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Improvement of Robotic Minimally Invasive Surgery with the addition of Haptic Feedback

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Declaration of scientific integrity

The author hereby declares that he has read and fully adhered the Code for Good Practice in Research of the University of Basel.

Abstract

Haptic feedback in robotic minimally invasive surgery (RMIS) is still mostly missing from current systems, due to problems concerning the efficiency, precision, and safety of the operations. This bachelor thesis tries to answer the question, how haptic feedback can improve RMIS and what kind of haptic feedback is best suited as an addition to RMIS systems. Different types of haptic feedback are explored and a short outline of haptic perception is given. RMIS is compared with laparoscopic surgery and advantages and shortcomings of current RMIS systems are explored. Current research about haptic feedback in RMIS is examined and the addition of different haptic feedback types to RMIS systems are evaluated. The addition of kinsthetic force feedback to RMIS systems can improve the accuracy in dissection tasks, improve tissue recognition, and reduce tissue damage during procedures. Cutaneous feedback can improve completion time and reduce the amount of errors. Due to safety concerns with kinesthetic force feedback, the approach of sensory subtraction was introduced, which substitutes kinesthetic force feedback with cutaneous feedback. Finger mounted feedback systems providing cutaneous feedback, have the advantage of easily being integrated into current RMIS systems and offer a good compromise between performance improvements and system stability.

Keywords: haptics, robotic minimally invasive surgery, cutaneous

Introduction

At the beginning of the 20th century, haptics was introduced as a new research field in experimental psychology, with its main focus on haptic research to improve the understanding of human touch, perception, and manipulation (Orozco, Silva, El Saddik, & Petriu, 2012). Machine haptics is a continuation of haptic research, focusing on design, construction, and the development of mechanical devices replacing or augmenting human touch (Orozco et al., 2012). Haptics refers both to cutaneous sensation and the kinesthetic sense (Freeman et al., 2017). Cutaneous sensations comprise vibration, pressure, touch, texture, and temperature (Freeman et al., 2017). Kinesthetic sense refers to internal signals sent by muscles and tendons, informing the body about the position and movement of a limb (Freeman et al., 2017). Mechanically generated haptic feedback has many use cases, ranging from applications in the consumer market in the form of vibrotactile feedback, generally known as vibrations in smartphones and smartwatches (Schneider, MacLean, Swindells, & Booth, 2017), to the use of haptic feedback in the area of gaming, to convey more immersive and realistic game experiences (Orozco et al., 2012). A different area where haptics is of growing importance is the field of medicine, specifically, the field of robotic minimally invasive surgery (RMIS) (Beek, 2016). RMIS is a form of surgery, wherein the surgeon is tele operating a robot, this means, the surgeon is remotely controlling the robot and the surgical instruments, to perform a RMIS (Beek, 2016). During RMIS, small incisions are made into the patient, through which a camera and surgical instruments are inserted, to perform a surgical procedure on site (Sarpel, 2014). For RMIS the concept of tele-presence is quite important, as it describes the way an operator feels during the interaction with the robot, while physically being at a different location (Orozco et al., 2012). During surgery, visual and haptic information is essential for the surgeon to perform his operation, just as musicians who use their fingers to produce sound and intonation, and to feel the vibration in string instruments for example (Stark, Benhidjeb, Gidaro, & Morales, 2012). Surgeons need haptic and visual information to perform a surgery, to feel the consistency and anatomical structures of tissue (Stark et al., 2012), and locate tumors using a finger (Pacchierotti, Prattichizzo, & Kuchenbecker, 2016; Beek, 2016). Visual information during RMIS is provided by multiple cameras, producing a three-dimensional image, that is used by the surgeon during a surgery (Beek, 2016). Haptic information is still missing from the most widespread RMIS system, the da Vinci XI (Tsuda & Kudsi, 2018), but haptic feedback has been incorporated and tested in RMIS systems, and new RMIS-systems released into the market like the Senhance surgical system have incorporated haptic feedback (Rao, 2018). However, there are still problems concerning the efficiency, precision, and safety when integrating haptic feedback in RMIS (Song et al., 2018). The absence of haptic feedback for example, has been linked to longer operation times and more errors during heart surgery (Bethea et al., 2004). Amongst other things, the addition of haptic feedback in RMIS systems has the potential of enhancing the surgeon's user experience, shorten operation times, reduce the number of significant errors, and allow for more precise interactions during a surgery (Enayati, De Momi, & Ferrigno, 2016).

This thesis focuses on different kinds of haptic feedback and the way these types of feedback are conveyed to the surgeon. The goal is to evaluate current research on haptic feedback in RMIS and to get a clearer picture of the latest achievements in this field of research. At first, the field of haptics and haptic perception will be explored, then a comparison of traditional laparoscopic surgery with RMIS is made, as both surgical methods offer similar benefits. The concept of laparoscopic surgery will be explained later on, when comparing RMIS with laparoscopic surgery. Furthermore, an outline of current RMIS systems will be given, as well as exploring the advantages and shortcomings of the different systems. Finally, research on different types of haptic feedback is examined, additionally comparing the most prominent types of haptic feedback. The results deduced from literature will be compared to answer the question of how haptic feedback can improve RMIS and what kind of haptic feedback is best suited as an addition to RMIS systems.

Haptics

During a RMIS, information from the inside of the patient is presented through visual feedback to the surgeon. A 3D image is streamed in real time to a 3D high-definition stereo viewer, which can be seen in figure 1, providing a depth of field for navigation as well as operation (Tsuda & Kudsi, 2018). This information is therefore presented through a single sensory modality.

Figure 1. The da Vinci XI surgeon console with a look at 3D high-definition stereo viewer. From Intuitive, n.d. Retrieved from https://www.intuitive.com/en-us/products-and-services/da-vinci/systems##

Computer interfaces generally provide information through visual modality only, but there are advantages of combining visual information with other sensory modalities like haptics and or audio (Freeman et al., 2017). One benefit of combining multiple modalities in a user interface, is the distribution of interaction across different senses, leading to better performance as well as to the usage of fewer cognitive resources (Freeman et al., 2017). Companies and researches are pushing the development of new systems and the improvement of currently available systems (Pacchierotti et al., 2016; Tavakoli, Patel, & Moallem, 2005; Tsuda & Kudsi, 2018). Haptic feedback is one of those technologies, at present mostly missing from RMIS systems like the da Vinci XI (Tsuda & Kudsi, 2018). But this described technology is starting to be implemented in new systems like the Senhance surgical robotic system (Tsuda & Kudsi, 2018).

In the following section, the focus lays on explaining the different types of haptic feedback, starting with a short outline of haptic perception, followed by an overview of the different types of haptic feedback modalities.

Haptic Perception

All types of haptic feedback either fall into the category of cutaneous sensations or kinesthetic sense (Freeman et al., 2017). Cutaneous perception refers to the sense of touch and the information is provided by two types of receptors, thermoreceptors, and mechanoreceptors (Beek, 2016). Both receptors are embedded in the skin and serve a specific function (Beek, 2016). Thermoreceptors are sensitive to temperature and can be further divided into two receptors, one responding to warmth while the other receptor responds to cold (Beek, 2016). Mechanoreceptors, on the other hand, are sensitive to pressure caused by force and displacement and can be divided into four different types of receptors, all contributing to cutaneous perception (Beek, 2016). These four receptors are called Meissner corpuscules, Merkel cell complex, Ruffini endings, and Pacini corpuscules, and are categorized in either their receptive field size or their adaptation rate (Beek, 2016). The adaption rate indicates how fast a receptor desensitizes to an unchanging stimulus, while the receptive field size indicates the size of the skin surface signaling information (Beek, 2016). The combination of these different sensory properties facilitates the perception of information about the temporal and spatial characteristics of objects being touched (Beek, 2016). Kinesthetic perception is possible through three mechanoreceptors placed within the muscles and joints (Beek, 2016). These mechanoreceptors are called muscle spindles and Golgi tendon organs. They provide information about the state of the muscle and the resulting state of the tendon, ultimately informing about arm position and movement (Beek, 2016). The third mechanoreceptor to provide kinesthetic information is called joint receptor, it delivers signals about joint angles based on strain and stretch of the tissue inside (Beek, 2016).

Haptic Feedback

The most important haptic feedback modalities belonging to the category of cutaneous sensations are vibrotactile feedback, pressure feedback, and thermal feedback. The most commonly used haptic output is vibrotactile feedback, and it is produced by vibrations from an actuator. This kind of feedback is found in smartphones, smartwatches, video game controllers, laptops, and many other use cases (Freeman et al., 2017). Most of the time, vibrations are used to attract the attention of the user, like in the case of notification alerts, but the various dynamic properties allow for a more sophisticated information encoding and the

(a) (b)

Figure 2. (a) Taptic Engine and the home button of an iPhone. (b) Vibration motor of an iPhone. From “Apples Taptic Engine: Entwickler können drei Modi nutzen,“ by Nicolas 2016. Retrieved from https://www.iphone-ticker.de/apples-taptic-engine-entwickler-koennen-drei-modi-nutzen-102452/)

creation of different sensations besides the buzzing of a classic vibration motor (Freeman et al., 2017). One example would be the solid state home button, as illustrated in figure 2, found in the iPhone 7 and iPhone 8, where the vibrotactile actuator is used to create the illusion of actually pressing a button even though there are no moving parts present. In the field of RMIS, vibrotactile feedback can be used to provide important information about the application of pressure when using an instrument during a procedure, also vibrations could be used to provide navigational information (Pacchierotti et al., 2016).

A far less utilized haptic feedback besides vibrotactile feedback is the thermal feedback, which is an essential part of the cutaneous sense (Freeman et al., 2017). Thermal feedback can convey information about objects and environments as well as information about social and emotional phenomena. Severe hot or cold temperatures could indicate danger whereas the warmth of an animal or a human being could indicate life (Freeman et al., 2017). Warmth, on the other hand, could also convey social and physical closeness or positive emotions like loving and warmth (Freeman et al., 2017).

Another method of conveying cutaneous sensations are Indentation displays. They target mechanoreceptors sensitive to deformation caused by force and displacement (Pacchierotti et al., 2016). Different methods can be used to provide these haptic informations to the user, like a pin array display, a pneumatic balloon system, and a platform based pressure system (Pacchierotti et al., 2016). A pin array display uses pins raised against human skin to provide information about shapes and tissue characteristics (Pacchierotti et al., 2016). A pneumatic balloon system uses balloons to provide cutaneous sensation to the user (Pacchierotti et al., 2016). The balloon is placed against the fingertip and by changing the amount of pressure exerted from the balloon, different tissue properties can be conveyed (Pacchierotti et al., 2016). The platform-based feedback system, as illustrated in figure 3, uses a finger mounted system, wherein a platform is used to apply different amounts of pressure to the fingertip, thereby providing information about tissue properties and the amount of forces applied by the surgeon (Pacchierotti et al., 2016). These methods of providing cutaneous haptic feedback will be explored more closely later on in the section *cutaneous feedback in robotic minimally invasive surgery*.

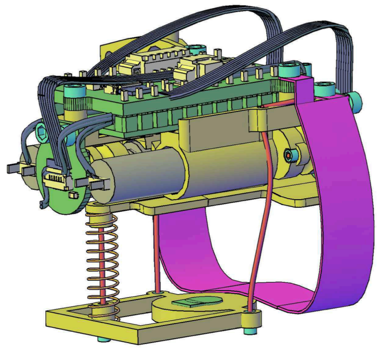
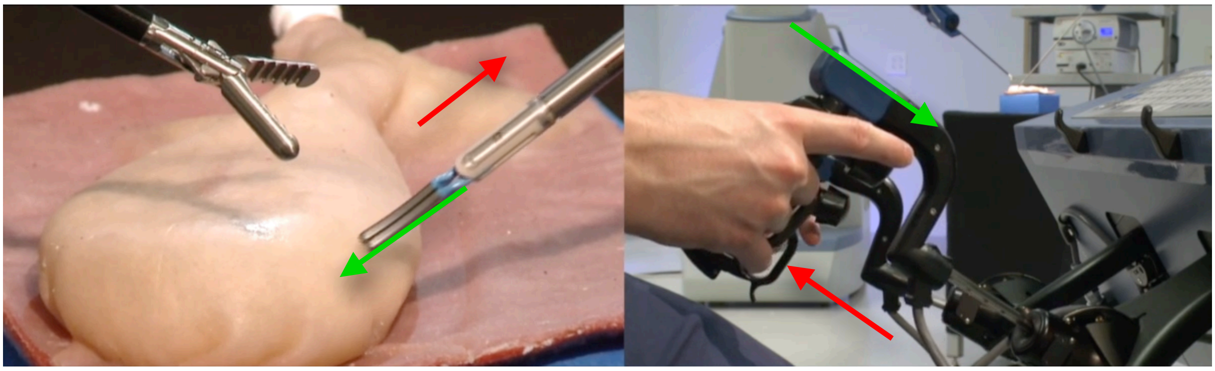


Figure 3. Finger mounted platform-based feedback system. From "Sensory subtraction via cutaneous feedback in robot-assisted surgery. " by Meli et al., 2016, Springer, (pp. 121–130).

Haptic feedback targeting the kinesthetic sense is called force feedback, it gives the user the feeling of resistance or attraction (Freeman et al., 2017). A more straightforward way to understand force feedback is to imagine two people pressing their hands against each other, when both start to press against the other hand, each of them would feel a resistive force. Opposed to this, the attractive force would be one person pulling the hand of the other into a specific direction, which to the person with its hand being pulled, would feel like an attractive force. In RMIS force feedback is provided by a mechanical system applying resistive or attractive forces to the controller operated by the surgeon. Figure 4 illustrates the integration of force feedback in RMIS where the resistive force can be used to indicate to the surgeon, that the tool he is using, is beginning to perforate tissue, the amount of resistance, thereby indicating the amount of penetration. The attractive force on the other hand can be used to guide the



(a) (b)

Figure 4. (a) Surgical instruments interacting with a synthetic tissue. The green arrow indicates the direction the instrument is moving, while the red arrow indicates direction of the force feedback (b) User operating the Controls of a Senhance system. The green arrow is indicating the direction the operator is moving the controls and the red arrow shows the direction of the force feedback. From "Senhance Surgery - Full Length Benefits. " by TransEnterix. (2017) Retrieved from https://www.youtube.com/watch?v=oHhVfxb-NyY&t=184s

surgeon's movement into a particular direction. Force feedback could also be utilized to make virtual objects feel deformable and physically interactive (Freeman et al., 2017). Another use case of force feedback is the creation of textures, giving the illusion of recesses or textured surfaces (Freeman et al., 2017).

Using multiple sensory modalities to convey information is called multimodal feedback and is divided into two design approaches (Freeman et al., 2017). Crossmodal feedback design uses different modalities to present the same information whereas intramodal feedback design uses different properties of the same sensory modality to present information (Freeman et al., 2017). An example of intramodal feedback would be the combination of vibrotactile feedback and thermal feedback to convey information (Freeman et al., 2017). One of the main advantages of crossmodal feedback is the information being presented with the appropriate modality based on context. In this way a smartphone location can be indicated both by vibrotactile feedback and audio feedback, depending on the user's context (Freeman et al., 2017). The advantage of intramodal feedback is the combination of different properties of the same modality to increase the recognition of the desired information presented (Freeman et al., 2017). Wilson, Brewster, Halvey, and Hughes (2012) could show, that the merging of vibrotactile and thermal feedback leads to a more accurate recognition of the transmitted message, than information that is presented through either thermal or vibrotactile feedback only. Intramodal feedback had a recognition of 97 % opposed to solely thermal feedback with a recognition of 83 %, offering the possibility of recognizing and interpreting tactile and thermal signals combined (Freeman et al., 2017).

Robotic Minimally Invasive Surgery

The invention of the first tele-operated mechanical arm by Raymond Goertz in 1951 marked the beginning of advancements in robotics and ultimately led to the introduction of the first robotic surgeon in 1978 (Ghezzi & Corleta, 2016). The programmable universal machine for assembly can be seen in figure 5 and was developed by Victor Scheinman in 1978, it was the first robotic surgeon used on patients, with applications in neurosurgical biopsies and in urological surgery (Ghezzi & Corleta, 2016). A drawback of this system was the fact that it had to be preprogrammed based on fixed anatomic landmarks, making it impossible to be used for dynamic surgical targets (Ghezzi & Corleta, 2016). Surgical robotic systems can be classified into two categories based on their level of autonomy, they are either an autonomous system or a non-autonomous system (Enayati et al., 2016). Like the name implies, autonomous systems execute tasks automatically, while the non-autonomous system requires an operator to control the system (Enayati et al., 2016). These non-autonomous systems allow the feeling of telepresence, which is the sensation of being present at a remote site (Pacchierotti et al., 2016). They allow the operators to sense and mechanically manipulate objects at a distance, as it is done in RMIS (Pacchierotti et al., 2016). Telepresence is achieved by transmitting different types of information from the remote environment to the operator, mainly visual and haptic information (Pacchierotti et al., 2016).

Figure 5. The programmable universal machine for assembly From “30 years of robotic surgery.“ by Ghezzi & Corleta, 2016, World journal of surgery, 40(10), 2550–2557.

Laparoscopic Surgery vs. Robotic Minimally Invasive Surgery

Laparoscopic surgery and RMIS both follow the principle of operating through small incisions (Sarpel, 2014). Eventough both surgical methods provide the same advantages, RMIS is much more costly, which is why this section explores the benefits and drawbacks of doing RMIS opposed to traditional laparoscopic surgery.

During laparoscopic surgery and RMIS, a camera and surgical instruments are inserted through small incisions into the patient's abdomen (Sarpel, 2014). After the access to the abdomen is established, carbon dioxide is insufflated, causing pressure to distend the abdominal wall outward thus creating a room for the surgeon to operate in (Sarpel, 2014). The benefits of laparoscopic surgery and RMIS for patients are small incisions causing an increased cosmetic postoperative appearance, reduced postoperative pain, lower rates of wound infection, and shorter hospital stays (Sarpel, 2014). Tam et al. (2016) have compared laparoscopic and robotic outcomes in colorectal surgery, focusing on conversion rates, hospital length stay and operative time. Tam et al. (2016) found significantly lower conversion rates for colon and rectal resections, meaning a decreased need to convert to open surgery. A significantly shorter hospital stay after RMIS was found, but operating times for RMIS were longer compared to laparoscopic surgery (Gavriilidis et al., 2016, Tam et al., 2016). Meanwhile different studies did not show any differences in hospital length stay, leaving this topic open for further research (Halabi et al., 2013; Keller, Senagore, Lawrence, Champagne, and Delaney, 2014). In the case of complication rates, there were also mixed results as Tam et al. (2016) displayed no differences, while other studies reported more postoperative infections, fistulas, and thromboembolic complications (Halabi et al. 2013; Baik et al. 2009; Patel, Ragupathi, Ramos-Valadez, and Haas, 2011). The interaction of the surgeon with the instruments during laparoscopic surgery has some drawbacks addressed by RMIS. The first drawback is a counter-intuitive motion of the instruments since the motion is pivoting around the incision point, as illustrated in figure 6, the motion of the surgeon is reversed, creating a upward motion of the instruments grip and leading to a downward motion at the tip of the instrument (Enayati et al., 2016). Other disadvantages of laparoscopic surgery are deteriorated vision and missing direct haptic sensations for the surgeon (Enayati et al., 2016). RMIS addresses these drawbacks by providing 3D vision, translating the movement of the controls by the surgeon, directly allowing for optimal hand-eye alignment, additionally providing motion scaling and tremor filtering (Enayati et al., 2016). The lack of haptic feedback is currently being researched and worked on with new systems coming onto the market, starting to implement haptic feedback in some form (Rao, 2018).

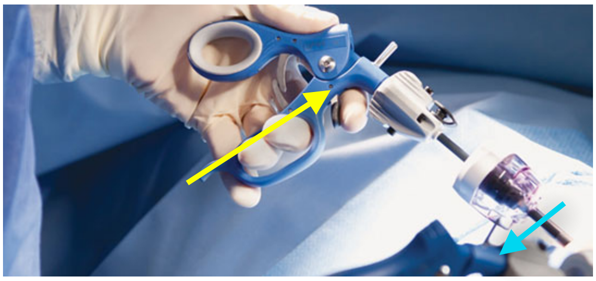


Figure 6. The yellow arrow shows the hand movement of the surgeon, which translates into the reversed direction of the surgical instrument moving, indicated by the blue arrow. From “Omnia“ by Informa Markets. (n.d.). Retrieved from https:/ www.omniagmd.com/product/ laparoscopic-surgery-instruments

The merits of RMIS over laparoscopic surgery at present mainly concern the surgeon himself, offering better delivery of visual information, increased degrees of freedom and improved articulation, a surgeon-controlled camera and a surgeon-controlled third arm, as well as the aforementioned optimal hand-eye alignment, motion scaling, and tremor filtering (Tam et al., 2016; Enayati et al., 2016).

Current Robotic Minimally Invasive Surgery Systems

Today the da Vinci Robotic Assisted Surgical Systems is the most widespread robotic surgical system selling over 3400 units (Palep, 2009). Even with divergent benefits for the patient showing, the RMIS system da Vinci has gained a wide adoption (Rao, 2018). Switzerland, for example, has the worlds highest density of robots in the operating theatre, with 32 da Vinci robots (Amrein, n.d.), in the region of Basel alone, there are four of the da Vinci system (Amrein, n.d.). The goal of this section is to give an overview of currently available systems and to compare the cost and features of the different systems as can be seen in table 1.

Device	Da Vinci	Senhance surgical robot	REVO-I
Console	Closed	Open	Closed
Optics	8 mm 3D HD	10 mm 3D HD	10 mm 3D HD
Instruments with articulation	Monopolar/bipolar/needle holder	Bipolar/needle holder	Monopolar/bipolar/needle holder
Instrument size	8 mm	5 mm/needle holder 10 mm	8 mm
Haptic feedback	No	Yes	Yes
Optic control	Handles + foot pedal	Pupil tracking	Handles + foot pedal
Reusability	Ten uses	No restriction	20 uses
Cost per use*	$ 1500	$ 200–500	NA (only in South Korea)
Cost of device*	$ 1.5–2 Million	$ 1–1.2 Million	NA (only in South Korea)
Approvals	Worldwide	US FDA for colorectal and Gyn, CE for all lap applications	Korean FDA for use in South Korea

*Approximate figures which will vary with country

*Table 1.*Currently available RMIS systems and their features. From " Robotic surgery: new robots and finally some real competition!" by Rao, 2018, World journal of urology, 36(4), 537–541.

The da Vinci system, as illustrated in figure 7, is used for urologic surgical procedures in general as well as for gynecological laparoscopic surgical procedures, inguinal hernia procedures and many more (Palep, 2009). Currently, the da Vinci system is practically without competition, but there are a few drawbacks within this system which leave the possibility for competition (Rao, 2018). Deficiencies of the da Vinci system are mainly the cost of equipment and the recurring costs for the operation of the da Vinci (Rao, 2018).

(a) (b) (c)

Figure 7. (a) The da Vinci XI surgeon console (b) The da Vinci XI patient cart (c) The da Vinci XI vision cart. From Intuitive, n.d. Retrieved from https://www.intuitive.com/en-us/products-and-services/da-vinci/systems##

Another drawback is the omission of haptic feedback (Rao, 2018), and finally, the use and setup of the system are cumbersome, time-consuming and bulky (Rao, 2018). Two new systems have emerged, addressing the drawbacks of the da Vinci system and adding other features to differentiate themselves. The Senhance Surgical System by Transenterix was developed by an Italian company called Sofar and is currently only one of two RMIS systems, offering haptic feedback to this date (Rao 2018). The Senhance system is shown in figure 8. The main differentiating feature is an eye-tracking 3D optic system, allowing the surgeon to control the camera using his eyes and head movement (Rao, 2018). Additionally, the

(a) (b)

Figure 8. (a) Senhance patient cart (b) Senhance surgeon console. From Senhance, n.d. Retrieved with permission from https://www.senhance.com/us/digital-laparoscopy#senhance-system

Senhance system provides haptic feedback in the form of force feedback, giving the surgeon the illusion of resistance when an instrument comes in contact with the patient’s tissue. By providing limitless reusability of the laparoscopic instruments in contrast to the ten uses in the da Vinci, the Senhance system can cut down on cost (Rao, 2018). With a use cost of approximately 200-500 USD, it is more economic than the use cost of 1500 USD of the da Vinci system (Rao,2018). There is currently limited research, evaluating the performance of the Senhance system.

The other system is called the REVO-I Robotic Surgical System by the South Korean company "Meere." The Revo system, as illustrated in figure 9, has a very similar setup like the da Vinci and Senhance system, consisting of a surgeon control system, a four-armed robotic operation cart, and a vision control cart (Rao, 2018). The instruments of the REVO-I are reusable up to twenty times, edging out the 10 times of the da Vinci (Rao, 2018). The cost per use and cost of the device are currently unknown, and the system has only a Korean FDA approval for use in South Korea (Rao, 2018).

(a) (b) (c)

Figure 9. (a) Revo-I vision cart (b) Revo-I surgeon console (c) Revo-I patient cart. From Revosurgical, n.d. Retrieved from http://revosurgical.com/#/main.html

Even though the Senhance and REVO-I system have both features, which the da Vinci does not have, they still lack in other areas (Rao, 2018). The Senhance system, for example, is missing an articulating cutting instrument, integral for efficient dissection (Rao, 2018). The REVO-I system, on the other hand, has a limited range of motion in its needle holder compared to the da Vinci system (Rao, 2018). There is also a limited assessment of the REVO-I system due to its limited release in South Korea (Rao, 2018). The most significant advantage of the da Vinci system over the other two is the vast ecosystem build up over the years, the massive database of procedures, more techniques available, and the advantage of a worldwide approval (Rao, 2018).

Haptics in Robotic Minimally Invasive Surgery

This section will focus on the evaluation of studies implementing haptic feedback in RMIS systems. At first explaining the challenges of haptic feedback in RMIS systems, then followed by the exploration of methods and the performance of kinesthetic force feedback in RMIS. Furthermore methods and performance of cutaneous feedback in RMIS will be explored. This is followed by the introduction of sensory substitution and sensory subtraction. Lastly, the performance of kinesthetic force feedback and cutaneous feedback will be compared.

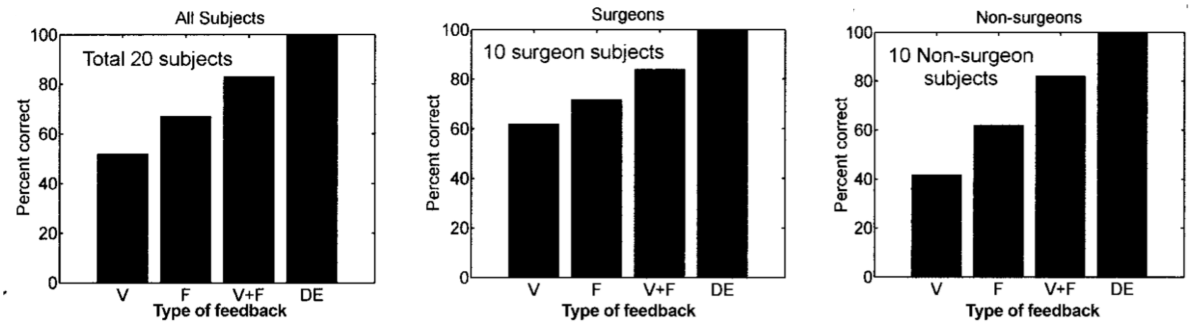
Challenges of Implementing Haptic Feedback in Robotic Minimally Invasive Surgery

The main reason for the omission of haptic feedback in RMIS systems is the negative impact it has on the safety and stability of the system (Pacchierotti et al., 2016). For a robotic minimally invasive surgery system to provide information about haptics and forces at the operation site, sensors are needed to first sense the impulses and then send the perceived information for it to be converted into haptic feedback (Enayati et al., 2016). This brings on some major challenges and limitations when designing sensors, mainly due to sterilization requirements in operation rooms, and limitation in size and robustness (Enayati et al., 2016). The sensors have to conform to surgical device regulations imposed by the U.S. Food and Drug Administration, and the European Medicines Agency, as well as to be reasonably priced (Enayati et al., 2016), altogether making the development of these sensors quite difficult (Enayati et al., 2016). The position of a force sensor is one of the major designing challenges as the sensor could be implemented in the external section of the instrument or at the instruments tip (Enayati et al., 2016). Integrating the sensor at the external section of the instrument's pole does not make sense even though it would provide information about forces from the abdominal wall, friction, backlash, and shaft contact with nearby tissue, for more accurate measurements, sensors closer to the interaction region are needed (Enayati et al., 2016). This means implementing the sensor at the instruments tip leading to size constraints and the need for robust insulation, as the sensor would be used inside the body (Enayati et al., 2016). For the sensors to be used inside the body, they must withstand the different types of sterilizations. The most common method is the application of saturated steam for about 15 minutes, another technique is the employment of chemical agents for sterilization (Enayati et al., 2016). Besides the risk of infection by using unsterilized instruments, there is the fact that non-sterilizable instruments can not be used multiple times, and need to be disposed of economically (Enayati et al., 2016). Another challenge of integrating haptic feedback in RMIS systems is the negative effect haptics can have on the stability of the whole system (Pacchierotti, 2015).

Kinesthetic Force Feedback in Robotic Minimally Invasive Surgery

One of the main reasons to integrate haptics into RMIS systems is, that the majority of errors occurring during RMIS are due to the application of too much force by the operating surgeon, leading to various injuries, as for example the perforation of the gallbladder (Enayati et al., 2016). Haptic feedback could help to prevent this exertion of too much force as shown by Tavakoli et al. (2005). With the help of force feedback in tool and tissue interactions, more adequate forces were applied, the disadvantage was longer task completion times probably due to higher cognitive load on the user (Tavakoli et al., 2005). Demi, Ortmaier, and Seibold (2005) examined the influence of force feedback on the performance of a dissection task. The instrument utilised was equipped with a force/torque sensor, capable of measuring forces up to 20 N and torques up to 200 NM (Demi et al., 2005). For this experiment, synthetically produced arteries and tissue were used, with the aim to dissect the material as fast and as uninjured as possible, within a time limit of four minutes (Demi et al., 2005). Twenty-five participants, mainly minimally invasive surgeons, were asked to perform this task, using three methods (Demi et al., 2005). All participants performed the task with the traditional laparoscopic surgical technique, or the RMIS system without force feedback, and using a RMIS system with force feedback (Demi et al., 2005). The results of Demi et al. (2005) show, that participants performed the task significantly faster when using the traditional laparoscopic surgery, thus dissecting 55.1 percent more surface compared to the RMIS without force feedback, also RMIS with feedback was 9.4 percent slower than RMIS without feedback. The accuracy variable RMIS with feedback was the most accurate one out of all three techniques, showing a significant reduction of artery transsection of 15.2 percent (Demi et al., 2005). An interview with participants revealed a preference for the RMIS system with feedback, with 60 percent of participants choosing the system with haptic feedback opposed to no haptic feedback (Demi et al., 2005).

The role of force feedback in the recognition of tissue stiffness was tested in a study by Tholey, Desai, and Castellanos (2005). A grasper instrument equipped with a force sensor was developed for the evaluation of tissue characteristics (Tholey et al., 2005). Three types of synthetically created tissues were used for the study, the soft tissue sample mimicked a healthy liver tissue, while the medium tissue sample represented a tumor in the formation stage, and the third type was a hard tissue sample that emulated a fully developed tumor (Tholey et al., 2005). Ten surgeons and ten non-surgeons had to characterize tissue samples in three conditions. The first time it was a setup with only visual feedback, the second time with force feedback, and the third time visual and force feedback were being combined (Tholey et al., 2005). For the evaluation of the tissue samples, the participants had no control over the grasper, but rather they had to evaluate the tissue with either visual information, haptic information or visual and haptic information combined (Tholey et al., 2005). The force feedback was not provided by the control unit of the robotic arm, but a haptic interface device called PHANToM was used for this task (Tholey et al., 2005). An operator with a keyboard controlled the robot, while the amount of force measured by the instrument was transmitted to the PHANToM, and was then translated into a vertical upwards directed force feedback (Tholey et al., 2005). This meant that the participant had to hold the edge of a desk with a thumb while the other fingers were resting on the top of the table, the PHANToM was attached to the forefinger and the force feedback was then delivered, representing a palpation done by surgeons using the thumb and forefinger (Tholey et al., 2005). The results comparing visual feedback with force feedback show a difference of seventeen percent of correct tissue differentiation, while participants only using visual feedback, characterized the tissues 50 percent correctly. On the other hand, participants identified the tissue samples 67 percent correctly when only using force feedback, but this result was not significant (Tholey et al., 2005). When Tholey et al., (2005) compared visual and force feedback combined against visual or force feedback on its own, a significant difference was found as the participants recognized the tissue samples 83 percent correctly, using both visual and force feedback



(a) (b) (c)

Figure 10. a) Percentage of successful tissue characterizations by all subjects for all three tissue samples using both vision and force feedback. b) Percentage of successful tissue characterizations for surgeons only and c) percentage of successful tissue characterizations for non-surgeons only. From "Force feedback plays a significant role in minimally invasive surgery: results and analysis." by Tholey et al., 2005, Annals of surgery, 241(1), 102.

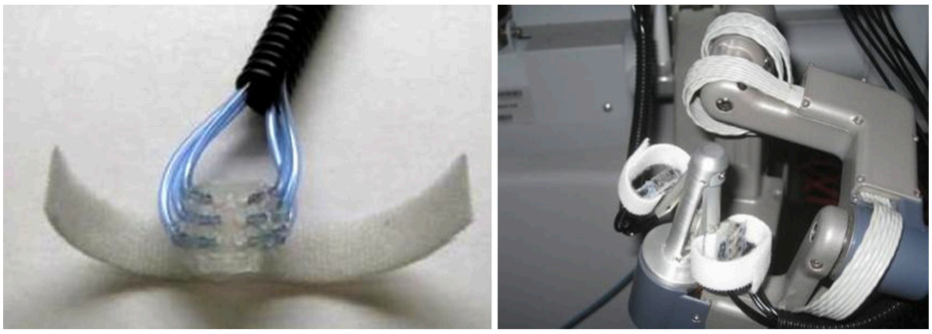
combined (Tholey et al., 2005). When the performance was evaluated between surgeons and non-surgeons only, as illustrated in figure 10, a significance was found which indicates that providing both visual and force feedback simultaneously is better than providing either feedback type alone (Tholey et al., 2005).

A different application of force feedback lays in the field of cooperatively-controlled robotic surgery. This is a non-teleoperated system, whereby the surgeon is placed in the operation room besides the patient and is manually guiding the surgical instrument fixed to the robot (Beretta et al., 2016). These robotic systems are used for the precise movements of a surgical instrument in the fields of orthopedic surgery, retinal surgery, and neurosurgery (Beretta et al., 2016). By applying force feedback, the motion of the surgical instrument is limited, based on the previously defined virtual geometrical constraints, allowing for a more precise and reliable placement of a prosthesis in orthopedic surgery (Beretta et al., 2016). Hand tremor filtering for example combined with force feedback is used in vitreoretinal surgery, allowing the micro-scale positional accuracy of instrument positioning (Beretta et al., 2016). These robotic systems also make use of the so-called scaled force reflection strategies.

These strategies limit the force used on a robot tool, so that the user cannot apply excessive force to the instrument, and the forces applied, are then scaled down into smaller movements. This allows the application of forces that are below the human sensory perception (Beretta et al., 2016). Force feedback can also be found in other areas, during needle insertions in key-hole neurosurgery with a robotic system for examples, force feedback can convey information about changing tissue properties of subsurface structures at different depths (Beretta et al., 2016).

Cutaneous Feedback in Robotic Minimally Invasive Surgery

Using cutaneous feedback to provide haptic information for the surgeon is a research field that gained much attention in recent years, because it provides the benefit of not affecting the stability of the teleoperation system, and the ability to convey rich information (Pacchierotti et al., 2016). Wottawa et al. (2016) conducted a study where they utilised a tactile feedback system, designed and integrated with the da Vinci system to provide cutaneous feedback to the surgeon's fingertip (Wottawa et al., 2016). By integrating a waterproof force sensor at the tip of the instrument, forces were measured and then proportionally converted into tactile feedback to the surgeon's fingertips, using a pneumatic actuator (Wottawa et al., 2016). The user feels tactile feedback as pressure applied by hemispherical silicone balloons, depicted in figure 11, which target the slow adapting mechanoreceptors (Wottawa et al., 2016). The goal of this feedback system was to convey the grasping forces by applying varying degrees of pressure to the fingertip, thereby providing a greater control over the gripping force (Wottawa et al., 2016).



(a) (b)

Figure 11. (a) Pneumatic actuator. (b) Pneumatic actuators mounted onto the da Vinci controls. From "Evaluating tactile feedback in robotic surgery for potential clinical application using an animal model." by Wottawa et al., 2016, Surgical endoscopy, 30(8), 3198–3209.

The application of too much grasping force to tissue is the reason for tissue damage. The addition of tactile feedback in RMIS systems could potential reduce tissue damage (Wottawa et al., 2016). The participants were asked to perform the task of passing the bowel of pork from one grasper to the next, thereby measuring the amount of damage applied by the gripper with or without haptic feedback (Wottawa et al., 2016). All participants completed the task three times, the first time without haptic feedback, the second time with haptic feedback, and the third time again without feedback (Wottawa et al., 2016). The differences in performance were then compared with the results of Wottawa et al. (2016) showing, that less force was applied when using the RMIS system with tactile feedback, correlating with less tissue damage to the bowel. Significant results were only found for the novice participants, while the five trained expert participants did not show significant differences in the measurement of grasping force (Wottawa et al., 2016). Interestingly there was a learning effect of the participants. During the third repetition of the task, the analysis showed that the grasping forces and the amount of damage remained low after the second task execution with haptic feedback. By using the haptic feedback system, the participants learned about the amount of forces needed for the handling of bowel tissue (Wottawa et al., 2016). These results are backed up by a previous study done by King et al. (2009) in which they used a pneumatic balloon system integrated in the da Vinci controls, to convey tactile information about the amount of gripping force the participant was executing. Therein, the haptic feedback reduced the amount of gripping force by more than a factor of two.

A different study by Pacchierotti et al. (2016) explored the usefulness of cutaneous feedback in RMIS, focusing on the task of palpation. Palpation in surgery is the process of feeling the patient's tissue to locate tumors by using a finger (Pacchierotti et al., 2016). With current RMIS system the task of palpation is not possible, as no haptic feedback about tissue interaction are provided. Similarly to Wottawa et al. (2016), Pacchierotti et al. (2016) too developed a cutaneous feedback system for the da Vinci surgical robot, delivering pressure as well as vibrotactile feedback to the fingertip of the console operator. The study setup can be seen in figure 12. The sensor used by Pacchierotti et al. (2016) is called BioTac and it is a tactile sensor, measuring contact deformation in addition to vibrational information. The BioTac sensor is designed to mimic the physical properties along with replicating the sensory capabilities of the human finger (Pacchierotti et al., 2016). However, this sensor has the drawback of being bulky and nonsterilizable, and is therefore at the present unusable for

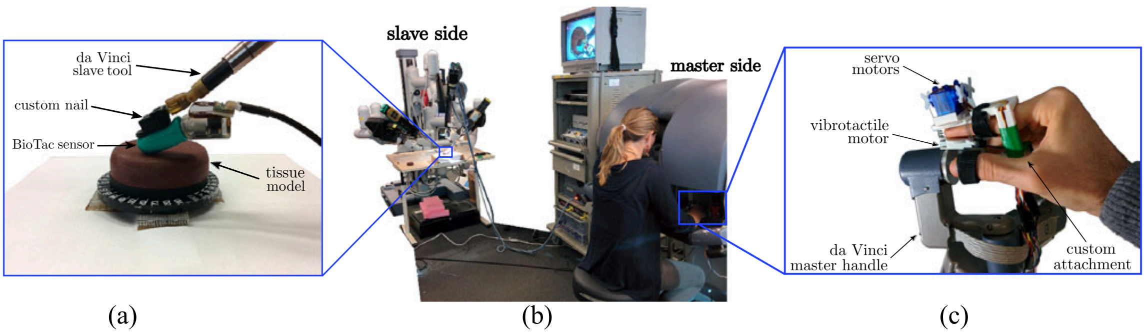


Figure 12. (a) BioTac sensor joined with a surgical instrument. (b) Surgeon control and patient cart. (c) Finger mounted platform-based feedback system combined with the da Vinci controls. From "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery." by Pacchierotti et al., 2016, IEEE Transactions on Biomedical Engineering, 63(2), 278–287.

medical applications. Despite these momentary shortcomings, Pacchierotti et al. (2016) stated that the sensor could be redesigned and miniaturized for future use in robotic minimally invasive surgery. The cutaneous feedback system is integrated into the da Vinci controls and has the feature of a servo motor controlled mobile platform and a vibrotactile motor (Pacchierotti et al., 2016). The servo motor is placed on top of the fingertip, it controls the mobile platform placed under the fingertip through a cable and spring system (Pacchierotti et al., 2016). Through this cable and spring system, the mobile platform is pulled up with varying amounts of force by the servo motor, and this results in different amounts of pressure applied to the fingertip (Pacchierotti et al., 2016). With the increasing height of the mobile platform, the pressure on the fingertip increases proportionally (Pacchierotti et al., 2016). The mobile platform can be oriented in a three-dimensional space and apply planar deformations to the fingertip. Thereby the pressure applied to the sensor on its left side, translates into pressure applied to the left side of the fingertip (Pacchierotti et al., 2016). Figure 13 shows the platform-based feedback system mounted onto a finger. For this experiment, a simulated heart tissue with an embedded plastic stick, simulating the presence of a calcified artery is used (Pacchierotti et al., 2016). The eighteen participants then had to identify the orientation of the plastic stick by examining the tissue model (Pacchierotti et al., 2016). Each participant completed the task under three conditions and with four repetitions, totaling in twelve trials of a palpation task (Pacchierotti et al., 2016). The

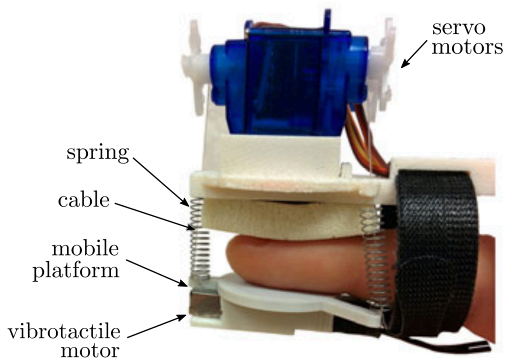


Figure 13. Platform-based feedback system with a finger inserted. From "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery." by Pacchierotti et al., 2016, IEEE Transactions on Biomedical Engineering, 63(2), 278–287.

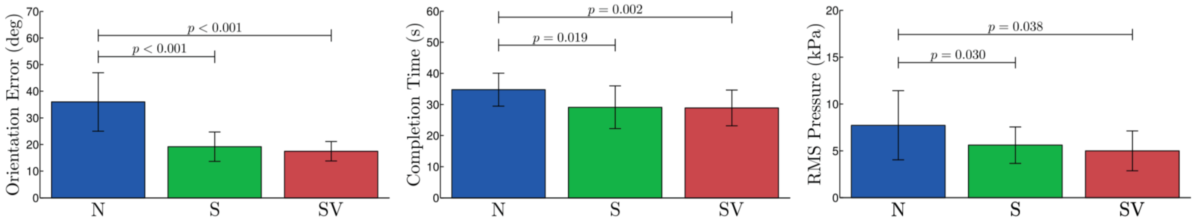


Figure 14. Experimental Results about orientation error, completion time, and pressure, with the three conditions no feedback (N), cutaneous feedback without vibrotactile feedback (S), and cutaneous feedback with vibrotactile feedback. Lower values indicate better performance of the task. From "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery." by Pacchierotti et al., 2016, IEEE Transactions on Biomedical Engineering, 63(2), 278–287.

three conditions were: doing the task with no haptic feedback, doing it with fingertip deformation provided by the servo motors, and lastly to complete the task with fingertip deformation in addition to vibrotactile feedback to the fingertip (Pacchierotti et al., 2016). The study also evaluated orientation error, that is to which degree the estimate of participants was off from the original orientation of the stick. The completion time, as well as the amount of pressure exerted were measured (Pacchierotti et al., 2016). Significant differences were found with the orientation error, the completion time, and the amount of exerted pressure (Pacchierotti et al., 2016). The results can be seen in figure 14. The number of orientation errors was significantly lower when the task was done with haptic feedback, compared to when no haptic feedback was used (Pacchierotti et al., 2016). Other results were in favor of haptic feedback too, as the completion time and the amount of pressure exerted were both significantly lower than without haptic feedback (Pacchierotti et al., 2016). All in all, cutaneous feedback improved the palpation performance in all measured metrics significantly, which all variable measurements showed. The participants reported, that they preferred conditions providing cutaneous feedback opposed to no feedback (Pacchierotti et al., 2016). The vibrotactile feedback had no significant influence on the performance of the participants (Pacchierotti et al., 2016).

Sensory Substitution and Sensory Subtraction

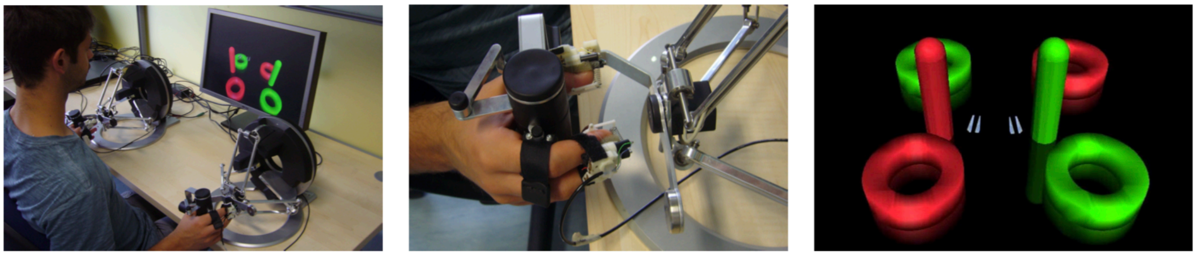
Haptic feedback in the form of kinestethic force feedback can affect the communication latency between the operator and the robot significantly, also destabilizing factors like hard contacts and a relaxed grasp can have a reducing effect on the effectiveness and safety of the system (Pacchierotti, 2015). One cause of concern about safety and stability is the way kinestethic force feedback is delivered to the user. The general approach is to provide the force feedback directly to the end-effector of the master device, this is the controller, who operates the robot (Pacchierotti, 2015). This means that the force feedback influences the controller of the surgical instruments, so that the operator has to counteract the action triggered by the force feedback to avoid instability (Pacchierotti, 2015). A way to deal with this problem is not to use any actuator on the master console, but to deliver the information about the amount of forces exerted through different sensory modalities (Pacchierotti, 2015). This approach is called sensory substitution and is a process of substituting force feedback with other forms of feedback, such as auditory and visual feedback (Pacchierotti, 2015). Whereas this approach of sensory substitution showed promising results and had the benefit of guaranteeing the stability of the system, sensory substitution still showed inferior performance, when compared directly to kinesthetic force feedback (Pacchierotti, 2015). A different approach to the deliverance of haptic information is the haptic subtraction, thereby cutaneous feedback is used instead of force feedback to deliver haptic sensations (Pacchierotti, 2015). The idea behind this approach is to subtract the kinesthetic part from haptic feedback, leaving only cutaneous feedback and thus making the system stable (Pacchierotti, 2015).

Kinesthetic Force Feedback vs. Cutaneous Feedback

In a study done by Pacchierotti (2015), sensory substitution, sensory subtraction, and force feedback were tested in a needle insertion task, to compare the usability of different feedback techniques with differentiating simulated tissue properties. Three methods of information delivery were used to convey active constraints, this signifies that software is used to regulate the motion of surgical instruments, and that the feedback, be it haptic, visual or auditory then conveys this restraint respectively (Pacchierotti, 2015). In the simulated needle insertion task, a forbidden region is generated, and subjects were asked to insert the needle until they could feel or see the feedback indicating this region (Pacchierotti, 2015). The amount of contact force was conveyed either by force feedback on the controls, or by visual feedback as a sensory substitution, displaying a horizontal bar which depicted the amount of contact force exerted. Lastly cutaneous feedback as haptic subtraction was provided by wearable devices similar to the one used by Pacchierotti et al. (2016), providing haptic feedback to the fingertip (Pacchierotti, 2015). Three experiments where conducted by Pacchierotti (2015), the first being the before mentioned needle insertion task with twenty-four repetitions. In the second experiment, two additional repetitions of the task were added, during which the region was suddenly moved backwards, leaving the user with no feedback, while at the same time the signal for the needle extraction was issued (Pacchierotti, 2015). The third experiment was a variation of the first one, but with the addition of a time delay (Pacchierotti, 2015). The results of the first experiment show that force feedback performed significantly better than visual and cutaneous feedback in the measure of average and maximum penetration beyond the forbidden region, while cutaneous feedback performed significantly better than visual feedback, and thus positioned itself between force and visual feedback (Pacchierotti, 2015).

For the second experiment, the difference between the maximum penetration after the sudden region movement, and the average penetration before the region movement was measured, to discern if there was an unwanted movement of the needle (Pacchierotti, 2015). The results display a significant difference in the amount of penetration for the force feedback condition, compared to visual and cutaneous feedback, with the force feedback condition performing worse (Pacchierotti, 2015). The results seems to suggest, that the use of force feedback could lead to a greater amount of unwanted motions of the needle, caused by the way by which force feedback is delivered to the participant, since it is executing force on the controls of the needle, the participant has to counteract this force (Pacchierotti, 2015). When the force feedback disappears, because the region is moved, participants are exerting too much force and move the needle forward unwillingly (Pacchierotti, 2015). The result of the third experiment show that the factor of time delay mainly impacted the condition with force feedback. When this instability was introduced, a significantly higher penetration beyond the constrained region and a significantly longer penetration time for the condition of force feedback, compared to visual or cutaneous feedback, occurred (Pacchierotti, 2015).

Meli, Pacchierotti, and Prattichizzo (2016) also compared force feedback with cutaneous feedback, but in contrast to the study done by Pacchierotti (2015), Meli et al. (2016) used auditory feedback instead of visual feedback as a sensory substitution. Auditory feedback was provided as a beep tone, and the changing repetition frequency of the beep tone indicated the amount of force being exerted (Meli et al., 2016). Each plier used by the surgeons left or right hand was connected to the respective side of the headphones he was wearing. This means, that sound is being played on the left side when the pliers controlled by



(a) (b) (c)

Figure 15. a) Experimental setup with a closer look (b) at a hand in an Omega 7 haptic interfaces with fingermounted cutaneous feedback device attached and (c) the peg board experiment. From " Sensory subtraction via cutaneous feedback in robot-assisted surgery." by Meli et al., 2016, Springer.

the left hand are touching the ring, and vice versa on the right side (Meli et al., 2016). To evaluate the performance of different feedback modalities, they conducted a peg board experiment in a virtual environment (Meli et al., 2016). Thereby each participant is to grab a colored ring with surgical pliers and put the ring around the same colored peg (Meli et al., 2016). The participants controlled the virtual surgical pliers with two Omega 7 haptic interfaces, one for each hand and responsible for force feedback, in addition, two fingers on each hand were equipped with a cutaneous feedback device (Meli et al., 2016). In the virtual environment of this experiment, the seven participants could move and rotate the surgical pliers as well as control the amount of grip force (Meli et al., 2016). The experimental setup is illustrated in figure 15. To evaluate the performance of the seven subjects, completion time, contact forces and ring's displacement were measured (Meli et al., 2016). Amongst all conditions, significant differences were found, with force feedback performing the best, followed by cutaneous feedback, and auditory feedback performing the worst across all three conditions (Meli et al., 2016). Similarly to the study done by Pacchierotti (2015), in a second round of the experiment a communication delay between the master and slave side was introduced by Meli et al. (2016). The conditions, the task, and the subjects staying the same but with a communication delay of 20 ms (Meli et al., 2016). In this experiment, in regards to completion time and the ring's displacement, force feedback performed significantly worse than both cutaneous and auditory feedback, while cutaneous feedback performed the best out of all three conditions (Meli et al., 2016). In regard to contact force, force feedback performed the same as cutaneous feedback, but compared to the first experiment without communication delay, the contact forces with the force feedback condition degraded significantly (Meli et al., 2016). Similar to the results of Pacchierotti (2015), as soon as a communication delay was introduced, force feedback degraded in performance and became unstable (Meli et al., 2016).

Discussion

Visual and haptic information are essential for the surgeon to perform his surgery. Nevertheless haptic feedback is still missing from most RMIS systems currently on the market. The comparison between traditional laparoscopic surgery and RMIS, puts the absence of haptic feedback into a greater perspective. Current RMIS systems provide many benefits for the patient, like a cosmetic postoperative appearance, reduced postoperative pain, lower rates of wound infection, and shorter hospital length. However, RMIS offers these advantages at a considerably higher cost than laparoscopic surgery. The advantages of the RMIS system for the patient do not yet justify its higher costs. Nevertheless, more and more units of the da Vinci system are being sold, with Switzerland having 32 units installed in hospitals across the country. RMIS currently outperforms laparoscopic surgery in ways of interaction and experience for the surgeon, as it offers a 3D video feed of the operation site. Other benefits are optimal hand-eye alignment, motion scaling, and tremor filtering. To improve RMIS and to justify its cost, the inclusion of haptic feedback is one of the most important new features to be developed for RMIS Systems.

The biggest competitor of the da Vinci system right now is probably the Senhance system. This new system mainly improves two shortcomings of the da Vinci. The Senhance system dramatically reduces the cost per use, from 1500 USD of the da Vinci, down to 200-500 USD. Senhance also tackles the other shortcoming of the da Vinci by adding haptic feedback in the form of kinesthetic force feedback. However, detailed information about the implementation and benefits of haptic feedback are not provided. The additional safety concerns connected with kinaesthetic force feedback as previously examined in the section:

kinesthetic force feedback vs. cutaneous feedback, are neither being examined in current research nor are they being addressed by the company. Due to a limited amount of research, comparing the performance of the Senhance with laparoscopic surgery, it is not yet possible to tell if this new system can overcome laparoscopic surgery. The biggest problem competitors of the da Vinci face, is the adoption rate and the amount of RMIS surgeons who were trained for the da Vinci system. If a hospital acquires a new RMIS system replacing a da Vinci unit, the surgeons need to be trained for this new system and this leads to an additional cost factor. As long as a newly installed system does not bring on efficiency and improvement at an affordable cost rate, it will be difficult for new systems to compete with the da Vinci.

Haptic feedback as an addition to RMIS has great potential, as the current research described beforehand shows. Keeping in mind the limited scope and the limited array of tasks explored in this thesis, the results of the studies evaluated, are in favor of including haptic feedback. Kinesthetic force feedback was a useful addition to RMIS, as it improved the accuracy of a dissection task compared to laparoscopic surgery. In comparison to the performance of a tissue recognition task, force feedback improved the correct recognition of different kinds of tissue significantly, the results are also in line with the multimodal feedback theory, as the combination of visual and haptic feedback led to the best performance. The inclusion of cutaneous feedback in RIMS was also valuable in several tasks because it led to a reduction in tissue damage due to the application of excessive grasping force. The additional haptic information through cutaneous feedback about grasping forces allowed for a more precise control over the instruments. The task of palpation also benefited from cutaneous feedback. During the process of examining a patient’s tissue and to locate tumors using either a finger or a surgical instrument, cutaneous feedback improved the completion time, reduced the number of errors, and lowered the amount of pressure exerted.

Both force and cutaneous feedback are a valuable addition to RMIS, but there a few drawbacks of force feedback to be looked at more closely. The way kinestetic force feedback is delivered to the operator can cause stability issues, which is why the methods of sensory substitution and sensory subtraction were introduced. Sensory substitution has the benefit of guaranteeing the systems stability, but it lacks in performance. Sensory subtraction in the form of cutaneous feedback, seems to be a more effective way of ensuring stability in addition to the benefits of haptic feedback as discussed previously. The studies by Pacchierotti (2015) and Meli et al. (2016) compared force feedback, cutaneous feedback, and visual or audio feedback. In the needle insertion task and the pegboard experiment, force feedback performed best, whilst cutaneous feedback performed significantly better than the sensory substitution method, but also significantly worse than force feedback. The results changed as soon as a communication delay between the controls and the robot slave was introduced, the performance of force feedback deteriorated and stability issues emerged, cutaneous feedback on the contrary was not affected by the communication delay, performing significantly better (Pacchierotti, 2015; Meli et al., 2016).

Implications for future research are that haptic feedback seems to be a valuable addition to RMIS systems. The method of sensory subtraction is a promising new approach to deliver haptic information, while keeping the system stable. Looking at all the different kinds of sensory feedback modalities, cutaneous feedback in the form of pressure to the fingertip seems to be the best option for delivering helpful haptic feedback for the operating surgeon. It can be used in a wide array of tasks while being stable and it seems to be able to replace force feedback to some degree.

Two limitations of the studies evaluated beforehand stand out. The First limitation is the small sample size of all studies, indicated by the twenty-five participants only, as the biggest subject number employed. The other limitation is the not explained inclusion of non-surgeons as participants, leading to an even smaller sample size, when actual surgeons only were taken into consideration. To solely include surgeons experienced with RMIS, would have made more sense, since they are the target audience, for which haptic feedback in RMIS systems is being developed. By including haptic feedback, the surgeon is provided with more information during surgery, this improves his performance and ultimately leads to better patient care. An important goal for future research is, to carry out studies with more trained RMIS surgeons as subjects. Missing in all of the beforehand mentioned studies, is the connection between tele-presence and the surgeons performance. The inclusion of haptic feedback could effectively improve tele-presence even more. As Pacchierotti et al. (2016) have stated, tele-presence is achieved by delivering both visual and haptic information to the operator. Since haptic feedback is mostly missing from current RMIS systems, not counting the Senhance system, the inclusion of haptic feedback should therefore improve tele-presence. It could be interesting to include a measure of tele-presence in future studies, to get a better idea of its importance in RMIS. The user experience of the surgeon could also be an additional variable worth exploring. The study done by Pacchierotti et al. (2016), explored this idea to some degree, as it asked the participants, which feedback modality they preferred. Thus future research could direct its focus more on measuring the surgeon's personal user experience, to improve RMIS. One possibility would be to examine if a better user experience of a surgeon correlates with a better performance and therefore a better outcome for the patient. The user experience in the context of RMIS is an aspect, that has not been explored in depth yet, even though it is possible, that studies not included in this thesis exit. Furthermore it is possible, that the companies behind the da Vinci and the Senhance, have taken user experience into consideration. Due to the limited scope of this thesis however, a clear answer to that question cannot be confidently given at present.

The comparison of RMIS with laparoscopic surgery highlights the advantages and drawbacks of RMIS. The results compiled from literature indicated, that haptic feedback can improve specific tasks during a surgery. Cutaneous feedback provided by a finger mounted feedback system has the advantage of easily being integrated into current RMIS systems and offers probably the best compromise between performance improvements and system stability. As a next step, cutaneous feedback could be evaluated in other surgical tasks, with the goal of getting cutaneous feedback ready for medical use and to further explore the relation between the surgeons user experience and tele-presence with the surgeons performance.

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