossible to interpose a real intuitive interface between man and computer [12, 13]. It is not the visual module in itself which has gained grounds, but the combination between it, force and touch. Research in the haptic devices field, as we must admit, benefited from various innovations, enthusiasm and technological support, and this has essentially contributed to designing the complex interfaces and amazing applications possible.

It all relies on the way in which one succeeds to "glue together" a man and a machine! In the end, it's the interface that matters! [14]

Creating a Surgical Virtual Environment (Surgical Virtual Reality)

This concept of modelling the simulation environment refers to achieving a highly realistic tridimensional simulation of human organs and tissues, as well as a simulation of their behaviour in reaction to external stimuli. A system of "deformable objects" is thus obtained, with specific geometrical shapes and "natural" physical-mechanical behaviour [11]. Another purpose pursued, critical for the realisation of the concept, is simulating the interaction among "deformable objects", the instrument kit and tissue and organ handling in real time [2,14]. Therefore, in order to meet this goal, indispensable for an efficient simulation, the following objectives must be integrated [15]: 1) the geometrical model – graphical representation; 2) the physical model (elasto-dynamic); 3) model-handling interaction.

Determining the Optimal Characteristics of a Haptic Device Required for Performing a Surgical Intervention

As a bidirectional connection between man and machine a haptic device must meet the following requirements:

a) to transmit the necessary information to the machine;
b) to be human-compatible in terms of shape and movements;
c) to transmit the relevant tactile or kinaesthetic information to the human [2, 16].

In the case in which the haptic device is part of a simulator it must resemble in shape the simulated instrument and, moreover, have the same degree of freedom and restrictions as the simulated instrument. Instrument analysis is important because they must not only be represented in the virtual space, but also handled by means of the haptic device [12,14].

A laparoscopic instrument kit is introduced into the peritoneal cavity by means of trocars. These instruments are not axially fixed, therefore we can note two degrees of freedom (translation on the Oz axe and rotation around the Oz axe in the instrument's own axial system). The connection between the trocar and the abdominal wall is not rigid. The translation movements of the trocars can be neglected, but we can however note another two degrees of freedom (rotation around Ox and rotation around Oy in the instrument's own axial system). Therefore, the instrument has four degrees of freedom (1 of translation and 3 of rotation) (Figure 5).

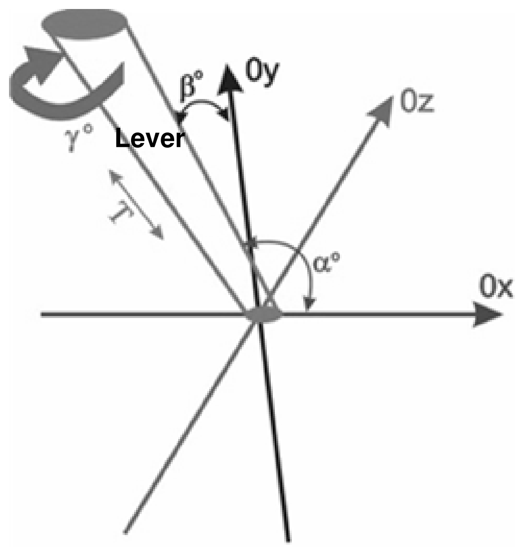

Figure 5. Freedom degrees of the surgical instruments

The two missing translations, on the Ox and Oy axes respectively, are the restrictions which any laparoscopic instrument has. Some instruments are provided with pedals (the electrode for electrosurgery), while others have mounting devices, unlocking buttons, cutting buttons, buttons to start suction or drainage etc. These buttons are not degrees of freedom, but play an on-off switch role. It is necessary for the haptic device to respect not only the number of degrees of freedom, but also of mechanical restrictions present in the real life configuration. The attempt to design a virtual environment with a haptic device provided with six degrees of freedom (3 of translation, 3 of rotation) and an instrument with 4 degrees of freedom (1 of translation and 3 of rotation) and two restrictions requires an enormous volume of calculations, including for applying an opposing force to counteract movements which would be restricted. It is a utopia, practically! The conclusion drawn is that the haptic device must bear the same number of degrees of freedom as the simulated instrument, and have at least similar restrictions.

The way to include a haptic device, from a logical point of view, into the laparoscopic virtual simulator is represented in Figure 6.

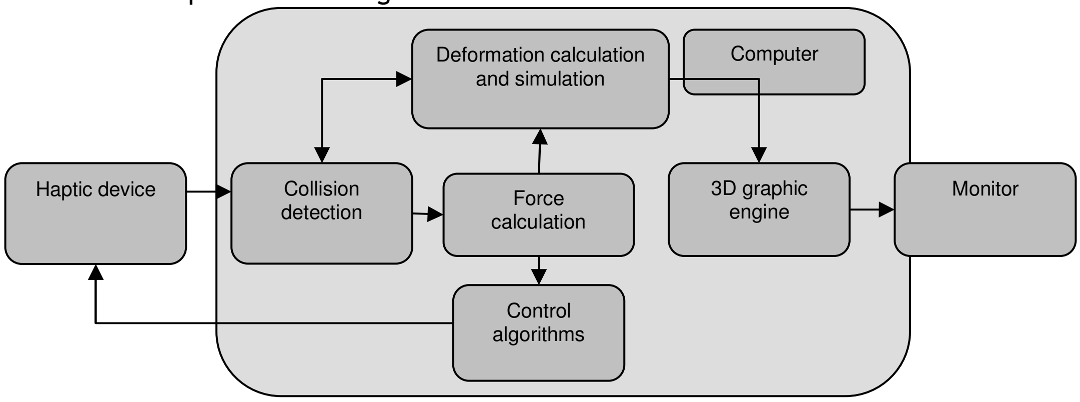

Figure 6. Haptic device within the virtual simulator (14)

As can be observed, the haptic device transmits positions relative to its degrees of freedom to the computer. The computer associates these positions to the configured instruments in order to be represented by the haptic device. Collision detection is executed, a process which offers information related to contact positions (if there are any), object pairs, contact areas [1,14].

Based on these data the following forces can be calculated: a) the actions, theoretically initiated by the user, are transmitted to the "Deformation calculation and simulation" module; b) the reactions are transmitted to the control module of the haptic device for counteracting force calculation. Deformation calculation and evidently the corresponding changes in the elastic objects involved can lead to collisions. Therefore, after applying deformations, collisions are again detected and possible new deformations are recalculated. The situation created is displayed by the 3D engine on the monitor. Figure 7 presents an actual case in which a moving instrument (the green arrow) touches a virtual organ [6].

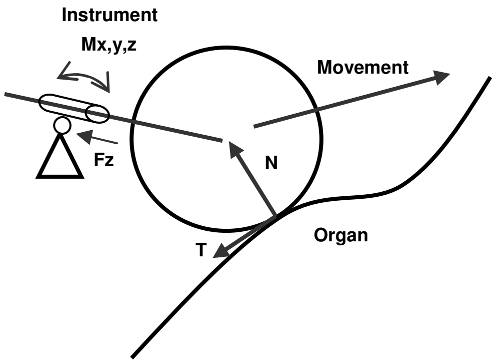

Figure 7. Transforming the calculated forces into representative returned forces

As a result of detecting the collision, the impact point, the counter-reacting forces are calculated (N and T respectively). According to the scheme, these forces should be applied to the contact point. The only difference comparing to reality is that the contact point is also virtual! The solution is transforming the force system by translation on the Oz axe of the instrument to the point where it is virtually articulated (with the trocar and, implicitly, the patient's body) and physically (the simulator's chassis), possible through the control algorithms of the haptic device. The result of the transformation is composed of a force Fz on the Oz axe of the instrument and a moment M with components pertaining to all three axes. This result can be logically and physically transmitted to the automation component of the haptic device, which will translate it into command tensions for the corresponding engines of the haptic device.

Advantages and Disadvantage of Haptic Technology

Advantages include the fact that, by mimicking sensorial response, the digital world can become a real world [1,9]. When an object is digitally manipulated, modified and resized, the working time decreases. In the medical field a simulator assists the surgeon in finding the technical procedure best adapted to the local situation, in training or creating new techniques before operating on the patient.

The disadvantages are represented by the hardware possibility to accomplish real time rendering of all the information involved [10]. There are limitations as well, because the forces returned by a haptic device are dependent on factors which aren't always obvious [2,15]. To exemplify:

1) the way in which virtual objects are described (they are generally hollow and if, due to velocity, the tip of the

instrument passes through the object's surface, there will be no counteracting force!);
2) the different speeds with which the software works, in detecting movement, in returning forces, can lead to moments in which the information is lost;
3) the discontinuous manner in which each component of the system works can lead to oscillating returned forces with divergent, destructive amplitude, due to (admissible) errors both in reading and processing, and in rendering, as well as to mechanical, electric or informatics related errors.

Perfecting haptic devices has opened the door to a series of opportunities in the fields of research, industry, nuclear sciences and in medicine. [1,2]. Concepts purely theoretical at first, such as *telerobotics*, *telepresence* or *telerepresentation,* have become a practical reality as calculus techniques, telecommunications and haptic devices evolved, virtual reality taking a new leap.

Future Directions

Just like simulators are a standard in aviation and aerospace sciences, we expect for surgical simulators to soon become a standard in medical applications [1]. These will correctly instruct future doctors in surgical techniques without there being a need for hands on patient instruction [17,18,19].

The current efforts of research groups are focused on several directions: improving the technical fidelity of the systems, defining new adequate standards for performance evaluation parameters, implementing simulators in educational programs. Studies evaluating surgical training efficiency increase are being conducted in various university centres, looking to determine the applicability of simulation programs in surgeon evaluation. How prepared is the surgical world for implementing virtual reality? Only 1% of future surgeons (on a global scale) are virtually trained. There is an intense conflict between tradition and change, just like in any other field, as well as an inexplicable anxiety towards computers manifested by some surgeons [1].

Over the last years it appears that the medical world is more and more convinced by the unique utility of VR in this respect. It is only a matter of time until these revolutionary technologies will begin being implemented, thus raising the quality of medical education and patient care [20].

In the field of surgery barriers and controversies still remain, regarding implementation and generalization of surgical virtual simulators. These obstacles remain connected to the high costs of this yet fully sufficiently developed technology, especially in the domain of haptic devices [21]. In spite of this, the efforts made so far have led to the development of the first generation of surgical simulators.

We believe that, if technological development will continue at the same pace, and the cost of this equipment will be reduced, VR will become the dominant method of learning and training for future surgeons [22]. The informatics era has cleared the way for remarkable possibilities in the domain of surgical education. As a consequence, the level of the medical act itself will significantly increase.

Finally, we should not forget that the sense of touch and physical interaction are the fundamental ways by which we understand how to change the world. The intense efforts to build interfaces and haptic devices show our intimate desire to give our hands a voice to describe, write and read our future!

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References

[1] Van der Geer J., Hanraads J.A.J., Lupton R.A., "The art of writing a scientific article", in *J. Sci. Commun.* 163 (2000) 51-59.
[2] Strunk W. Jr., White E.B., *The Elements of Style*, third ed., New York: Macmillan, 1979.
[3] Mettam G.R., Adams L.B., "How to prepare an electronic version of your article", in: Jones B.S., Smith R.Z. (Eds.), *Introduction to the Electronic Age*, New York: E-Publishing Inc., 1999, pp. 281-304.
[4] Cochior D., Custură-Crăciun D., Ciobanu-Oprea C., *Realitatea virtuală chirurgicală - utilă sau necesară?* [The surgical virtual reality - useful or necessary?], București: Editura Electra, 167 p. ISBN 973-7728-24-6, 2005.
[5] El Saddik A., Orozco M., Eid M., Cha J.. *Haptic technologies bringing touch to multimedia*. Hardcover, 218 p. ISBN: 978-3-642-22657-1, 2011.
[6] Satava R.M., "Emerging medical applications of virtual reality: A surgeon's perspective".

in *Artificial Intelligence in Medicine*, 6:281-288, 1994.
[7] Salisbury K., Conti F., Barbagli F., "Haptic Rendering: Introductory Concepts". in *IEEE Computer Graphics and Applications*, 24(2):24-32, 2004.
[8] Singh A.K., Tripathi A.M., Kumar M., "Haptic Feedback System". In *International Journal of Societal Applications of Computer Science*, Vol 1, Issue 1, 29-34, 2012.
[9] Coles R.T., Investigating Augmented Reality Visio-Haptic Techniques for Medical Training, Bangor University, Wales, 2011. Phd Thesis
[10] Bolanowski S.J.J., Gescheider G.A., Verrillo R.T., Checkosky C.M., "Four channels mediate the mechanical aspects of touch". In *Journal of the Acoustical Society of America*, 84(5), 1680–1694, 1988.
[11] Sánchez-Peralta L.F., Sánchez-Margallo F.M., Moyano-Cuevas J.L., Pagador J.B., Enciso-Sanz S., Sánchez-González P., Gómez-Aguilera E.J., Usón-Gargallo J.. "Construct and face validity of SINERGIA laparoscopic virtual reality simulator". In *Int J Comput Assist Radiol Surg*. 5(4):307-315, 2010.
[12] Hayward V., Yi D., Change of height: an approach to the haptic display of shape and texture without surface normal, 570–579. Springer Verlag, 2003.
[13] Cochior D., Ciobanu-Oprea C., Peța D., Custură-Crăciun D., Pripiși L., Tecuceanu V., „Realitatea virtuală chirurgicală - prelucrarea şi interpretarea software (randarea) în timp real a suprafeței organelor în simularea laparoscopică". In *Medicina Modernă*, vol XI, nr 11, 2004, pg 571-577.
[14] Cochior D., Ciobanu-Oprea C., Peța D., Custură-Crăciun D., Pripiși L., Tecuceanu V., „Realitatea virtuală chirurgicală – conceptul de modelare a mediului de simulare laparoscopică". In *Medicina Modernă*, vol IX, nr 9, 2004, pg 461-466.
[15] Cochior D., Peța D., Pripiși L., „Realitatea virtuală în chirurgia mini-invazivă". In *Medicina Modernă*, vol X, nr 11, 2003, pg 577-579.
[16] Coles R.T., Investigating Augmented Reality Visio-Haptic Techniques for Medical Training, PhD Thesis, Bangor University, Wales, 2011.
[17] Gregory S.R., *Interactive Soft Tissue for Surgical Simulation*, PhD Thesis, Flinders University, South Australia, 2011.
[18] Dankelman J., "Surgical Simulators Design and Development". In *World J Surg*. 2008; 32(2):149-155.
[19] Bergamasco M., "Artificial Life and Virtual Reality", in N. Magnenat Thalmann and D. Thalmann editors, JohnWiley, Chap. *Manipulation and Exploration of Virtual Objects*, pp. 149-160, 1994.
[20] Tomulescu V., Popescu I., "Utilizarea simulatorului de realitate virtuală LapSim Basic Skills în evaluarea abilităților în chirurgia laparoscopică. Rezultate preliminare". in *Chirurgia*, 99 (6): 523-527.
[21] Cristian D., Sgarbură O., Jitea N., Burcos T., „Curba de învățare şi consecințele ei în intervențiile laparoscopice antireflux". In *Chirurgia*, 100 (1): 47-52.
[22] Târcoveanu E., Moldovanu R., Vasilescu A.. "Învățământul virtual în chirurgia minim invazivă". In *Jurnalul de Chirurgie*, Iași, 2010, Vol. 6, Nr. 3.
[23] Gaspari A., Di Lorenzo N., *La chirurgia mini-invasiva del torace e dell'addome*. Milano, Elsevier Masson, 409-414, 2007.
[24] Calatayud D., Arora S., Aggarwal R., Kruglikova I., Schulze S., Funch-Jensen P., Grantcharov T., "Warm-up in a virtual reality environment improves performance in the operating room". in *Ann Surg*. 2010; 251(6): 1181-1185.
[25] van der Meijden O.A., Broeders I.A., Schijven M.P., "The SEP «Robot»: A Valid Virtual Reality Robotic Simulator for the Da Vinci Surgical System?" in *Surg Technol Int*. 2010; 19: 51-58.

Biography

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