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Perspective

Information and Communication Technology Trends in Telesurgery

Abbreviation

ICT: Information and Communication Technology; ARMC: Active Relative Motion Canceling;

Introduction

In 2001 a woman underwent a cholecystectomy in Strasbourg, France. What was new? The surgical team who performed the operation was 14,000 km away, in New York [1]. It was the first case of remote robotic surgery. The operation had no complications and the patient had a decent postoperative follow-up. This epoch-making event was dedicated to Charles Lindbergh, the pioneering American aviator who flew across the Atlantic in 1927.

Normally, the surgeon operates with the robot assistance at 2-3 meters from the operatory table and the device, developed for military purpose, reproduces the surgeon's gestures into surgical instruments motion.

The battle field has always been a privileged space to boost technical improvements, from the antibiotics to the GPS, particularly in the medical sector. Given the background, it has been assessed that in combative situations 9 severely injured soldiers out of 10 die before reaching a medical facility, the main cause being hemorrhage that could be arrested by a prompt intervention [2]. The will to save them, and protect the other personnel as well, has led to the introduction of the concept of remote surgery, also known as telesurgery.

The robot-assisted surgery is now routinely performed by several surgeons all over the world. Although it has demonstrated a significant advantage in urologic surgery, controversy exists regarding the other applications [3-12]. It is widely accepted the non-inferiority in comparison with laparoscopic and thoracoscopic techniques, by which the surgeon directly controls instruments at the surgical bed, but few data exist demonstrating objective clinical superiority [13].

Telesurgery uses millimeter-scale robotic manipulators controlled by the operator, accommodating the direction and force of movements to achieve complex tasks. The will is to faithfully reproduce the hand sensitivity and ability by means of small accesses to the organs with less immunity perturbation, pain and risk. However, these gains, already obtained by laparoscopic surgery, have shown several limitations.

Clear benefits of telesurgery on traditional mini-invasive surgery include the 3D vision, an ergonomic system with several hand motion degrees of freedom, and consequently a favorable learning curve. The disadvantages are represented by costs, the absence of haptic (tactile) feedback, and the effectiveness and safeness of data transmission. The Information and Communication Technology (ICT) at the base of telesurgical development faces a number of challenges in reducing the limits related to data collection, selection and transmission.

The potential applications of telesurgery are immense and so the beneficial consequences that could revolutionize healthcare delivery where the access to facilities is lacking and the timing of the required intervention inflexible.

Technical state of art

The primary purpose of robotic surgery is to provide the access to surgery where and when it is impossible for geographical or time constraints. Nowadays this goal has not been achieved yet, because there is always the need of a surgical team at the operating table to administer the anesthetics, disinfect the equipment and the patient's skin and insert surgical instruments in an aseptic and safe way.

Advances in robotics could allow surgeons to perform distant operations in a safe manner. In the future, surgical tasks will be probably entirely performed by robots, as it partially happens in eye surgery. It is not unlikely that the algorithms reproducing and ameliorating stimulus processing and reaction will overcome human limits.

The velocity and safety of data transmission are some of the main current constraints. During the Lindbergh operation, a transatlantic high-bandwidth fiber-optic service running at 10 Mbits per second permitted to register delays inferior to 200 milliseconds, which is an extraordinary result comparable to the clinical practice [1]. The audiovisual fidelity (input) and the transmission of hand gestures (output) achieved in this case an exceptional level of reliability that, however, cannot be currently extended all over the world because of logistic and economic restraints.

Since the delay due to data registration, transmission and processing is crucial to create a trustworthy virtual reality during surgery and to limit errors, it has been the object of many studies which tried to quantify its impact on simple and complex tasks. It has been assessed that there is a substantial tolerance to delay, that significantly affects the operational performance when exceeding 500 ms [14]. When the delay, obtained during sequential training

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tasks by an interference-creator system, is up to 500 ms there are no remarkable differences in error frequency compared to zero latency. The currently accepted maximum latency is 330 ms.

Robotics aims to reproduce, and potentially improve, human abilities. In the master-slave architecture, the only available since there are no autonomous systems, the delay of the computer has to be added to the physiologic latency due to human perception, transmission and elaboration of the sensory stimulus, and obviously the reaction time. The result is the sum of two delays, one of which is highly subjective and variable. In this context the perceived time latency (TP) during a simple task is def

$$T_P = T_{en} + T_t + T_r$$

where T_{en} is the time for encoding/decoding, T_t is the time for network transmission and T_r is the operator's reaction time to the output. When the task is composed by a series of motions, the total time to complete it equals the perceived time latency plus the time for the maneuver rearrangement and the time for the elaboration, comprehension and definition of the next gesture. So an operation is described by a summatory function of complex tasks, which gives an idea of the time constraint influence.

The ICT development is bound by the reduction of T_{en} and T_t, which requires several efforts and the evolution of both processing software and transmission channels.

Other possibilities to attenuate the consequences of latency regard the *move-and-wait strategy*, so a conscious practice of staccato maneuvers that however reduces the reality-effect, and also *predictive displays*, that allow showing to the operator what will be expected to happen after his/her motion [15]. This computational anticipation of the input repercussion, which has been used on ship and air traffic control pilot's displays, would permit to complete a task with more confidence, leading to a sensory motor adaptation. The predictive model calculates a complex probabilistic visual outcome on the base of the stability of the present conditions, decreasing task time as much as 50%. Nevertheless, the information provided is essentially non correspondent to reality and they have to be corrected at the delay compensation. Time-based algorithms are also used to synchronize multiple operator tasks in experimental conditions.

Another fundamental technical issue in Telesurgery is safety of data transmission. Redundancy of channels, data protection protocols, elaboration systems and contingency plans in case of technical failure have been used and extensively studied [16]. Their evolution is ongoing and institutions have to be more and more involved to control the adherence to regulation and to adjust the latter accordingly to the technical advancements.

Institutional implications

Robotic urologic surgery has demonstrated a significant advantage over laparoscopic procedures [17], while controversy exists regarding its application to other surgical fields.

However, the robot is much more expensive than laparoscopic equipment: it requires an initial investment of millions of dollars and maintenance costs of hundred thousands of dollars per year. The investment recovery requires an almost daily usage, reasonable only in high volume hospitals. Paradoxically the learning curve is steep and fast compared to laparoscopy: this could avoid the complications registered before reaching its critical number of operations and make telesurgery a suitable technique for less experienced centers. Moreover, the computer controlled camera system could definitely eliminate the need of a second operator in the procedures with no need of instrument change [18]. Also, telementoring, teleconsulting and teleproctoring (intended as the remote credentialing of trainees) could be achieved. This would be a further implementation of the ICT component in telesurgery allowing organizations to share data, surgical training and consultations in a globalized environment. This could ultimately result in standardization of surgical pathways and in quality of surgical care homogenization.

Procedure-related issues

Robotic surgery has a favorable learning curve compared to laparoscopy [19]. Since the laparoscopic training before reaching the cut-off is characterized by a higher percentage of errors and complications [20], it follows that an extensive usage of robotic surgery, also in the fields in which it has not shown significant advantages, could reduce the total amount of complications and their impact.

The restraints encountered with the current technology will probably decrease. Tactile feedback, which is very important in surgical practice, mainly depends on data transmission: the feedback deriving from the touch of anatomical structures by instruments will be perceived by the operator and orient their manipulation. This leads to the introduction of the concept of virtual sensitivity, different from the tactile feedback that already exists in laparoscopy, being the apparatus a static prolongation of the operator's hands.

The technical improvements on camera and instruments control will be possibly make the first surgeon independent from the help of assisting surgeons. One of the reasons of the fast learning is the reliable translation of hand natural motions into the device, which has been made possible by the extension of the degrees of freedom leading to reproduce the complex articulation of the body-shoulder-elbow-wrist-finger system.

The current body-machine reciprocity, although satisfactory compared to the traditional mini-invasive methods, is not perfectly natural. The ICT and robotics will implement this function fulfilling the need for a better correspondence between surgeon's gestures and the machinery dynamics, recreating an authentic open-surgery effect with a mini-invasive approach.

Imaging-guided strategies could further reduce the human error margin by transmitting data to the console in real time, helping surgeons to recognize vital structures and reducing unnecessary manipulations and traumas to avoid lesions [21]. This already happens in neurosurgery, where the neuronavigation and stereotactic approaches have ameliorated the outcomes of many procedures [22].

Anatomical structures, however, are not motionless: static information, obtained by imaging or by real time sensors, have to be adapted to the positional changes due to peristalsis, diaphragmatic

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excursion, and heart pulsatility. Many of these adjustments cannot follow a previously defined pattern: while the mechanical ventilation performed during anesthesia makes the respiratory movements predictable, allowing a subsequent reliable equipment regulation, heart beats intervals are not always calculable.

The Active Relative Motion Canceling (ARMC) is a technique aimed at tracking these anarchic motions and adjust the position of the instruments accordingly, giving the operator the effect of working on a stable tissue [23]. In the case of cardiac surgery it would open up new horizons in the fields of off-pump surgery, where the surgeon operates a beating heart (off the cardiopulmonary bypass, or pump) without the need of its arrest and potentially less Peri-operative complications related to it [24]. Off-pump surgery is characterized by sub millimeter-precise procedures: it is intuitively technically challenging and exposes to errors. The ARMC would add the advantages of a mini-invasive approach synchronizing all the components of the surgical equipment. However, important issues related to the heart positioning, that is not possible with a closed chest, remain. The data about the motions of the patient's body and the surgeon have to be rapidly transmitted, elaborated and translated into instantaneous positional adjustments. This ICT-integrated sector is generally referred to multimodal communication or telepresence-teleaction and accomplished – with many limitations – in experimental contexts by multimodal sensors-actuators connected to a human system interface, which reflects and integrates the virtual sensory information [25]. Other limitations are signal noise, as well as the potentially excessive amount of sensory information. The latter could be due to an excessive sensitivity of the device, with the generation of feedbacks not perceivable or not influential for the surgical practice, but also too copious to be understood and considered by the operator. The virtual perception and the computation of outputs have to be regulated accordingly to their usefulness, and obviously the latency of all the process as well. For example, several systems adopt the Weber's Law of Just Noticeable Differences, which defines the smallest haptic signal that can be detected, to select the "useful" tactile stimuli [26]. It is an application of artificial intelligence: the selection of the sensitive inputs candidated to the cortical elaboration is one of the keystones of the evolutionary organism's adaptation to the environment, and so reflected at many levels, from the peripheral to the central neural stations. This fundamental law of psychophysics can be described by $\Delta I/I = k$, (where I is the stimulus intensity, ΔI is the Difference Threshold or the Just Noticeable Difference and k is a constant), and made experimentally possible by a signal adaptive packet reduction. However exceptions to this linear relationship have been observed [27].

In addition, the computational algorithms underlying the visual and haptic feedbacks have to face complex, irregular geometries: layers, viscoelastic materials with several different characteristics. The elasticity of anatomical structures is conventionally considered linear up to a certain measure, but the soft tissues require another model, defined by the equation $K \cdot u = f^e - f^h$, where K is the model stiffness matrix, u and f are the nodal displacement and nodal force vectors. An analytical contact force model would allow the surgeon to be more precise and avoid excessive tension and manipulation, ameliorating its virtual reality.

In the next future, with the advancement of ICT techniques applied to telesurgery, healthcare providers could safely serve also remote and disadvantaged areas. This would be especially true for the battle fields, where an immediate intervention is rarely feasible due to geographical and risk restraints. This perspective is far, also by effect of the issues regarding the need of anesthesia and the eventuality of a conversion to open surgery.

Cost-effectiveness and strategic improvements

Telesurgical procedures and robot-assisted surgeries come at a high cost and controversy exists about the impact of hospital, surgeons' volume, and other factors on their cost-effectiveness. Costs associated with telesurgery are mainly related to the purchasing of robots and communications infrastructure. Economic impact of maintenance and training costs, academic/research costs, insurance, expenditures for ethical guidelines and intellectual property right are other areas of interest in the analysis of telesurgery/robotic-surgery cost-effectiveness.

Robotic machines have prices ranging from $1 million to $2.5 million for each unit [28], that have to be added to obvious infrastructure costs including space renovations, since robotic equipment and consoles are bulky instruments, and communication infrastructure costs (satellite links, fiber-optic networks, and aerial vehicles as communication nodes).

The system also require costly maintenance and proper education to the staff which require both a time investment and actual training costs, estimated to be $250,000 for training of one single team to use one robot.

The experience with the existing telesurgery systems tells that improvements to telesurgery technology come from the research sector, likely through government funding as well. For example, the da Vinci machine was developed by SRI International, and was funded by agencies including the National Institute of Health and the Defence Advanced Research Projects Agency. This contributes to the final expenditure.

Barbash et al. [29], estimated that performing a surgery in a robotically-assisted fashion add about $1,600 per procedure, or about 6% of the cost of the standard surgery. When the amortized cost of the robot itself was included, the additional total cost rose to about $3,200, or about 13% of the standard procedure.

The scenario changes if, instead of considering the operative costs, the perioperative expenditure is analyzed. Length of stay in the hospital and readmissions after the first surgery substantially impact the expenditure in favor of robotic surgery in some observations [30], however, due to the scarcity of the articles stating a superiority of robotic surgery, this advantages have to be considered theoretical.

In the future, industry competition would probably render instrumentation costs more affordable, and centralized decisions from governments, hospitals, and insurance companies are needed to bring telesurgery from a possible technology to treat some procedures to a critical transforming factor of health care aiming at excellence of care at a population level.

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Future perspectives

Despite the numerous limitations requiring improvement mentioned above and reported in Figure 1, telesurgery hold tremendous promise. As previously reported, telesurgery is not the only aspect of the vast field of telemedicine; telementoring, teleproctoring and teleconsulting are, by themselves, a promising application of telemedicine [31]. These various sub-specialties offer substantial opportunities to enhance patient care and medical education both in the surgical and clinical fields.

This is particularly true when considering more disadvantages geographic and socioeconomic areas where dissemination of knowledge and real-time access to physician expertise has been proven to be feasible, cost-effective and above all to bring a high degree of patients' satisfaction [32].

As the progresses in telecommunications technology expand and the associated costs diminish, these various sub-fields of telemedicine, including telesurgery, are primed to make a significant impact on a global health level.

Conclusion

The potential benefits of telesurgery are immense and not fully foreseeable. They regard both ICT and robotic innovations, which lead to an increased virtual reality, with a possible extension of human sensory limitations and a reduction of errors. The costs, which currently affect the diffusion of the technique, will be reduced by the advancements. Therefore, it is licit to expect a future exponential expansion of telesurgical techniques.

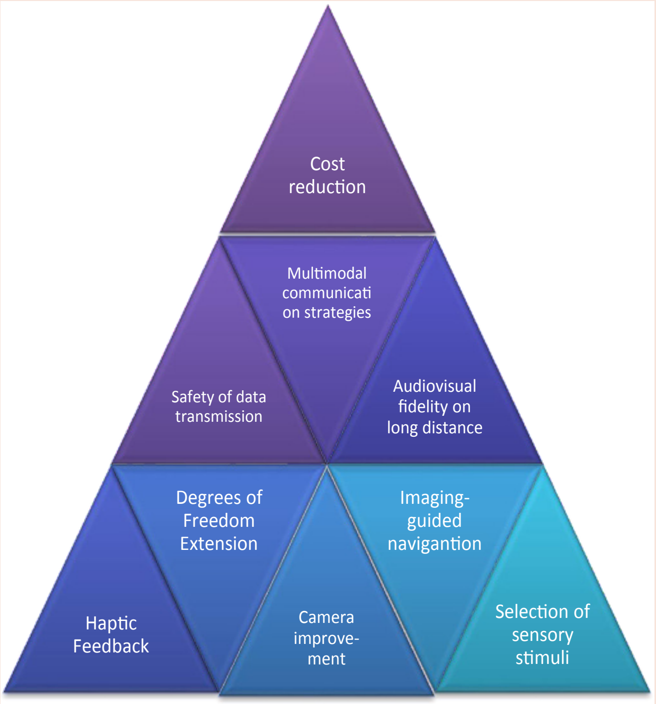

Figure 1: Telesurgery limitations in relation to equipmen (base of the pyramid), channel (central body), and market (vertex).

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