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PUPPET MENTORING: A NEW SIMULATION SCENARIO FOR LEARNING SURGICAL ABILITIES

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ABSTRACT
Surgical simulators are now able to teach in a way that the learning curve of young surgeons can progress in a lab faster than when using other teaching models (cadaveric or animal) or real patients. The impact of surgical simulators is confirmed by the fact that, in the US, standardized training courses are needed to acquire the Board of Surgery certification. The virtual simulator set up at the University of Genoa (eLaparo4D) is based on two key features: a convincing haptic feedback and a limited cost. Nevertheless, the main issue of eLaparo4D is the "simplicity" of the virtual scenario. To improve it, a new model of simulation is proposed in this project: the "puppet mentoring", that might enhance its characteristics. The "puppet mentoring" is based on the recording of the movements of the surgeon in the real clinical scenario, that are transferred to the virtual machine. The apprentice, in his learning session, could be led through the operation by the simulator itself, in a scenario and in a way is the same of the real one.

Keywords: Surgical Simulator, Virtual Reality, Training, Haptic Feedback, Validation

1. INTRODUCTION

The European Society for Translational Medicine (EUSTM) defines Translational Medicine (TM) as an interdisciplinary branch of the biomedical field supported by three main pillars: benchside, bedside and community. The aim of TM is to enhance prevention, diagnosis, and therapy (Cohrs 2015). Translation describes "translating" laboratory results into potential health benefits for patients. Research on medical education contributes to translational science because its results enrich educational settings and improve patient care practices. Simulation-Based Medical Education has demonstrated its role in achieving such results (McGaghie 2012).

In April 2004, the Food & Drug Administration became involved in the discussion about the didactics of young surgeons, demanding the development of a learning program based on simulators that were primarily tested and validated by industry experts, thus sanctioning the start of the "Simulation era" (Roberts 2006; https://www.fda.gov/advisory-committees/advisory-committee-calendar/june-12-2018-circulatory-system-devices-panel-medical-devices-advisory-committee-meeting). Surgery requires learning in a simulated and safe area before operating on the patient (Grantcharov 2008; ACGME Program Requirements for Graduate Medical Education in General Surgery. Revised Common Program Requirements effective: July 1, 2016), also to respect ethical and social implications. For these reasons, the Accreditation Council for graduate medical education decided that all accredited facilities for surgical teaching must include simulation (Bjerrum 2017).

At present, many medical training centers are equipped with simulation areas, but there is still significant disagreement about how to develop training programs: efforts are needed to standardize these training paths (Kurashima 2017; Tavakol 2008; Alaker 2016; Kostusiak 2017; Zendejas 2013; Nagendran 2013; Vapenstad 2013). To this purpose, in the United States, standardized training courses (e.g. FLS - Fundamentals of Laparoscopic Surgery) are needed to acquire "American Board of Surgery" certification (Bjerrum 2017). The new Italian medical specialization teaching system was approved in 2017, but the integration of simulation into training programs is not mentioned. Despite this gap, many surgeons are aware that proper simulation training is of mainstream importance for the education of young surgeons: to this purpose, dedicated programs are being set up, but only in a few settings (Stefanidis 2010; Shanmugan 2014). These programs can be supported following two main paths: 1) using devices that are already on the market (the more expensive option) and/or 2) with research projects aiming to develop custom-built surgical simulators (Kowalewski 2017; King 2016; Belykh 2017).

Two main simulator models are currently available: physical and virtual platforms. Physical simulators (box trainers) were the first to be introduced. They are cheap, and the haptic feedback is authentic. They reproduce basic gestures but do not allow to reproduce entire surgical procedures or intraoperative complications. These restrictions have been overcome by the introduction of virtual platforms that allow to simulate, in addition to basic skills, more complex and realistic surgical scenarios (Munz 2004; Mohammadi 2010; Loukas 2012).

Several studies have shown the effectiveness of virtual platforms on surgical training, but their high costs and unrealistic haptic feedback do not allow their diffusion in the departments involved in teaching programs. Haptic feedback is a key feature of a mixed physical/virtual simulator because its realism is essential for the correct learning of laparoscopic gestures. Nevertheless, it is often the most neglected part of the system mostly because of the lack of a suitable algorithm able to estimate the best force feedback during the interaction with virtual organs and tissues.

To improve the surgical training program, a team of general surgeons and engineers of the University of Genoa developed a mixed (virtual/physical reality) robotized surgical simulator (eLaparo4D) focused on two essential features: the lowest possible cost and a realistic haptic feedback (Frascio 2016; Mandolfino 2016; Perino 2015; Sguanci 2015; Sguanci 2014a; Sguanci 2014b). As established by the FDA's protocol, the validation study performed to verify if the simulator was able to discriminate surgical abilities demonstrated that eLaparo4D allowed to differentiate young surgeons (residents with limited surgical experience) from students that had no experience in laparoscopic surgery (Minuto 2018; Stabilini 2013; Fornaro 2009; Fornaro 2008). The eLaparo4D has been patented in 2018.

The main implementation of eLaparo4D, and the focus of this project, is a totally new approach to teach surgical gestures, inspired from what happens in a real surgical setting, where the teaching surgeon "moves" the hands of his apprentice to favor the movements the way he prefers. The "Puppet Mentoring" is a scenario where a virtual machine can record the movements of the surgeons and the assistants in a real surgical operation and is able to reproduce and "induce" them in a simulated environment, driving the young surgeon toward a correct performance of his movements and, finally, of his surgery. Fine motion tracking of each surgical act is possible within a controlled area (the simulated operational scenario) where kinematic and dynamic data of tools, instruments and people involved in the scenario are collected using an IoT (Internet of Things) based low-cost infrastructure.

2. MATERIAL AND METHODS

The eLaparo4D system is composed of hardware and software components that interact to simulate the environment, its physical and visual rendering, and its haptic feedback.

2.1. Software

a. The simulation system. The backend system is based on a server developed with a Node.js application that allows interactions among the visual system, the different components of the hardware and the database containing the user data. The server technology works as a "gate" among all the elements of the system (hardware or software). The user interacts with the system through an web-based real-time user interface based on the Unity multiplatform game engine, a largely used software for videogames and 3D/VR applications development. The use of a web page interface was chosen because of its standardized data exchange and because, being inherently multi-user, it might permit quick interactions with another user or a supervisor (e.g., a tutor).

b. The rendering system. The meshes were shaped, starting from real and artificial data, using 3D Studio Max®, developed by Autodesk© (2016 Autodesk Inc) [30], and then imported in Unity together with texture and UV maps. Finally, different visual effects (e.g., the shader effect) have been added to the meshes in Unity to create deformable objects with the most realistic result possible. Physical modeling was developed using more dynamic parametric protocols to avoid system overloads.

2.2. Hardware

c. The haptic feedback system. The key feature of the simulator is obtained through an innovative device (a robotized simulator of a standard laparoscopic instrument and the endoscopic camera) based on low-cost off-the-shelf electronics (potentiometers, vibrating engines, and other sensors/actuators), connected to three Geomagic Touch® (formerly known as Phantom Omni®) haptic devices, and managed by the Arduino electronic card.

d. The real-time control board. The Arduino card is essential for the real-time control of the realistic simulated scenario; it limits the grip of a forceps when tissue is grabbed, and it allows the vibration of the tissues that are being manipulated or cut to be felt. The three haptic devices are directly connected to the handpieces of the surgical instruments and are used to simulate the resistance of the tissues while moving the instruments or pulling the different tissues and to render limitations from the surrounding structures (e.g., simulating collisions). During the training session, the ELaparo4D hardware interacts with the software component through instruments that are made using real laparoscopic surgery instruments.

2.3. Simulated scenario setting

To improve eLaparo4D's current limits, the idea behind the Puppet Mentoring relies on a preliminary robust analysis of the standardized procedures of competence build-up and skill assessment of those professions that use the virtual simulation as a focal part of their training (e.g. aviation, military, engineering).

A preliminary analysis will include stress-tests and data acquisition of the performances of surgeons during their real surgeries, recording data from both young and experienced operators. An evaluation of the results obtained from the two groups of surgeons will be then performed. The Puppet Mentoring is based on the acquisition of a video stream from a real laparoscopic operation and the synchronized recording of sequence of movements of the hands/upper limb (positions/velocities/accelerations) of both the surgeon and his assistant. This acquisition could be obtained with the use of low-cost miniaturized IMUs - Inertial Measurements Units - embedded/weared into the surgical gowns of the surgeons. On the surgical side, hands gestures, upper and lower limb movements, camera tracking, the forces applied on the instruments and their directions (e.g. the movements in the 3D space: rotation, extraction, insertion of the instruments) will be recorded (allowing to measure the haptic feedback), as well as the position of the patient. These all are the kinematic/dynamic data that will be re-elaborated by the Puppet Mentoring system, and will be added to the eLaparo4D machine. The engineers of the research team will analyze, organize, and build up a software that might fit this entirely new simulating scenario. All the data will be used to reproduce the video and the relative movements of both surgeons and could be replicated on the enhanced Laparo4D platform: the trainees can therefore exercise in the real environment, performing the surgery under the guide of the machine. In this way, the student and/or the resident, grasping the instruments of the simulator that autonomously reproduces the sequence of the real movements performed by the surgeons during their same operation, could be led, as a "puppet", throughout all the phases of the real operation, following on the monitor the real anatomic situation, as seen by the surgeon.

3. DISCUSSION

Over the past several decades, surgical learning has been based on three different models: the traditional triad "see one, do one, teach one", the cadaveric model and the animal one. According to the first method, the young surgeon needs to initially learn from the more experienced colleague's surgical movements, reproduce the same gestures under a gradually decreasing level of supervision, and then teaches them to less experienced trainees: this model has no economic impact, but needs a long time for trainees, especially in complicated and rare operations. The cadaveric and animal models are focused mainly on the acquisition of gestures repetitively performed on human cadavers (in a real, although bloodless, surgical field) and/or live animals (in a surgical field that is similar to that of a human, but with a real hemorrhagic risk). These learning strategies are associated with ethical, legal and economic issues, and are currently not easily available in Italian academic or teaching environments.

The simultaneous upgrade of both technology and surgery has allowed the development of surgical simulators, focused mainly on training the laparoscopic branch of surgery. Simulators allow the basic surgical techniques to be learned in a lab before being transferred to a patient in the operating room, allowing a faster learning for the trainees. The surgical simulators that are currently available on the market are indeed extremely appealing from a graphic point of view, look realistic, but are still far from a real surgical experience. Their major limits are organs reconstruction and virtual anatomy scenario, as well as the haptic feedback that is unreliable. These limits make the virtual simulators closer to an extremely expensive videogame than to a machine that allows the reproduction and the teaching of a real surgical gesture. It should also be added that a virtual machine, without the guide of a tutor, cannot lead an apprentice through the sequence of the many different movements (that could be performed in many correct ways, and in a few wrong ones) that might drive the surgery to its final completion and success. In fact, the virtual reconstruction of the anatomical details, although often enjoyable from a graphic point of view, is still too coarse, simplified and "clean" compared to a real surgical scenario (it is always easy to orientate in the virtual scenario and recognize the different structures, organs, tissues, and to understand the task of the virtual surgery). All the same, the basic surgical gestures (e.g. dissection, traction) are not adequately reproduced yet (e.g. the adhesions between organs simply "disappear" with the simple contact of the virtual dissector).

Further on, the current simulators allow the apprentice to perform his movements in total freedom and autonomy, but do not teach a correct sequence of body movements that are needed in a real surgical environment: this is composed of a patient (in a due position), of three nurses, the anesthesiologists, and two or more surgeons. It is therefore important to teach and tutor the young surgeon in his movements and posture, so that, in a correct sequence of movements, he/she can be able to help and not to hinder the surgeon or the other actors in this setting during the different phases of a surgical procedure.

Using the current simulators, the trainees performing the virtual exercises, could learn and acquire wrong sequences of movements that may not be recognized as wrong or useless by the software, but could be dangerous if carried out on the patient or hinder the movement of the other surgeons during the operation. In fact, one of the major problems for the young surgeons is to learn the ability to calibrate the movements, the force and the manipulation of the different organs and

tissues (e.g. the epiploon, the fatty tissue covering the peritoneal organs can be handled differently from the more delicate tissue of the liver or from the intestine) and the correct sequence of movements to always be synchronized with the other surgeons, especially the use of the non-dominant hand.
The student should be at first guided passively by the simulator in carrying out the correct sequence of movements to be performed for acquiring in a good way all phases of different operations. This is of mainstream importance to avoid the problem of a possible wrong learning due to a lack of guidance regarding the learning of the various phases of the surgical intervention on the simulators. To support this hypothesis, there is the practical and real evidence that in the operating room the hands of the residents are often positioned and corrected by the hands of the experienced surgeon. In this way he actively guides the trainees in the correct movement sequences, in the position of the instruments, in the direction and in the traction force on the organs.
The "puppet mentoring" is a new strategy for teaching and learning surgical gestures, that takes inspiration from what happens in those professions where a simulation has been already proved to be effective (e.g. in aviation), but also from what happens in a driving school, where the apprentice can use the help of the tutor only when and if needed. The main point of this project is not only to allow trainees to learn the basic and advanced skills of surgery, in a setting that is the reproduction of a patient with his real clinical scenario and peculiar characteristics, but also train the experienced surgeons to upgrade their surgery in a clinical and surgical scenario that can be that of a difficult or complicated case, allowing a continuous exchange of clinical situations that are not standardized, because obtained from the recordings of different surgeries. In the immediate future, it can be foreseen that these records can be annotated and classified in order to build an "experiential" virtual knowledge base: a repository that can be used for different purposes. It could be queried and explored by apprentices and by experienced surgeons before a critical surgery, but it can be also mined and used by surgeons and researchers in general to plan new patterns, strategies, or techniques.
To our knowledge, this approach has never been applied to surgical teaching, representing then a completely new field in the development of surgical simulators.
The social impact of this project would be the faster and safer evolution of young surgeons that would be mature and ready for their tasks in a shorter time, and without the need of developing the first part of a learning curve on a real patient, thus allowing also to avoid undesired morbidity and complications, that are costly for the national health system.
The setup of the simulator would lead to further studies aimed at validating it as an effective trainer of surgical abilities, and also at verifying its impact on the learning curve of surgical trainees. If its efficacy will be demonstrated, the possibility of exchanging real surgical cases and scenarios might lead to its possible use in the certification of the Italian Board of Surgery.
The new learning method proposed by the Puppet Mentoring aims to overcome these problems inherent to the graphic and gestural realism and sequence of movements of surgical simulation during the different phases of the operation.
Our multidisciplinary team (composed of medical doctors, engineers, informatics) already realized and validated a low cost virtual surgical simulator, with a reliable haptic feedback (e-Laparo4D, patent pending).
The results of the validation study showed that the simulator still has some flaws.
Mainly there were:
- the lack of real and consistent reality of the all environment, that is limited to a machine that although forged with real surgical instruments is limited because located in a lab;
-the computer graphic although acceptable, is not comparable to the real surgical situation;
- the haptic feedback was not totally satisfactory.
The focal point of this virtual simulation is the possibility that the trainees have to interact with a surgical scenario that not only adheres or reproduces a real one, but is in fact a real clinical situation, with its intraoperative peculiar findings. The machine can then drive the trainees in different ways and at different levels, starting from an almost complete assistance for the younger and less experienced surgeons, to an extremely limited help for the more experienced ones.
Another important feature is that, in the simulated environment, there is the possibility of playing the role of the assistant surgeon at first, and, only after the acquisition of the due skills, switch to the position of the first surgeon. Of notice, as in a real situation, the training includes the necessity of synchronizing with the instruments of the assistant surgeon, or, at the beginning of the training, with the instruments of the first surgeon, a peculiarity that is not reproducible with other virtual simulators, where a trainee works alone. It is also important to mention the opportunity of recording the performances and review them after the practical training, to visualize, focus, and discuss the mistakes that are made during the virtual procedures with the tutors. The Puppet Mentoring thus assumes the ambitious didactic role of implementing the classic triad "see one, do one, teach one" in the new sequence "see one, do a driven (puppeted) one, do a real one, teach one". The main goal of the puppet mentoring is indeed to impact the learning curve of young surgeons, but, with an extended vision, also to allow experienced ones to refine their skills and exchange their most difficult surgical cases. The Puppet mentoring would then allow to learn and improve the basic and advanced surgical skills, acquire the right operative times in synchrony with the movements of the other operators and the various phases of the surgical intervention previously performed by more experienced surgeons. This would allow to learn more realistically the various surgical

techniques and phases of operation in a laboratory on a surgical simulator and not directly on the patient in the operating room.

This would have a positive impact on the safety and benefits in terms of patient's outcome and it also could reduce the learning curves of surgeons, allowing to reduce the overall costs of the operative room.

This new method of surgical training, based on the puppet mentoring, would allow the young surgeons to effectively acquire a faster and progressive autonomy of surgical gestures, in a real surgical scenario, but also in the safety of a lab.

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