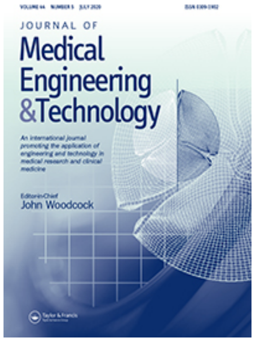

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REVIEW

A review of haptic feedback in tele-operated robotic surgery

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ABSTRACT

During traditional surgery, the surgeons' hands are in direct contact with organs, and surgeons rely on the sense of touch to perform surgery. In teleoperated robotic systems, all physical connections between the surgeon and both the robot and patient, are absent. The surgeon must estimate the force exerted on organs, based only on visual deformation of tissues he is pulling, pushing, gripping, or suturing. It is hard to imagine how to operate with no haptic sensations, and it is surprising that commercially available robots didn't include until now any Haptic Feedback, despite reports about tissue injury, and inability to perform complex manipulation. The sense of touch must be created by stimuli sensed by the surgeon. Haptic sensors are required to collect and send haptic information, and display them on the operator's side, creating telepresence, known as transparency. Multiple ways have been developed to improve transparency through force feedback and tactile feedback. However, this interferes with the stability of the closed-loop controlling interactions between master, robot and remote environment. Cutaneous feedback is more stable and less transparent; force feedback is more transparent and less stable. Thus, multimodal platforms of haptic feedback would try to find the best trade-off between both modalities.

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Robotic; minimally invasive surgery; haptic; tactile; force feedback

1. Introduction

During traditional open surgery, the surgeons' hands are in direct contact with tissues and organs; Thus, surgeons use all their senses, and integrate all haptic feedback they receive, including shape, pressure, vibration, stretch, and temperature [1,2]. This allows them to identify the different tissues, and the forces they are exerting on them. This haptic feedback, also known as the "sense of touch", is divided into two modalities: Kinaesthetic, and Tactile [2–4]. Kinaesthetic feedback is related to the forces exerted on things we touch, while tactile feedback is related to the impact the things we touch have on our skin [5,6].

In traditional laparoscopic minimally invasive surgery, the surgeon operates by manoeuvring a camera and instruments mounted on long shafts, inserted into the body through incisions measuring less than 10 mm; hence, tactile feedback is typically absent, since the surgeon doesn't directly touch the tissues or organs [7]. Kinaesthetic feedback on the other hand, is still present, though attenuated by the size and material of the long shaft [7,8].

In teleoperated robotic systems, the camera and instruments are inserted into the patient similarly to laparoscopic surgery. However, the surgeon doesn't touch them for manipulation: A grounded robot is positioned directly over the patient with robotic arms connected to the camera and mounted instruments. The surgeon controls the movements of the robotic arms by manoeuvring controls that provide fingertip precision of movement, on a console located across the room, in a remote office, or even in a different country [9]. The robot's arms replicate exactly the movements of the operating surgeon who visualises the surgical field on a stereoscopic display, but cannot feel what the instruments are touching; all physical connections between the surgeon on one hand, and both the robot and patient on the other hand, are absent [10]. Thus, haptic sensations such as texture of tissue, tension when tying a suture, and even collision between instrument and tissue, or between the robotic arms, are imperceptible to the surgeon [11,12]. This total absence of the touch sensation creates a cognitive overload on the surgeon's sight, since all the available information is conveyed only through the visual display in front of him [13]; the surgeon must estimate the force he is exerting through the robot's arms on the organs, based only on the visual

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deformation of the tissues he is pulling, pushing, or gripping [14,15]. The lack of haptic feedback is therefore a major challenge in teleoperated robotic surgery. Studies have shown that using a haptic feedback system can improve the performance and accuracy of expert surgeons in robot-assisted surgery, and reduce the learning time needed by new surgeons who might have difficulty learning robotic surgery techniques with visual cues alone [1,2]. It has been intensively tackled in the past decade by researchers everywhere, and numerous haptic feedback solutions for surgical robotics are still being investigated. The objective is to provide as precisely as possible, kinaesthetic and tactile feedback, in order to recreate the remote environment and feel it, without being in it; this is more commonly known as “Transparency” [16–19].

We shall review in depth the status of haptic feedback in tele-operated robot-assisted surgery.

2. Haptic technology

2.1. Haptics key points

Haptics encompass everything related to the sense of touch [2,20]. It is what allows humans to perform a broad range of tasks like touching, grasping and manipulating, inferring also insights on multiple areas such as determining material characteristics, and estimate fragility or danger [21]. From the beginning of human history, the sense of touch has helped Man in most of his primordial tasks; touch became “an integral part of human nature”. As previously said in the introduction, sense of touch is better explained if it is divided into two complementary modalities: Kinaesthetic and Tactile/Cutaneous.

Kinaesthetic sensations, such as forces, torques and position of muscle joints, give a better vision of the representation of body position in space, relative to other objects; they are sensed by muscles, joint and tendons [2,5].

Tactile sensations, like shape, texture, softness, temperature, vibration, or shear, elicited by physical contact or touch, are sensed by specific sensors and organs called “Mechanoreceptors”, located inside the skin; each mechanoreceptor detects a specific sensation processed by the brain [5,6].

Since haptics occupy a very salient place in all the manipulation of humans, it is hard to imagine how surgeons manage to operate with no, or very little haptic sensations. For this reason, in teleoperation, the sense of touch must be created again by a signal or a stimulus sensed by the surgeon’s body, creating the illusion of spatial constraints and physical characteristics similar to the ones of the remote environment [16,19]. This sensation of telepresence through which the surgeons feels that he is in the remote environment, is called Transparency in the field’s literature [18]. It is one of the two key features of teleoperated systems, along with stability [18,22]. In order to achieve high transparency, haptic sensors are required in the remote environment to collect all the haptic information. Similarly, haptic displays are required on the operator’s side, to send all the necessary information, creating telepresence [22].

2.2. Force feedback

Kinaesthesia is associated with the sensation of displacement, and the perception of the amount of force inflicted on the body [23]. This type of perception is usually taken for granted, but involves an important number of receptors present in almost all muscles, joints and tendons [14]. For example, muscle spindles are transducers for any strain on the muscles and can detect any change in the length of the muscle; another good example would be the Golgi tendon which is a proprioceptive sensory organ for tension in the muscle [15]. Kinaesthetic haptic devices must therefore stimulate these receptors in order to create the illusion of force-displacement relationships, imitating the remote environment [16].

Historically, the bulk of haptic feedback research has been on Force Feedback [24]. The salient advantage of Force Feedback is the realism that it brings to telepresence, as it increases the transparency of the teleoperation [19]. In fact, the purpose of force feedback is to measure the forces and Torques exerted by the operated tool on the tissues and organs, then to transcript these haptic cues to the surgeon; this can assure a better control of the force that the surgeon is exerting on the tissue and therefore improves the transparency of a tele-operated loop system [6,18]. Transparency allows the surgeon to have the illusion of presence inside the patient’s body [18]. A 100% transparent system would mean exact force detection with zero error, zero time-delay, and similar impedance [25]. Such a “perfect” kinaesthetic feedback system can cause oscillations in the “closed-loop” with a detrimental high instability [22]. Hence, there must be a trade-off between transparency and stability, discussed later in this review.

The sensors used to detect Force information are Force and Torque sensors. A complete 6 Degrees of freedom (DOF) force and torque sensing is preferred for most of the applications since omitted forces might be detrimental to the task. Force sensors and torques are required, most of the time, in the three directions *x*, *y* and *z* [7,25,26]. However, some applications might need less DOFs to be accomplished, and systems with less DOFs and with a reduced cost have been tested. The location of the sensors must be as close as possible to the interaction environment, which is the tip of the surgical tool, in order to get the most accurate results [6,15]. If the sensors are too far from the tool-tip, deflection, noise and vibration on the tool shaft might heavily false the sensed information [25]. The sensors are in most cases single-point detectors that sense force and Torque at a desired position [27]. The type of sensors that can be used for this type of applications are various, and may be capacitive, piezoresistive, piezoelectric, optoelectric, inductive, through strain gauges, or a combination of sensing techniques assembled in a multi-component sensor [6]. The sensors already available on the market for these types of measurements are already very accurate and cover a very wide range of forces, including the ones required for robotic surgery [6]. Nonetheless, the challenges of sensing come from the fact that sensors must be placed on the instrument, close to the tip [15,27]. This causes multiple problems, such as size (physical constraints), cost, sterilisation and biocompatibility, in addition to the requirements of the European Medicine Agency (EMA) or the U.S. Food and Drug Administration (FDA) [28]. Various solutions were explored to fix these issues, with different DOF and feedback modalities, which resulted in systems with different costs and sizes: 1 DOF [29]; 6+ DOF four capacitance transducer, 6 DOF optic fibre [30]. They can be either gripped to the surgical tool or embedded within the system.

Once the sensors have registered the necessary haptic cues, the system processes them, and sends a feedback to the surgeon. One conventional way to display Force Feedback is to use motors and actuators to stimulate directly the surgeon's hand or finger, to recreate the forces detected by the sensors on the patient side [17]. However, it is also popular to display Force Feedback through visual display, as shown by Rieley et al., in order to conserve the stability of the closed-loop. Visual display uses different colours to express the force exerted on the tissue: Low force is in green, ideal force in yellow, and excessive force in red [12]. Another type of display can be applied through vibrations, as shown by Pacchierotti et al. [31].

Experiments on force feedback made on phantom tissues were promising, and showed great potential: Lower average force on tissue, lower peak force on tissue, and faster tissue detection time, an improved accuracy and a faster learning time for surgeons [14,16,31].

2.3. Tactile feedback

For some surgical tasks such as knot tying or grasping, force feedback is a critical key factor that affects outcome 928). For other surgical tasks such as palpation, Tactile Feedback becomes essential. Tactile sensors are meant to sense mechanical properties, such as shape, pressure, Temperature, viscosity, shear and normal forces [32]. The type of the sensors used are the same as for force sensing [9]: It requires sensing in the remote environment, and displaying in the master's side. The applications of the sensors however, vary for tactile cues. In fact, instead of registering only single-point cues such as forces and torques, it is necessary to measure an array of data in multiple points in space, to process tactile information, such as pressure and viscosity [22,27]. This challenge, coupled with the constraints imposed by the environment, and the high cost, are the main reasons why tactile feedback has been somehow ignored for a long time by the research community [6,22].

Tactile Feedback is different from Force Feedback concerning the closed-loop Master-Slave system. Force feedback is detected by a force or torque on the slave's side, and the feedback is exerted *via* a force or torque on the master's side. This type of feedback requires actuation on the master side, and this is the main reason why increasing transparency decreases stability because of oscillations created in the loop. Tactile Feedback on the other hand, is detected by mechanoreceptors on the skin, and consists of multiple stimuli. The fingertip is the location with the highest mechanoreceptor density [2,33,34]. Therefore, most of the tactile feedback is sent to the operating surgeon *via* his fingertip. Tactile Feedback doesn't affect the stability of the system and can still increase its transparency [18].

Tactile feedback can therefore be the solution to create a stable loop, while keeping a high transparency for the operator. Kinaesthetic Force Feedback has relatively little ways of displays to the operator compared to tactile Feedback. Cutaneous devices are usually wearable, and provide forces (direction, intensity, timing) or vibration to the finger tip of the user. Some of these devices were modified to be wearable by a surgeon adapted to the workflow of the operating room, and improved in a way to exert tangential force on the fingertip, inflicting shear deformation on the finger, creating a more realistic stimulus for the surgeon [18,22,35].

Vibration feedback has been also investigated and then introduced to several types of these cutaneous feedback devices for clinically trial on patients [5,10,34,36].

Tactile devices are still prone to research by many scientists and engineers. It might be the best way to find the ultimate trade-off between stability and transparency. The results of Tactile feedback are experimentally less efficient than Force Feedback, and therefore, a combination of the two types is a good way to solve both issues [27].

3. Tele-operation: a collaboration

3.1. Stability

In a teleoperation, the closed-loop that controls the interactions between the master, the robot and the remote environment is a key feature, and the stability of this closed-loop is essential, considering the nature of the application where any instability can be detrimental [2,15]. Direct Force Feedback includes the presence of dynamic forces that can affect importantly the stability of the closed-loop [21]: Dynamic forces are the forces acting outside of the system, and can be compared to disturbances acting on the system, a simple example being a motion-controlled robot hitting a wall [37]. When using Force Feedback and therefore dynamic forces in a haptic system, as one pushes the transparency of the loop, meaning an increase in the frequency of the dynamic forces, the stability gets affected [19]. In fact, multiple time delays are created, and the remote environment's impedance isn't precisely depicted to the user. In addition, hard contacts and relaxed grasp may be caused by dynamic forces, which could also affect the stability of the system [11,34]. Dynamic forces are not linear forces, what makes it very hard to predict a working model with linear control [37].

Enayati et al. and Pacchierotti et al. presented detailed technical reports about the chronologic development and progress of stability in haptic control systems [21,22]. The papers explained that the three interacting systems (master, slave, environment) should be treated as passive (= no generation of energy) [38]. This makes the whole system easier to control and predict. In addition, another important consideration can also help anticipating the dynamic forces: It is the reaction of the remote environment after its interaction with the robotic arms. This reaction can be predicted following virtual approximation of the characteristics of the remote milieu, such as stiffness or viscosity. Furthermore, factors such as time delays, sampling and quantisation, if shared between operator and environment, can improve the impedance matching between both, and therefore improve the stability of the loop.

Years of technical research and a large amount of data are now available to help increase the stability of control systems where dynamic forces are present. Notably, the scattering algorithm [39], Time domain passivity already discussed [38], and the energy algorithm [40]. However, the multiple techniques always led to a loss of transparency in the system. It is therefore very challenging to build a highly transparent and stable system using Force-Feedback. Hence, Pacchierotti et al. proposed two techniques for improving stability in a haptic teleoperation [18]. The first technique is the avoidance of Force Feedback, without any actuator on the master side; instead, the system would rely on another sensory channel that would not affect stability: Tactile Feedback. This method results in loss of transparency, but an intrinsically stable close-loop, commonly called "sensory substitution", established by Prattichizzo. The second method would be to create a stable control system with the best trade-off between stability and Transparency. Abiri et al., and Lim et al. reported a third technique: Multimodal Platforms, which would combine Force Feedback and Cutaneous Feedback [15,27]. In fact, since cutaneous feedback is more stable and less transparent, and force feedback is more transparent and less stable, these platforms would try to find the best trade-off between Force Feedback and cutaneous feedback.

3.2. Transparency

Telepresence is the perception of the remote environment required in a teleoperation: The surgeon needs to feel inside the body of his patient. The performance of telepresence is determined by transparency and accuracy of motion. Accuracy of motion is achieved in most of the experimental devices and is not the challenging part of it. It is not relevant for the scope of this review and therefore it will not be discussed. Transparency is the most salient and common characteristic considered to appreciate and judge the performance of tele-operation [18,22].

Ideally, a haptic device must have zero mass, infinite supply of force and torque, and unlimited bandwidth [32]. Moreover, a completely transparent system transcripts the exact sensed forces and impedance of the remote environment to the operator [17]. However, the dynamic forces in the haptic device affects the impedance transmitted: These forces are created mostly by the actuator in the system, but also by the linkages. In fact, in Force feedback, actuation is needed on the master's side to transmit the forces. This actuation causes an actuation Force and Torque, and consequently parasitic friction and inertia [41]. These parasites can mask the forces and torques sensed in the environment, and therefore affect the desired impedance and the stability of the loop. It is therefore challenging to design a transparent system for many reasons: 1-Sensors are limited as previously explained, which affects the accuracy of the sensing; 2-Parasitic forces and Torques induced by actuations and linkages of Force Feedback decrease the stability of the systems; 3- Increasing Transparency decreases stability, and a good trade-off must be found.

In order to overcome these challenges, it is possible to redesign the device removing the actuation on the master's side and therefore the dynamic forces. It is the equivalent of the sensory substitution since it will not involve Force Feedback [18]. The second option would be to decrease the effect of the dynamic forces on the system; the most common way of doing this is by implementing efficient compensators [32,41]. Mahvach et al. showed detailed reasoning behind friction compensation and torque compensation that would be exhaustive to detail in this review [17]. The second option, that is keeping Force Feedback, is important for multi-modal platforms as Force Feedback has proven to be an efficient haptic feedback.

4. Trade-off experiments

4.1. Sensory substitution

It is already established that force feedback increases the sensation of telepresence, but decreases the stability of the system. As discussed above, one way to overcome this problem is to find new sensory modalities to stimulate the master's side, without the grounded devices that create actuation. These modalities must provide ungrounded cues that will not affect the stability of the closed-loop [18]: This is known as sensory substitution.

Various senses can be put to contribution for sensory substitution. Auditory cues have been tested by Kitagawa et al. [42]; although results were promising, auditory feedback is hard to implement in the surgical workflow, since the surgeon needs to communicate with his team during surgery [43]. As previously discussed, Visual Feedback also showed motivating results, and improved the transparency of the system compared to No-Feedback at all [12]. However, Prattichizzo et al. showed clearly that Cutaneous Feedback with an ungrounded moving platform improved transparency more than visual Feedback [44]. Therefore, we will mainly focus on sensory substitution through Cutaneous Feedback, as it is part of haptics, and has been shown to be the most efficient sensory substitution.

Cutaneous cues make a system intrinsically stable. Nonetheless, the tactile stimuli are less intuitive than Force Feedback as they do not deliver space constraints. Thus, the goal in sensory substitution is to improve the transparency of any system involving only tactile cues [44]. Prattichizzo et al. stated that sensory substitution can also be called sensory substraction since the force component, the destabilising factor, is removed; whereas in a normal haptic system, Force and Tactile cue are both used [44].

Multiple ways have been developed to improve transparency through Cutaneous Feedback. McMahan et al. proposed a high frequency vibratory feedback system, where accelerometers report the oscillations of the surgical tool, which are recreated on the surgeon's hand [20]. Skin Stretch techniques have also been studied for cutaneous feedback: Skin stretch delivers cues about force direction and intensity, whereas vibrations only give insight on intensity [19]. Quek et al. investigated a haptic system providing tangential forces on the user's fingertip, and found that awareness was significantly improved [19].

4.2. Multi-Modal platforms

We discussed how single modalities such Force Feedback, Cutaneous Feedback, or Vibrotactile Feedback work individually. We showed that every single one improves results, compared with a No-Feedback robotic system. However, even if single modality haptic systems achieved improvements, they are still a lot less intuitive than normal touch [15]. In order to make it more intuitive, and increase transparency, Multi-Modal Platforms (MMP) were thus created, combining Force, Tactile and Vibration Feedbacks. These platforms are a better representation of the human's natural sense of touch, and should improve haptic feedback in robotic minimally invasive surgery. Today, the most commonly used robot for teleoperated surgery is the Da Vinci, and it is a No-Feedback system.

MMP targets the different mechanoreceptors in the skin and the muscles, for a promise of a more natural touch impression [15]. Research and development of MMP were mainly based on Bi-Modal systems consisting of Force and Tactile Feedback, and were mainly carried out by Schoonmaker et al. and Okamura et al. [45,46]. One key feature of Bi-Modal systems is the Decoupling of these 2 types of Feedback. In fact, both cannot be controlled by the same closed-loop, otherwise Force Feedback would decrease the stability of the overall system, degrading the stability of Tactile Feedback. Pacchierotti et al. published a technical overview of the decoupling mechanism, also showing its limitations: Once both feedbacks are independently controlled, finding the best trade-off between Tactile and Force feedback, can give the best Stability/Transparency compromise [18,22].

Abiri et al. reported a Tri-Modal platform, adding Vibrotactile feedback to Force and Tactile Feedback, and compared Tri-modal, Bimodal and No-feedback systems. Results were interesting, and revealed that both Bi-modal and Tri-modal haptic devices showed a reduction in the average grip force, compared to No-Feedback, while the peak force for the Bi-modal was still too high for tissue safety [15]. Another study from Lim et al. showed a 40% force reduction on tissue with Bi-Modal Feedback, compared to No-Feedback [27]. MMP may probably provide a solution that reproduce best natural touch. Other research involving grasping [15], palpation [8,45], suturing [42], needle insertion [47], cutting [23], and dissecting [48], all showed improved safety and results when haptic feedback was added to teleoperation. However, studies are still too superficial and more research is needed for more conclusive results [15].

5. Clinical applications today

Robotics have started a new era in medicine, and have opened the door for tremendous advances in clinical surgery. Robotic surgery is one of the most important surgical innovations over the last decade; it enabled surgeons to perform minimally invasive approaches to complex procedures, when they would otherwise resort to conventional open surgery. Because of their huge positive impact on minimally invasive surgery, teleoperated robots have spread worldwide, and have become an integral part of surgical training in most surgical subspecialties. For this reason, the bulk of scientific research during the last decade, has targeted teleoperated robots. But research comes at a cost: The Da Vinci system costs around 2 million dollars, and surgery using the robot is 3 to 6 thousand dollars more expensive than conventional minimally invasive surgery [49]. However, this hasn't prevented more than 1,500 hospitals in the United States to install the Da Vinci surgical robot since it came to market in 2000. Moreover, it is expected that within 5 years, one in three surgeries will be performed with the robot [50]. The most widespread and commonly used commercially available system is the Da Vinci Robot (USA). It is the only FDA approved system. Several other teleoperated robotic systems exist, including Senhance, Zimmer-Biomet, and Mako (USA), Versius (England), Titan (Canada), Revo-I (South-Korea), and Avatera (Germany), but their use in clinical settings has been limited.

It is surprising that until very recently, commercially available robots didn't include any Haptic Feedback to the operator; the surgeon can only see the surgical tool and robot's arms inside the body, but can't feel anything. The lack of haptic feedback has shown to be a serious challenge, with reports about tissue injury, and inability to perform complex manipulation such as tying a knot. Haptic Feedback was therefore considered as an important component to add into Teleoperation. This led in turn to the multiple challenges discussed earlier, in order to provide the best platform in terms of stability and transparency.

There are several solutions to the trade-off problem between stability and transparency; it can either be by removing Force Feedback and Improving Tactile Feedback, or use both in a multi-modal platform, or even use other sensing modalities. However, despite all these solutions, Haptic Feedback in commercial teleoperated systems is rare/inexistent; the research community may in fact be at a stage where too many ways of feedback are being studied, and few advancements are being done in each. Most of the developed devices are still prototypes, without any serious in-vivo validation. Moreover, another aspect is the difficulty of the Cutaneous Feedback representation. It is very hard to replicate multiple human mechanoreceptors acting simultaneously, even if some authors claim they found the "holy grail": Skin Stretch and tangential forces are only a mere replication of tactile proprioception perceived during conventional surgery. Force Feedback, on the other hand, seems to be the most efficient type of feedback concerning transparency, but causes instability issues that can be detrimental. One important point to underline is that the medical field is much more meticulous and cautious concerning the implementation of any new system, which has led to the fact that the only commercialised system is the fully stable one. It is there possible to infer that Safety is the most important point: Even if the performance of innovative methods are better than the existing Da Vinci, the "worst case scenario" of these systems may be detrimental to the patient, while the worst case for the Da Vinci system is what is done every day, that is an extra average force exerted on the patient. However, robotic surgery is spreading to several specialties other than urology, visceral, and gynaecological surgery. Cardio-thoracic surgeons are increasingly including surgical robots in their armamentarium, and cardiac procedures include fine suturing of delicate tissue. Thus, haptic feedback will undoubtedly be a tremendous technical addition to the existing robots, allowing surgeons to use them more intuitively in delicate and complex procedure. Ultimately, problems related to haptics will be solved, and this will lead to more capabilities and more applications to meet the requirement of the future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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