"Can augmented feedback on haptic information enhance the surgeon's control of laparoscopic grasp force?"

Complications arising during laparoscopic surgery may occur by improper grasp control. This thesis focuses on the improvement of laparoscopic grasp control and the related learning aspects, by means of augmented feedback received on haptic information.

The results show that surgeons need haptic feedback, which is reduced when traditional Minimally Invasive Surgery (MIS) instruments are used and is completely absent in Robotic, assisted Minimally Invasive Surgery (RMIS). Experiments show that having augmented tactile feedback on grasp-forces is a good way to enhance laparoscopic grasp control for surgeons at all levels of experience. With the help of augmented feedback they learn to control their grasp force more quickly and the overall grasp forces are reduced. When the augmented tactile feedback is removed they continue to perform at the same level, which leads us to conclude that they learned to deal with the intrinsic feedback available. Even learning to use augmented feedback with two hands simultaneously is possible without causing confusion.

It can be concluded that augmented haptic feedback on grasp forces can improve laparoscopic grasp control even when it is only provided during a training period. Apart from this conclusion, the research resulted in a working prototype of a laparoscopic grasper that provides augmented tactile feedback on grasp forces, together with guidelines for training with augmented haptic feedback providing instruments.

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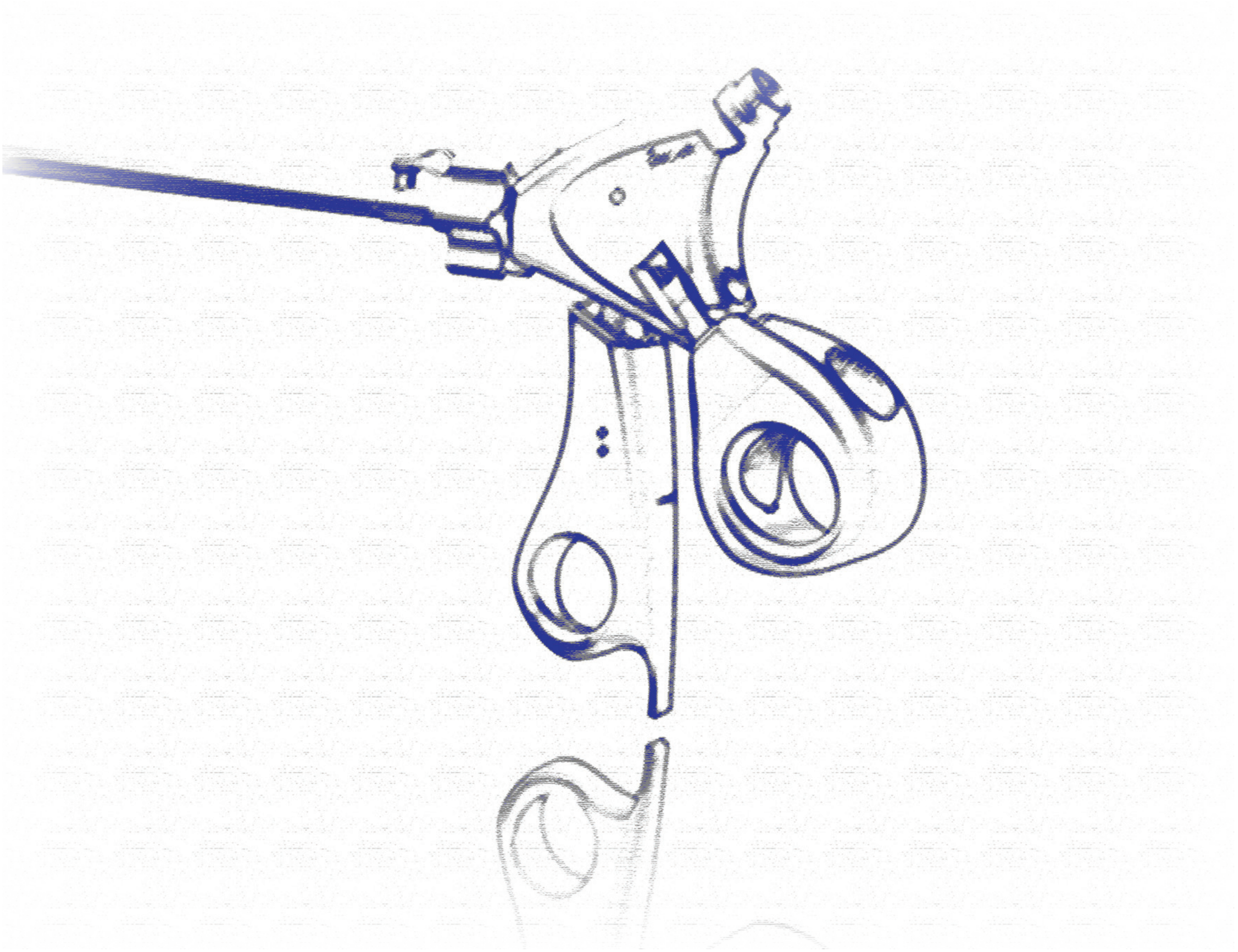
A Sense of Touch in Laparoscopy

Eleonora P. Westebring - van der Putten

A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control



Eleonora P. Westebring - van der Putten

Uitnodiging

Voor het bijwonen van de openbare verdediging van mijn proefschrift

A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control

De verdediging zal plaatsvinden op **maandag 24 januari** om **12:30 uur** in de senaatszaal van de Aula van de TU Delft, Mekelweg 5, te Delft

Voorafgaande aan de verdediging zal ik om **12:00 uur** een korte toelichting geven op de inhoud van mijn proefschrift.

Na afloop zal er een receptie zijn.

Eleonora Westebring-van der Putten
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0624421523

Propositions

Accompanying the thesis

A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control

By
Eleonora P. Westebring-van der Putten, Delft January 24th 2010

1. Surgeons will experience less irreversible events in training if they have learned to control laparoscopic grasp forces with the aid of augmented tactile feedback. *(This thesis*)
2. Training of laparoscopic grasp control with the aid of augmented tactile feedback should be obligatory in a surgeon’s training. *(This thesis)*
3. The barehanded grasp control of my 4-year-old nephew is similar to the laparoscopic grasp control of an expert surgeon.
4. A decision should never be made because: “the computer says ….no”.
5. The human body is still more ingenious than technology.
6. The controlled motion of trained animals is beyond our control without the willingness of the animal.
7. I trust my child with my best china after the age of 8. Hence, I cannot trust my surgeon to grasp my bowel after only 30 laparoscopic procedures.
8. The best experts are the ones open to change and alternative methods even when suggested by a non-expert in the field.
9. Your own horse kicks just as hard as any other horse when approached from behind but it feels much worse.

These propositions are considered opposable and defendable and as such have been approved by the supervisors, Prof. dr. Ir. R.H.M. Goossens, Prof. dr. J. Dankelman and Prof. dr. J.J. Jakimowicz.

Stellingen

Behorende bij het proefschrift

Tastzin bij laparoscopie

Verbeterde knijpkracht controle door gebruik van toegevoegde haptische feedback

door

Eleonora P. Westebring-van der Putten, Delft 24 januari 2010

1. Chirurgen zullen minder irreversibele fouten maken tijdens training als ze geleerd hebben hun laparoscopische knijpkracht te controleren met behulp van toegevoegde tactiele feedback. *(dit proefschrift)*

2. Trainen van laparoscopisch knijpkrachtcontrole met behulp van toegevoegde tactiele feedback zou verplicht moeten zijn in de training van chirurgen. *(dit proefschrift)*

3. De controle van de knijpkracht van mijn vier jarig neefje is vergelijkbaar met de laparoscopische knijpkrachtcontrole van een chirurgisch expert.

4. Een beslissing zou nooit gemaakt mogen worden omdat: “de computer zegt ...nee”.

5. Het menselijk lichaam is nog steeds ingenieuzer dan technologie.

6. De gecontroleerde beweging van getrainde dieren valt buiten onze controle zonder de bereidwilligheid van het dier zelf.

7. Ik vertrouw mijn kind pas mijn mooiste porselein toe als het ouder is dan 8. Dit wetende kan ik mijn chirurg, die slechts 30 laparoscopische ingrepen heeft uitgevoerd, niet vertrouwen mijn darmen vast te pakken.

8. De beste experts zijn diegenen die open staan voor veranderingen en alternatieve methodes ook al worden ze gesuggereerd door iemand van buiten het veld.

9. Je eigen paard trapt net zo hard als ieder ander paard als je het van achteren benadert maar het voelt veel harder.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren, Prof. dr. Ir. R.H.M. Goossens, Prof. dr. J. Dankelman en Prof. dr. J.J. Jakimowicz.

A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control

Eleonora P. Westebring – van der Putten

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A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control

Proefschrift

Ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 24 januari om 12:30 uur.

door **Eleonora Patricia Westebring – van der Putten**

Ingenieur Industrieel Ontwerpen
Master of Science in Bewegingswetenschappen
Geboren te Leiderdorp

Dit proefschrift is goedgekeurd door de promotoren:

Prof. dr. ir. R.H.M. Goossens
Prof. dr. J. Dankelman
Prof. dr. J.J. Jakimowicz

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
Prof. dr. ir. R.H.M. Goossens, Technische Universiteit Delft, Promotor
Prof. dr. J. Dankelman, Technische Universiteit Delft, Promotor
Prof. dr. J.J. Jakimowicz, Technische Universiteit Delft, Promotor
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Prof. A. Cuschieri, University of Dundee, Scotland, UK
Prof. ir. D.J. van Eijk, Technische Universiteit Delft, reservelid

Dr. J.J. van den Dobbelsteen heeft als begeleider in belangrijke mate aan de totstandkoming van dit proefschrift bijgedragen.

This PhD project is a collaborative project between the faculty of Industrial Design Engineering (IDE), the faculty of Mechanical, Maritime and Materials Engineering (3ME) and the Catharina Hospital Eindhoven (CH) and it has been carried out within the Medisign group. The research that forms the basis of this thesis was supported by a grant from the Scientific Fund of the CH

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Chapter 1. Introduction

Judith has just arrived in the recovery room after having had her appendix removed via key-hole surgery. Tomorrow, she will be allowed to go home with only three little scars on her stomach. Within a year they will have disappeared almost completely so that she can wear a bikini when on the beach without anyone noticing that she has had surgery.

The next day, though, Judith feels miserable and does not want to go home at all. Her tummy hurts a lot. Because the pain becomes unbearable the medical team is called and they decide to operate to see what is causing the pain. During surgery the surgeons discover a perforation of the bowel, a result of the bowel having been grasped too firmly during the prior key-hole surgery. The surgeon had not noticed that his grasp force had been excessive.

Judith was lucky that they discovered the bowel perforation when she was still in the hospital, otherwise it could have been fatal. Wearing a bikini next summer is probably not something she will now enjoy.

In this Chapter the background, problem statement, focus and research questions of the PhD project will be described. In addition, an outline of the thesis as a whole will be given.

1.1. Background

Minimally Invasive Surgery (MIS) procedures have gained general acceptance over the last two decades. MIS is performed through small incisions in the body (it is also sometimes referred to as Minimal Access Surgery (MAS) (Cuschieri 1992). An endoscope (i.e. an optical telescope coupled to a small camera) is used to view the internal operative field and long thin instruments are used to manipulate the tissue. The advantages of this approach are generally recognized and when compared to open surgery they include: less trauma, a shorter hospital stay and reduced recovery time for the patients (Cuschieri 1995, Moreno-Egea *et al.* 2005, Dedemadi *et al.* 2006, Fullum *et al.* 2010).

MIS comprises many types of procedures, one of which is laparoscopy. Laparoscopy is MIS performed in the abdomen. To create a larger workspace CO_2 gas is insufflated at a certain pressure into the abdomen of the patient. The first laparoscopic cholecystectomy (gall bladder removal) was performed by Prof Dr Med Erich Muhe on September 12, 1985 (Reynolds 2001). Only 15 years later approximately 30% of abdominal surgery was being done laparoscopically (Berci 1998). At present between 75 and 95% of all cholecystectomies are performed laparoscopically (Tang and Cuschieri 2006, Zehetner *et al.* 2010).

Due to the benefits for the patient and the reduced costs incurred for hospital stays when compared to the costs attached to open surgery it is already noticeable that MIS procedures are continuing to spread. However, this technique brings difficulties for the surgeon (Stassen *et al.* 2001, van Veelen 2003, Siani *et al.* 2009) that can lead to a higher number of errors and complications during surgery, especially during the first 35 to 100 procedures a surgeon performs (Dankelman *et al.* 2003, Schauer *et al.* 2003, Bege *et al.* 2009, Oomen *et al.* 2010). These problems can be generally attributed either to ‘perception problems’ due to the indirect visibility of the operation field and reduced haptics, or ‘performance problems’ arising from these perception problems, the reduced degrees of freedom of the instruments, distorted hand-eye coordination, and bad ergonomics in the operating theatre.

1.2. Problem definition

This PhD research will focus on the problems in the domain of haptic perception that occur during laparoscopic tissue manipulation. The perception problems can lead to jeopardised performance and complications during surgery. The safety of the patient is then at risk because of these problems. For example, laparoscopic-grasping instruments often damage tissue (Marucci *et al.* 2000a, Marucci *et al.* 2000b, van der Voort *et al.* 2004).

The perception problems are: reduced depth perception leading to e.g. disturbed hand-eye coordination, and reduced haptics[1]. The perception problems do not only occur during surgery but also during training. Mostly, training situations, in a skills lab setting, provide even worse environments so that all the information needed to operate safely cannot be correctly perceived. On the other hand, training can help a surgeon to learn to perform well in suboptimal conditions.

Considerable research has already been done in the field of reduced hand-eye coordination. For example, in the thesis by Wentink (2003) hand-eye coordination during MIS was discussed and the illustrated theoretical insight gained provided an important basis for the development of solutions to improve hand-eye coordination during MIS. In the dissertation produced by Voorhorst (1998) depth perception and the implementation of viewpoint parallax (creating shifts by moving a camera on the head of the surgeon) in laparoscopy is discussed. Less research has been done in the field of reduced haptics.

In laparoscopy, the hands manipulate the tissue indirectly. What the surgeon can feel (haptics) when using his/her instruments is not well documented in the literature. Some research has been done on the ability to feel texture shape and the consistency of tissue by using laparoscopic graspers (Bholat *et al.* 1999, Heijnsdijk *et al.* 2004c, Picod *et al.* 2005). These studies show that haptics is reduced compared to barehanded contact, except in the case of texture discrimination. However, all these studies used artificial tissue by employing materials such as sandpaper, and plastic cubes and cones.

In the case of semi direct (gloved hand) tissue contact, as in open surgery, the surgeon can perceive the temperature, shape, structure and mechanical properties of the tissue touched. Compared to barehanded contact a glove does reduce the haptics to some extent but the surgeon can directly feel the amount of force and pressure applied to the tissue when pinching or feel whether the tissue is slipping through the fingers or not. The surgeon can adjust the applied muscle force according to this natural haptic feedback loop in such a way that the tissue is, in general, not damaged, but still held on to securely.

Other research has been performed in the field of force perception and interference factors (Sjoerdsma *et al.* 1997, Heijnsdijk *et al.* 2004b, Heijnsdijk *et al.* 2004c, Picod *et al.* 2005, van den Dobbelsteen *et al.* 2007). Perceived haptics are interfered with by indirect tissue contact, trocar friction, resistance of the abdominal wall, scaling and mirroring of tip forces, and friction in the system mechanics. These interference components of haptic sensation during MIS can be as big as the interaction forces with the organs themselves.

---

[1] Haptics: Combination of tactile (through sensory skin receptors) and kinesthetic (through muscle, tendons and joint sensory receptors) perception.

[2] Natural in this context means that the haptic information obtained from the object touched is

The difference in perception both for haptics via instruments and vision via endoscopes, could be one of the reasons why the learning curve for laparoscopy is longer than that of open surgery (Kaul *et al.* 2006). Laparoscopic training is currently provided in different ways. For many procedures it is advised to train in all these settings. One method of training is by means of box training where real laparoscopic instruments are used to operate on a simulated belly (a box covered with elastic cloth to simulate the skin); also alternatively called a Pelvi-trainer. Another method/tool for training is virtual reality (VR) training where everything except the instrument-handles is located within a simulator. An alternative training method is the box-trainer with augmented reality where a computer tracks the instruments and additional feedback is given on a screen. Training is also occasionally done on animals (mostly pigs), and (not often practiced) on human cadavers, and there is the training situation where novice surgeons are allowed to participate in clinical operations, where they perform and assist certain procedures under the supervision of an expert surgeon. All these training methods give different forms of haptic feedback to the user.

The training in a clinical setting, on animals, and on animal models is by far the most realistic but it is very expensive and there are ethical questions surrounding it. Because there are other costs involved than those involved in mock-ups or animal tissue, an opportune way to give students training is through virtual reality training (one-time investments for multi usage). It is also believed that there is less need for an instructor to give feedback on performance than with the Box-trainer (but only when there is an adequate performance feedback module). The disadvantages of the current Virtual Reality trainers are that they show non-realistic tissue deformation and no haptic feedback or non-realistic haptic feedback. This is because not much is known about the mechanical properties of human tissue and the forces surgeons apply to it and also the technical implementation difficulties.

A promising training method is the box-trainer with augmented reality (Botden *et al.* 2007). In this way it is possible to practice on realistic tissue (artificial or animal) models with more or less realistic haptics. VR training has the advantage that the performance can be assessed automatically. Augmented feedback makes it possible to add all kinds of additional information including extra force feedback and, finally, to enhance learning compared to training in a normal box-trainer or virtual reality training setting.

1.3. Focus Area

Due to the diversity of different MIS procedures and the manipulation movements performed on a diversity of tissues, it was decided, within the scope of this thesis, to perform research on grasping. Grasping is one of the common manipulation actions seen during MIS procedures where stress injury from graspers may result in perforations, bleeding, adhesions, and lesions, thus leading to pathological scar tissue and loss of bowel motility (Kalff *et al.* 1998, Anup and Balasubramanian 2000, Marucci *et al.* 2000b, Heijnsdijk *et al.* 2002). The ideal grasping instrument holds tissue securely without damaging it (a safe grip).

The factors that contribute to a safe grip include the mechanical properties of the tissue grasped, the pressure applied to the tissue via the instruments and the jaw properties (shape, texture, material). A variety of tissues, that have different mechanical properties, are grabbed with different types of laparoscopic graspers. Some tissue, such as bowel tissue, is more delicate than other tissue. Therefore, there is a need to handle such tissue with extreme care.

When grasping tissue, pulling is often involved, for example when it is stretched for dissection or when tissue is held out of view. Consequently, to grasp tissue safely, the pinch and pull forces should lie within a certain safe area, which is different for each instrument and tissue combination. In Figure 1.3.1 this area can be seen (and it is discussed in Chapter 4). The boundaries of the safe area are the damage-line and the slip-line. The damage-line is the boundary above which a certain pinch/pull force combination will damage the tissue. The slip-line is the boundary beneath which a certain pinch/pull force combination will cause the tissue to slip. To conclude, a surgeon should remain within the safe area when pinching and pulling tissue. Augmented feedback on grasp information might be an aid to learning safe grasping.

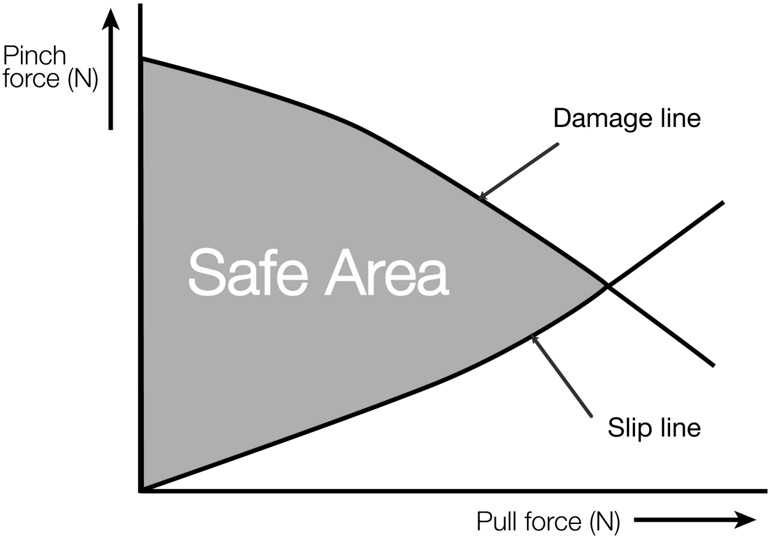

Figure 1.3.1. Slip and damage forces adapted from (de Visser *et al.* 2002).

Because of the limited research that has been done and the problems that occur in the field of haptics during MIS, this PhD research will concentrate on the improvement of haptic perception in laparoscopic grasping using augmented feedback. Consequently the outcomes of the research questions will be used as input for instrument design as well as for improving training facilities.

1.4. Goal

The aim of this thesis is to answer the following research question:

> ***"Can augmented feedback on haptic information enhance the surgeon's control of laparoscopic grasp force?"***

From the resulting insight a practical solution to improving laparoscopic bowel surgery has been found and evaluated.

1.5. Outline of the thesis

This thesis is divided into 6 Chapters (Figure 1.5.1). In each chapter the focus will be on a different part of the research topic.

Chapter 2 focuses on the fundamentals of barehanded grasp control and the current status of haptics in MIS by means of a literature study and a questionnaire. It helps to provide an overview of what has already been done in the field of haptic perception during MIS and it gives insight into the needs of the surgeons who perform MIS.

In Chapter 3 a comparison between barehanded grasping and grasping with an instrument will be made. The learning curve of a grasping task and the exerted force profiles during the grasp will be compared. The experimental research presented there provides insight into the accuracy of human perception of mechanical load through a generally used laparoscopic grasper. It gives information on the factors that influence the amount of grasp force applied to the tissue.

Chapter 4 provides insight into the sensory information that can be of help for perception during laparoscopic tissue grasping. Different feedback modalities will be described and compared. The question of how augmented tactile feedback can help grasp force to be adjusted to the tissue in order to grasp without causing damage is also addressed. The learning curve, task distraction and dependency on the augmented feedback signal will be studied.

In Chapter 5 the outcomes of the previous sections are combined in order to give a practical solution to safer tissue grasping with laparoscopic instruments. The design of a laparoscopic grasper with enhanced tactile feedback to safely grasp tissue is described and tested.

Chapter 6 provides the discussion, conclusions and further recommendations.

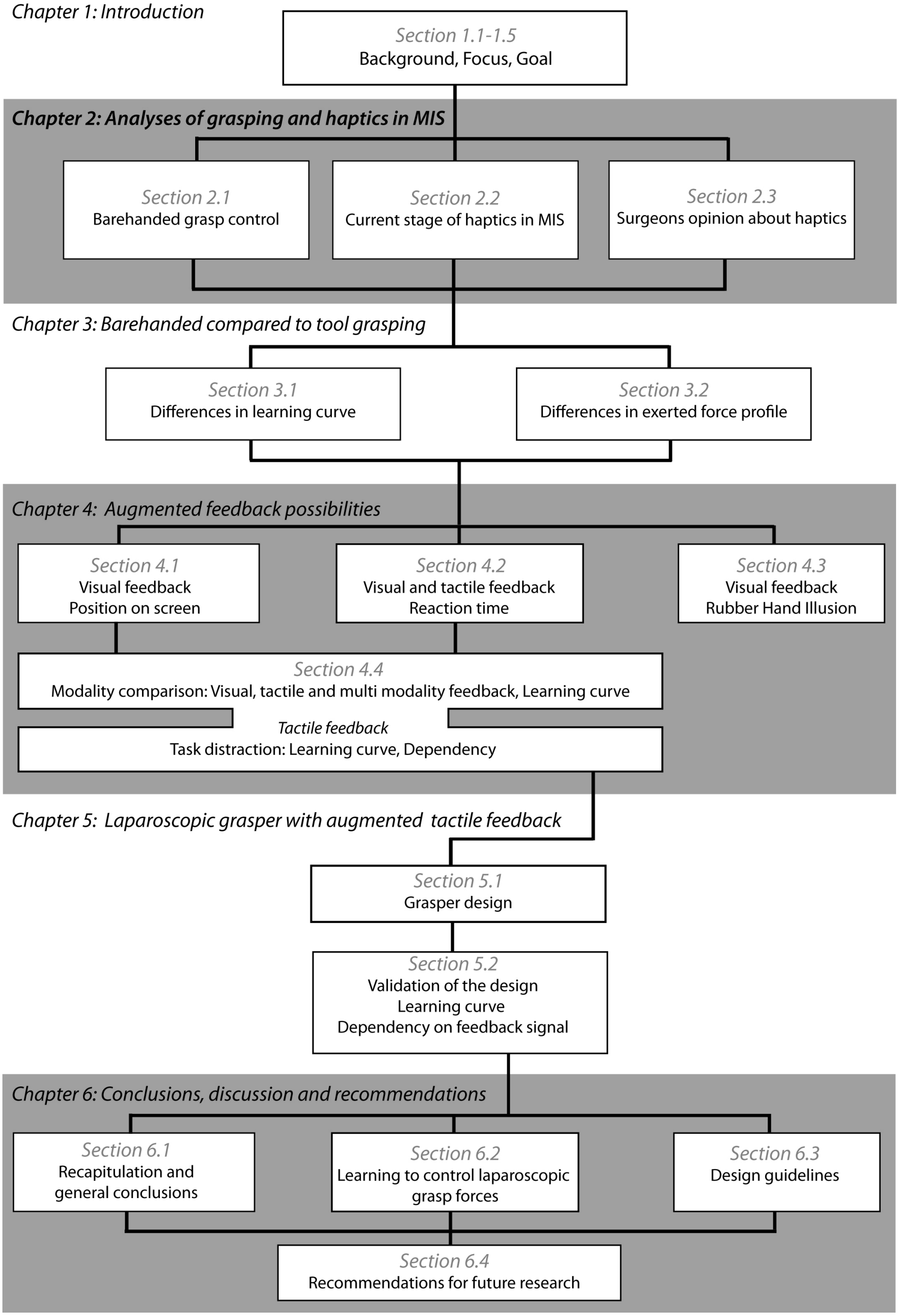

Figure 1.5.1. Schematic overview of the Chapters

Chapter 2. Analyses of grasping and haptics in MIS

My daughter who is 3 years old always spills lemonade when she tries to drink from a drinking carton. She squeezes so forcefully that the whole content rapidly shoots up through the straw and ends up on the ground. My 5 year old can handle these cartons without spilling. Apparently she has better grasp control.
Have you ever tried drinking from a plastic cup with thick winter gloves on? I cannot do it without the cup slipping out of my fingers or squeezing it tightly.

To understand natural[2] haptics and perception this chapter will describe the parts of the human motion control system that are involved in grasping. Barehanded human grasp control and the working principles of the sensory systems involved will be described.

In the second part of this chapter the current state of haptics in MIS will be described by means of a literature review. In addition, the factors, which influence the amount of grasp force applied to the tissue and precisely what sensory information is at present available when using a laparoscopic grasper is described.

The third part of this Chapter shows the importance of this topic from a surgeon's point of view and it takes the form of a questionnaire.

Section 2.2 is published as:

"Westebring-van der Putten, E. P., R. H. M. Goossens, et al. (2008). "Haptics in minimally invasive surgery - a review." Minimally Invasive Therapy and Allied Technologies 17(1): 3 - 16."

Section 2.3 is published as:

"Westebring - van der Putten, E. P., M. Berben, et al. (2010). " The opinion and experience of surgeons with laparoscopic bowel grasper haptics." J. Biomedical Science and Engineering 3: 422-429."

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[2] Natural in this context means that the haptic information obtained from the object touched is not interfered with by an instrument but is directly received by the human hand.

2.1. Barehanded Grasp Control

To efficiently move around in his/her natural environment the human uses a complex control system. The skeleton is moved by the muscles (actuators) and controlled by the Central Nervous System (CNS). The different sensory systems (visual, taste, smell, hearing, somatic, chemical and vestibular senses) provide input for the CNS about the status of the system. Nerves connect all the different parts of the control system.

In this chapter a brief description of the aspects of the human motion control system that are relevant to this thesis is given. More detailed information can be found in various relevant literature e.g. (Boff *et al.* 1986, Guyton 1986, Atkinson *et al.* 1996, Kandel 2000, Jones *et al.* 2004, Widmaier *et al.* 2004, Magill 2006, Rosenbaum 2010).

2.1.1. Central nervous system

The central nervous system (CNS) consists of the brain and the spinal cord, and it controls and organizes a facet of the activities known collectively as human behaviour. Voluntary movement, like grasping, is a complex process that begins with a cognitively derived intention to perform an action. The CNS is composed of trillions of nerve cells distributed in a network. These cells communicate with each other by means of electrical and chemical signals. The CNS receives information from the different sensors via afferent nerves (also sometimes called sensory neurons) and sends commands to the muscles to contract or relax via the efferent nerves (also known as motorneurons). Interneurons interact in the spinal cord between sensory and motorneurons. The length and type of the nerves influences the transport time delays of the signals.

2.1.2. Muscles

In the human control system, the skeletal muscles act as actuators. They generate force when activated by the CNS and act on the skeleton via the tendons that connect them. A muscle consists of thousands of parallel muscle fibres grouped into motor units innervated by a single α-motorneuron[3]. The motorneuron is situated in the spinal cord and receives its commands from the brain and the spinal cord. A command from a single α-motorneuron results in the contraction of the muscle fibres that correspond with the innervated motor unit. The generated muscle activity can be

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[3] Motorneuron: efferent nerve fibre that innervates a motor unit (groups of muscle fibres) and prompts the muscle to contract or release. Different types of motorneurons exist (for further information see literature Jones, D., Round, J. & De Haan, A., 2004. Skeletal muscle from molecules to movement, first ed.: Churchill Livingstone.

measured by monitoring the electrical activity of the muscle, electromyography (EMG).

2.1.3. Sensory systems

The sensory systems consist of: sensory receptor cells that receive stimuli from the environment, the neural pathways that transport the sensory information to the brain or the spinal cord, and those parts of the brain that deal with the processing. Sensory information processed by the CNS does not always lead to a conscious awareness of the stimuli. When the information does lead to conscious awareness it is called a sensation. When a person understands or interprets a sensation it is called a perception.

Perceptual processing involves arousal, attention, learning, memory, language, emotion and comparisons made between information presented via one type of sensation with that of another. For example, a surgeon can feel a wet environment, but his/her perception of the situation and his/her response can vary remarkably, depending on whether his visual system detects bleeding or just rinsing fluid.

A special characteristic of all sensory receptors is that they partially or completely adapt (no response anymore) to their stimuli after a period of time. The time taken to adapt varies depending on the receptors. Some sensory signals need to travel to the CNS very fast, or otherwise the information is useless. For example signals from changing joint positions during running need to be fast whereas prolonged pain does not need to be rapidly transmitted. The range of conducting velocities lies between 0.5 and 120 m/s. The sensory systems that are involved in grasping are the visual and the somatosensory systems, they are the ones that will be discussed.

2.1.3.1. Somatosensory systems

There are three different categories (modalities) of somatosensory systems. The first, discriminative touch is the perception of pressure, vibration, and texture (also called tactile perception or cutaneous sense). This system relies on different receptors in the skin (cutaneous mechanoreceptors). The second is the pain and temperature system that does not have specialized receptor organs. Instead, it uses free nerve endings located throughout skin, muscle, bone, and connective tissue to perceive changes in temperature and pain peptides. The third modality, kinesthetic sensation, relies on receptors in muscles, tendons and joints.

Proprioception is the perception of posture and position (sensory information) that deals with the position and movement of the limbs, body and head in space and its parts relative to each another (including the vestibular system, cutaneous sense and kinaesthesia). The main area of interest for this PhD thesis is haptic perception (or haptics), which is a combination of tactile perception and kinesthetic perception.

Pain and temperature are used for haptic perception but are not the focus of this research.

Tactile perception*:* When a human touches something during grasping, tactile perception results from combined inputs derived from all kinds of cutaneous mechanoreceptors in a given skin area, as all skin sensors are stimulated simultaneously. The cutaneous receptors send their information to the CNS and may exert an inhibitory influence on α-motorneurons as they detect deformation in the grasped tissue. When tactile information is absent movement accuracy will decrease, especially at the fingertips (Witney *et al.* 2004). For example; maintaining a precision grip is impossible (Ebied *et al.* 2004, Witney *et al.* 2004). Movement force adjustments are dependent on tactile feedback, such as maintaining grip force during precision grip (Johansson and Westling 1987b, Nowak *et al.* 2002, Augurelle *et al.* 2003, Monzee *et al.* 2003). The perception of grip force is affected when there is no tactile feedback (Jones and Piateski 2006).

During grasping the glabrous skin of the hand palm and fingers is touched (see Figure 2.1.1). The neural elements of the glabrous skin consist of the free-nerve endings, Ruffini organs, Pacinian corpuscles, Merkel disks and Meissner corpuscles.

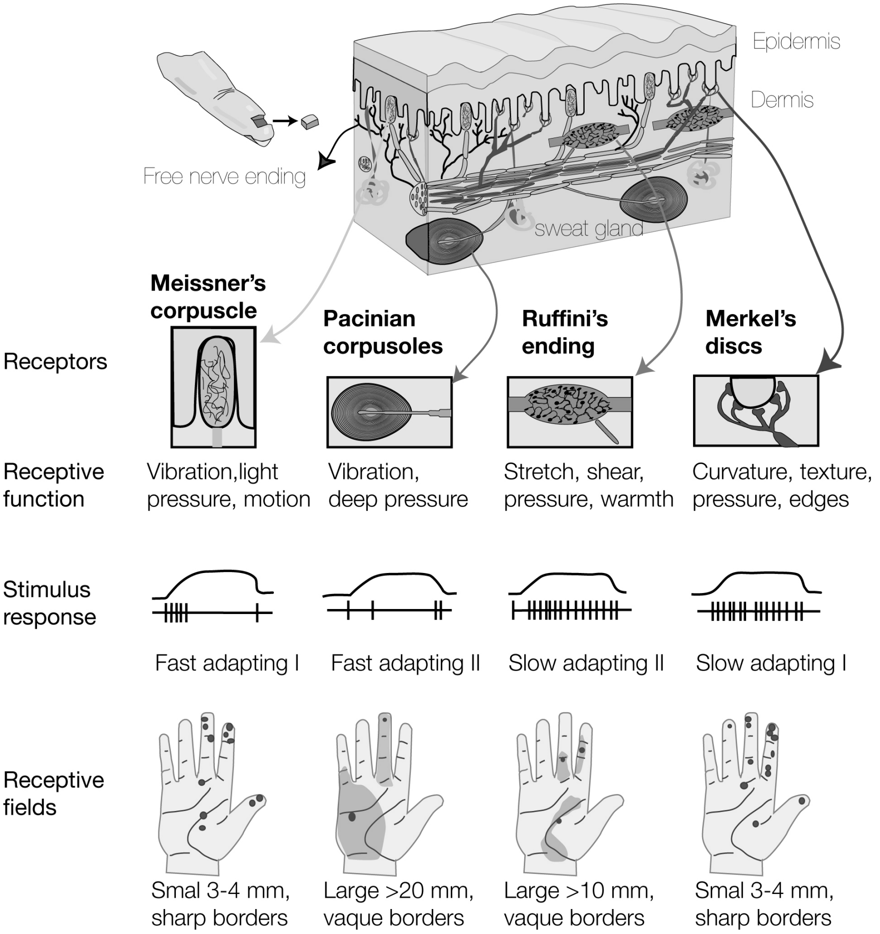

Figure 2.1.1. Glabrous skin *Top row*: type of skin receptor; *Middle row*: electro-physiological response. *Bottom row*: Size and type of receptive field (Adapted from (Kandel 2000, Purves *et al.* 2001)

Nerve fibres that are attached to different types of skin receptors either continue to discharge during a stimulus ("slow-adapting" SA) or respond only when the stimulus starts or when a stimulus ends ("fast-adapting" FA). In other words, SA nerve fibres send information about on-going stimulation; FA nerve fibres send information related to changing stimuli. To give an example, if a surgeon picks up a grasper in the palm of his hand, the Meissner's and Pacinian corpuscles will fire rapidly as it first touches down, to let the surgeon know that something has landed. When the handle stops moving, they will stop firing almost immediately. The Merkel's and Ruffini endings, however, will continue to fire to let the surgeon know that something is still there. The receptors in the deep layers are called type I and have small receptive fields and well-defined boundaries. Receptors located closer to the surface are called type II and have large receptive fields with poorly defined boundaries. The Pacinian corpuscle is a classic example of a FAII type receptor. The Ruffini organ is a SAII type receptor.

Kinesthetic perception: Kinesthetic sense is associated with receptor types in the muscles, tendons, ligaments and joints. Muscle spindles located in the depths of the muscles detect muscle length and the velocity of length changes. Golgi tendon organs located in the tendons monitor stresses and forces in the tendons and active positioning and static limb position. Ruffini endings, Golgi endings and Pacinian corpuscles located in and near the joints (Joint receptors) monitor stresses and forces in the joints. Kinaesthesia is an important source of feedback during a closed loop[4] action. It allows movement corrections when a human moves. Kinesthetic sensory perception plays a role in the coordination, timing and accuracy of movements.

When the afferent sensory neurons from kinesthetic receptors are not available (i.e. have been surgically removed) research shows (e.g. in monkeys) that subjects are able to perform a known skill but that the degree of precision is less than before (Taub *et al.* 1966). Research shows that patients who have a sensory neuropathy (no feedback from kinesthetic receptors but an efferent motor system that is intact) are able to perform skills as accurately as normal people that but without visual guidance the accuracy of the movement is less accurate (Teasdale *et al.* 1993). Without kinesthetic feedback full perception of grip force is affected (Lafargue *et al.* 2003).

2.1.3.1.1 Reflexes

Mechanoreceptors send their information to the CNS, but also straight back to α-motorneurons in the spinal cord thus forming a fast feedback loop called a spinal reflex. Reflex activity is an involuntary contraction of skeletal muscles in response to a stimulus. The reflex may travel along a short pathway via the spinal cord or it may take a longer route via the higher centres of the brain. The two can be identified on the basis of the time needed for the signal to traverse the reflex arc. Spinal reflex time is around 10-20 ms and supraspinal reflex the time is 50 ms or more (used for balance keeping) (Kandel 2000). Almost any type of cutaneous sensory stimulus on a limb can cause the flexor muscles from the limb to contract. This is called a withdrawal reflex.

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[4] A closed-loop control system is a system of control in which during the course of action, feedback is compared to a standard or reference to enable the action to be carried out as planned. Magill, R.A., 2006. Motor learning and control, concepts and aplications, 8th ed., 8 th ed. Louisiana: McGraw-Hill.

Spinal reflexes play an important role in coordinating the local groups of muscles in the hand where a variety of excitatory and inhibitory reflexes arise from the skin, joints and muscles regulating such delicate actions as grasping without crushing or grasping without slippage (Magill 2006, Rosenbaum 2010).

2.1.3.2. The visual sensory system

Humans have the tendency to use and trust the visual system more than all their other sensory systems. Especially when learning new motor skills vision is important. Research has shown that humans even have the tendency to ignore proprioception when it conflicts with visual perception. The moving room experiment by Lee and Aronson (1974) showed that people standing in a room with moving walls, but a stationary floor, did have postural responses.

Vision results from sensory receptors in the eyes that receive wavelengths of lights through structures such as the cornea, pupil, lens and retina and then transmit the information that reaches the retina to the visual cortex in the brain by way of the optic nerve. Vision plays an important role in motion control; such as in providing depth perception for interacting with the world; identifying objects, people and the environment; providing information so that one can move through the environment; coordinating movements involved in hand-eye coordination and making movement correction as we move. Further information on this field can be obtained from (Widmaier *et al.* 2004, Magill 2006).

2.1.4. Multi-sensory interaction (Vision and Haptics)

Grasping is one of many human motor actions which is controlled by the processing of haptic information feedback and visual information feedback. Since vision and haptics provide fundamentally different types of information, combining these precepts can have benefits. A surgeon looking at the tissue to be manipulated can identify a number of attributes instantaneously (form, size, colour and so on). If the surgeon uses haptic sense alone, he has to gather information progressively by exploring the tissues' physical aspects (texture, weight, solidity, temperature and so on). Combining the two sensory modalities helps the surgeon to identify tissue properties more quickly and accurately. Many studies have examined brain activity during multi-sensory tasks involving haptics and vision. Strong links have been found between vision and haptics by Gray and Tan (2002). Dynamic tactile cues and the reverse could support reoriented visual attention. This phenomenon is called a cross-modal effect.

Exactly which sensory modalities are most effective for feedback usage during the grasping of objects is largely determined by the mechanical properties of the object. For example, the stiffness of an object allows switching between modalities or even switching within the haptic modality (Mugge *et al.* 2009). The grasping of soft objects gives large deflections and position (vision and kinesthetic (muscle spindles)) feedback can be used to determine applied force in contrast to with hard objects where there are no deflections and position does not give information about applied force. In the latter case, force feedback derived from mechanoreceptors and Golgi tendon organs is more important. All modalities are noisy, nevertheless, sensory integration and weighting provides more accurate feedback than one modality alone (Mugge *et al.* 2009).

2.1.5. Learning to control grasp forces.

Babies discover grasping very early in life and start grasping as a reflex from the second to fourth week of life. If an object touches the skin of the palm of the hand, the hand closes around it and proprioception and tactile perception are a prerequisite (Twitchell 1970). Voluntary grasping emerges at the age of 4 months in the form of a palmar grasp[5] where the radial fingers lead (Lantz *et al.* 1996). By 10 months children can perform a grasp between thumb and index finger (precision grip) (Connolly 1970). Vision is not necessary for this early grasping development, although from 3–5 months of age infants can use visual feedback, next to haptic feedback, to adjust their grasping actions when they sense the effect of their actions (McCarty *et al.* 2001, Oztop *et al.* 2004).

Performance in force production and control during grasping increases throughout childhood (Forssberg *et al.* 1991, Forssberg *et al.* 1995). Practice is a contributing factor to performance improvement alongside the more effective use of visual information with advancing age in childhood (Deutsch and Newell 2002). Reduction of sensorimotor system noise[6] with advancing age in childhood is another key factor that reduces variability or enhances performance consistency (Connolly 1970) but it is neglected after the age of 6 (Kelso 1995, Deutsch and Newell 2002) where improvement in performance span arises from improvements in the ability to adapt the organization of force output from the system to action-related output.

In grasping and lifting objects motor output is adapted to the physical properties of the object and relies on robust and intermittently updatable memory representations related to the object’s weight, size and friction in relation to the skin, based on tactile sensory signals (Johansson *et al.* 1992, Johansson and Cole 1994) (Gordon *et al.* 1994). For adults, using a precision grip, parallel change in pinch force and pull force (vertical lifting force) is critical for anticipatory grip control and for the adaptation of

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[5] The Palmar grasp is characterized by a pronated hand and flexion of all fingers around the object

[6] Sensorimotor system noise: an information-carrying signal picks up noise from the channels of the sensorimotor system during transmission. This noise is assumed to be stochastic and is measured by the degree of variability surrounding the mean. Deutsch, K.M. & Newell, K.M., 2002. Children's coordination of force output in a pinch grip task. Dev Psychobiol, 41 (3), 253-64.

the force output to objects of various weight and friction in relation to the skin, based on sensorimotor integration (Johansson and Westling 1984, Johansson and Westling 1988). This synergy of coupling the pinch (grip) and pull (load) force generators providing parallel force defined by a central coordinative organization is not innate (Forssberg *et al.* 1991). Figure 2.1.2 and 2.1.3 show plots of grip and load force data in children of different ages performing object lifts. As can be seen from Figure 2.1.3, young children generate pinch and pull forces in a sequential manner. In young children the pinch (grip) force is increased prior to the pull (load) force compared to adults and may reflect a strategy which compensates for the absent parallel coordination and serves to prevent slip (Forssberg *et al.* 1991).

In adults force ratios are upgraded within 60-80 ms after tactile afferents have fired, induced by slip (Johansson and Westling 1984). These reflexes are not yet present or are weak in children and become greater as they grow older (Evans *et al.* 1990).

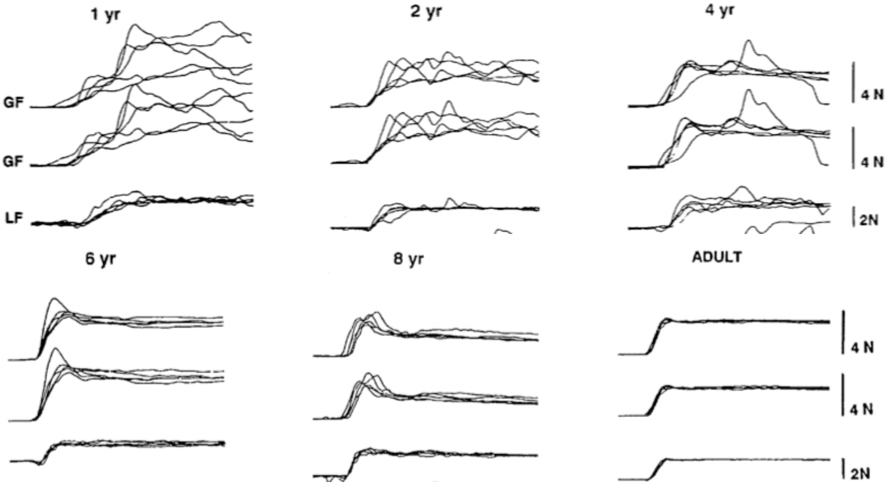


Figure 2.1.2. Superimposed records of five representative lifts performed by each of five children at different ages and by one adult subject. Grip force (GF), load force (LF), are shown as a function of time, the weight of the test object was 200 g and the grip surface was suede (printed with permission from (Forssberg *et al.* 1991)

Another difference between children and adults is that the grasp forces young children use are often excessive and have multiple peaks (up until two years of age), although they are similar to adults with impaired tactile sensibility (Johansson and Westling 1984). Forssberg *et al.* (1991) showed that sensorimotor mechanisms such as tactile control mechanisms in young children are not yet fully developed. Frictional adaptation begins to develop during the 2nd year of life. The improvement of the frictional regulation continues until late in development. During grasping, the safety margin used to prevent slippage decreases with age and rapid force adjustments attributable to unexpected frictional changes are only present in adults (Forssberg *et al.* 1995). Hence, the differences in force control between children and adults are a result of a change from feedback control to anticipatory control concerning the force output as well as the shortening of peripheral reflex latencies when growing up.

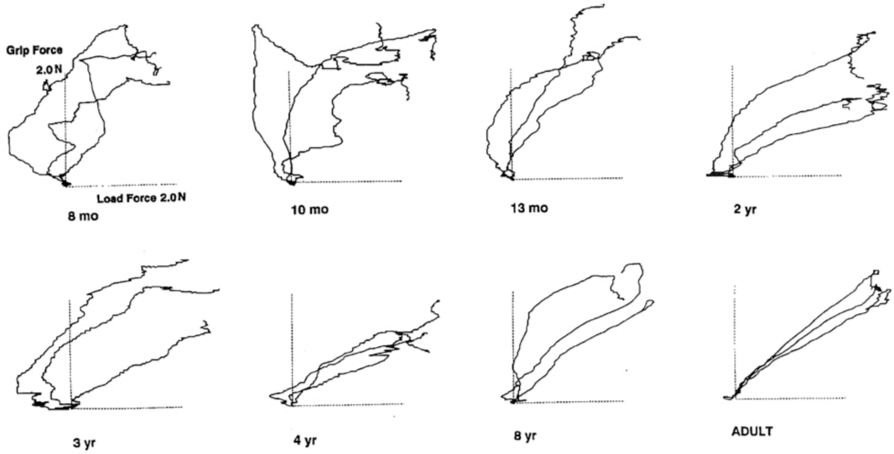


Figure 2.1.3. The grip force during the preload and the loading phase is plotted against load force in children at different ages. Three trials are superimposed for each subject. Printed with permission from (Forssberg *et al.* 1991).

2.2. Current stage of Haptics in MIS

This article gives an overview of research performed in the field of haptic information feedback during Minimally Invasive Surgery (MIS). Literature has been consulted from 1985 to present. The studies show that currently, haptic information feedback is rare, but promising, in MIS. Surgeons benefit from additional feedback about force information. When it comes to grasping forces and perceiving slip, little is known about the advantages additional haptic information can give to prevent tissue trauma during manipulation. Improvement of haptic perception through augmented haptic information feedback in MIS might be promising.

2.2.1. Introduction

Minimally Invasive Surgery (MIS), which is surgery performed with long thin instruments through small incisions, has been used for more than 25 years. The main reason for the rapid developments in MIS are the benefits for the patient, like less trauma, shorter hospital stay, and reduced recovery time (Cuschieri 1995, Moreno-Egea *et al.* 2005, Roumm *et al.* 2005, Dedemadi *et al.* 2006, Stefanoni *et al.* 2006). However, this technique brings severe difficulties for the surgeon (Stassen *et al.* 2001) that can lead to a higher number of errors and complications (Dankelman *et al.* 2003).

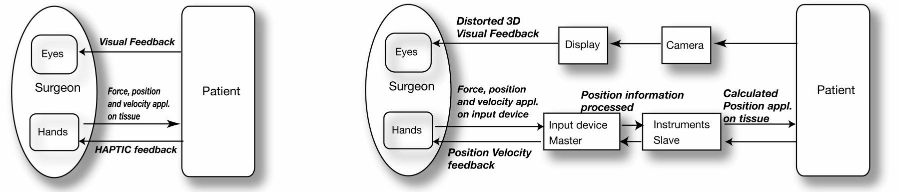
The indirect vision through an endoscope (camera), and the indirect manipulation of tissue are the main causes of perception problems, which can be divided into disturbed hand-eye coordination, reduced depth perception, and reduced haptics. Haptics are here defined as the combination of tactile perception (through sensory skin receptors) and kinesthetic perception (through muscle, tendons and joint sensory receptors). The MIS technique can endanger the patient's safety, for example when grasped tissue is damaged by the instruments (Marucci *et al.* 2000a, Marucci *et al.* 2000b, van der Voort *et al.* 2004, Barbosa Barros *et al.* 2005). Much attention has been paid to perception problems due to reduced hand-eye coordination (Tendick and Cavusoglu 1997, Wentink 2003, Dutkiewicz *et al.* 2004, DeLucia *et al.* 2006) and depth perception (Tendick *et al.* 1993, Voorhorst. 1998, Breedveld *et al.* 2000, Breedveld and Hirose 2004), but not much research has been done in the field of reduced haptics.

In MIS the hands manipulate tissue indirectly by instruments. However, how the instruments interfere with the sensory perception of the surgeon is not completely understood. In open surgery there is semi direct tissue contact (with gloved hands), so the surgeon can feel the temperature, shape, structure, and consistency of the tissue touched. Compared to bare hands, a glove will reduce haptics to some extent, but the surgeon can still directly feel the amount of force applied when pinching or feel when the tissue slips through the fingers. According to this (natural) haptic feedback, the surgeon can adjust the applied force in such a way that the tissue is not damaged, but is still held securely. Basically, what the surgeon can feel through the instruments is unknown. Nonetheless, a correct perception of the operation field is needed to manipulate the tissue safely.

Some handheld instruments currently on the market do not provide reliable haptic feedback, but are still used for a variety of MIS tasks. Similarly most robotic surgery systems do not provide any haptic feedback, but are still used to perform delicate procedures (Stephenson *et al.* 1998). Despite this ability to work without haptic feedback, the skilfulness with current instruments is far from optimal in MIS. In a review of 148 cardiac surgeries performed with a robotic surgical system (The da Vinci telemanipulation system (Intuitive Surgical, Mountain View, CA.)) Mohr *et al.* felt that the lack of haptics might lead to identification problems (Mohr *et al.* 2001). Currently, it is unclear what haptic feedback systems can do in MIS to improve the skilfulness of surgeons and reduce risks for patients. In order to improve these systems, we have to understand the role of haptic sensation during MIS. Of course, not all tasks require the same amount of haptic information.

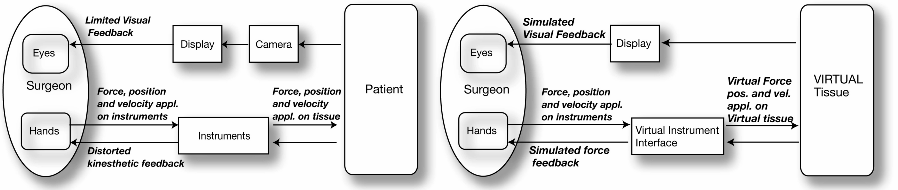
A Note on terminology

Because different terminology is used in literature confusion can occur. Therefore, we explain the terminology used in this article. **Haptic perception** (or haptics) is the combination of tactile perception and kinesthetic perception. Pain and temperature are used for haptic perception but are not the main focus of this research. **Tactile perception** is the perception of pressure, vibration, and texture (also called **discriminative touch or cutaneous sense**), and relies on different receptors in the skin (cutaneous mechanoreceptors). **Kinesthetic perception** relies on receptors in muscles, tendons and joints and senses position, movement and forces. Another common term used to describe haptics is **proprioception.** However**, proprioception** is the perception of posture and position of the limbs, body and head in space and its parts relative to one another, including the vestibular system, cutaneous sense and kinaesthesia (Widmaier *et al.* 2004). In Figure 2.2.1 simplified models of the types of surgery can be seen and the role the sensory system to perceive information (including Open Surgery).



A. Open Surgery

C. Minimally Invasive Robotic Surgery



B. Minimally Invasive Surgery

D. Virtual Reality Training in Minimally Invasive Surgery (With Force feedback)

Figure 2.2.1. Simplified models: A., Open Surgery B., Minimally Invasive Surgery C., Minimally Invasive Robotic Surgery and D., Virtual Reality Training in Minimally Invasive Surgery (with force feedback).

In order to find solutions for the difficulties in haptic perception during MIS, a research project was initiated at the Delft University of Technology in cooperation with the Catharina Hospital in Eindhoven. As part of the project, an extensive literature review was carried out. The aim of this review article is to describe the current knowledge about haptics in MIS, Minimally Invasive Robotic Surgery (MIRS) (also called tele-operations / robotic surgery), and Virtual Reality Training for MIS (VRT). The article ends by identifying several important research areas.

2.2.2. Methods

The literature review focused on research of haptics in conventional MIS, MIRS and VRT. At first, a thorough *PUBMED and SCOPUS* search was performed in order to find relevant literature in English. The electronic databases from 1985 to February 2007 were searched, using the following search terms: 'haptics OR haptic OR tactile OR force AND/OR feedback' AND 'Minimally Invasive Surgery OR MIS OR laparoscopy OR laparoscopic OR virtual reality OR simulation OR robotic OR tele-surgery OR tele-operation OR Minimally invasive Robotic Surgery OR MIRS OR master AND slave'. After the database survey all relevant papers in the reference lists of the already found papers were consulted in addition to conference proceedings and books about the topic. The survey resulted in 118 relevant papers and documents. Two review studies (Breedveld *et al.* 1999, Dario *et al.* 2003) were found that provided some information about haptics during minimally invasive surgery, but since they did not focus on this subject their results were far from complete.

After data collection, the results from the review were divided into three main groups: Haptic sensation in conventional Minimal Invasive Surgery, Haptic sensation in Minimally Invasive Robotic Surgery, and Haptic sensation in Virtual Reality Training. The groups are discussed in detail in the Results with each subsection, starting with an overview of research into what a surgeon can actually feel through his instruments, followed by a survey of technical improvement aids that have been found.

2.2.3. Results

2.2.3.1. Haptic sensation in Conventional Minimally Invasive Surgery (MIS)

In theory, a surgeon wants to feel the forces, position and tactile information generated by the instruments applied on the tissue in order to control them. The ability to feel texture, shape, size and consistency of tissue using MIS graspers has been studied (Bholat *et al.* 1999, Heijnsdijk *et al.* 2004c, Picod *et al.* 2005, Lamata *et al.* 2006b, Schostek *et al.* 2006). These studies show that haptics are considerably reduced compared to bare hands, except for texture discrimination, although one is able to distinguish shape, size and consistency of tissue. Unfortunately, all these studies used artificial tissue like sandpaper and plastic cubes and cones.

Bholat *et al.* (1999) showed, that the surgeon is provided with some haptic feedback in laparoscopy (MIS performed in the belly alcove) (determine primitive shapes, texture and consistency of springs), and experts performed better, which means that surgeons learn to understand and interpret the haptic information presented. Only experts distinguished different textures (abrasive materials) better with a dissector than with bare hands, probably due to the experience to sense vibrations along with amplification by the lever effect of the trocar. Boer *et al.* (1999) showed that reusable dissectors were 8 times less sensitive than bare hands trying to feel a simulated arterial pulse.

In general, interposition of instruments reduces haptic feedback considerably in minimally invasive procedures (Bholat *et al.* 1999, den Boer *et al.* 1999, Picod *et al.* 2005, Schostek *et al.* 2006).

2.2.3.1.1 Interference components of haptic sensation

Items, attributes and techniques establish the link between the surgeon's hands and the treated tissue, thereby interfering with the desired haptic perception (see Figure 2.2.1). These interference factors consist of the following components (see Figure 2.2.2 for an overview of the interference factors in conventional MIS).

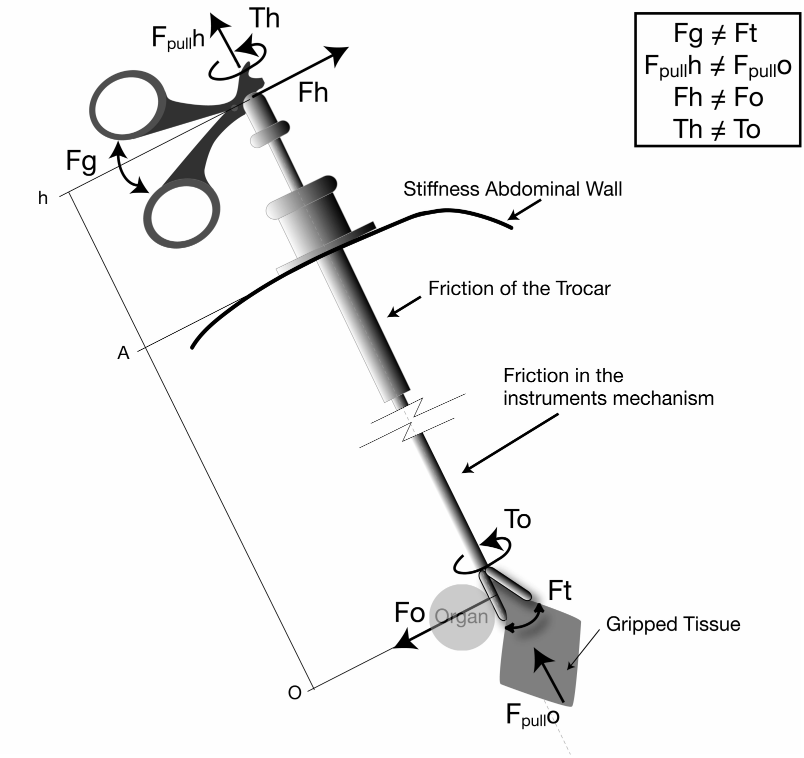


Figure 2.2.2. Interference factors in Conventional Minimally Invasive surgery. The grip force (Fg) is not equal to the Tip force (Ft) due to the instruments mechanism. The hand force (Fh) is not equal to the organ force (Fo) due to the scaling factor (ideal Fh=Fo(OA/Ah)) and the resistance of the abdominal wall. The pull force at the handle (F_{pull}h) is not equal to the pull force at the organ (F_{pull}o) due to trocar friction. The torque, applied at the handle (Th), is influenced by the trocar friction as well.

Friction between trocar and instrument shaft. The trocar placed in the patient's skin, where the instruments are inserted, prevents insufflated CO2 gas to come out and protect against skin rupture as well. During instrument movement, the shaft is in contact with the airtight wall of the trocar that causes friction, which works against the movement (Cuschieri 1995, Salle *et al.* 2001). This friction is different, but constant for each trocar, and can exceed 3N with some trocars (Picod *et al.* 2005, van den Dobbelsteen *et al.* 2007).

The resistance of the abdominal wall during a lever movement. When the instruments are levered, the resistance of the abdominal wall (skin, subcutaneous fat, facial and muscular layers) can vary because the biomechanical properties are not isotropic and differ among individuals. This force torque, with respect to the abdominal wall, can range from 0 to 0.7 Nm according to angle and direction of tilt (Picod *et al.* 2005).

Scaling and mirroring of tip forces. Because the incision point transfers the instrument shaft into a lever, it scales and mirrors the forces at the tip of the instrument (perpendicular to the shaft) (Tendick *et al.* 1993). The length of the lever arm depends on the insertion depth of the instrument, the patient's abdominal wall thickness, and the target location. Theoretically, the force felt by the surgeon's hand can range from 0.2 to 4.5 times the actual force generated by instrument tissue contact. This induces an additional distortion of haptic feedback. The interaction forces of the instrument with organs applied by the surgeon were measured in the range of 0 to 10-12 N (Ft) (Rosen *et al.* 1999b, Toledo *et al.* 1999, Picod *et al.* 2005).

Instruments mechanism Each instrument has a mechanism, which differs in construction and thus mechanical properties (Sjoerdsma *et al.* 1997, Heijnsdijk *et al.* 2004c, Picod *et al.* 2005). During grasping, the operating force experienced by the surgeon should be a measure for the grasp force applied to the tissue. In theory, this force should be transmitted without distortion and losses. Due to friction in the mechanism, commercially available MIS graspers show a mechanical efficiency of less then 50% (Sjoerdsma *et al.* 1997). The force transmission is not constant during the grasping movement due to backlash and play in the mechanism. The relative variation in force transmission of commercially available graspers is between -6.1 and + 1.9 (Sjoerdsma *et al.* 1997). This means that with some instruments, the grasp force increases with an increasing angle of the handle while with others, the force decreases under the same circumstances. This results in a variety of grasp forces with the same operating force and therefore uncertainty about the grasp force information delivered to the surgeon's hand. An accompanying problem occurs when a surgeon changes instruments that differ in their mechanical properties.

Haptic sensation is greatest during low velocity of translation movement, the smallest angle of tilt, and an efficient-accurate mechanical mechanism. The interference properties of haptics can be of the same order as during contact with the organ. This makes it difficult for a surgeon to discriminate between somesthesic information generated by the organ and information resulting from friction or resistance of the abdominal wall (Picod *et al.* 2005).

2.2.3.1.2 Technical improvement aids

The addition of haptic information feedback in MIS can give the surgeon the ability to sense slip and applied forces in order to control grasp forces. This haptic sensation can reduce tissue trauma. There are two approaches to improve haptics: improving the mechanical construction and adding extra information feedback (sensory substitution), transmitted electromechanically. (Examples of both the approaches will be mentioned further.)

Mechanical approach

In the Daum-Hand (EndoHand) (Melzer *et al.* 1997, Jackman *et al.* 1999) the contact forces on the grasper were detected by membranes and transmitted hydraulically to membranes connected to the surgeon's fingers, so an average grasping force was felt. However, (Melzer *et al.* 1997) the dexterity (measured by time and errors) of the grasper was less compared to conventional graspers (Jackman *et al.* 1999).

The low-friction forceps of Herder *et al.* (1997, van der Pijl and Herder 2001) consists of a rolling link mechanisms (Kuntz 1995) to transmit movements and forces with a mechanically efficiency of 96%. One was able to feel a pulse with this laparoscopic instrument, but still reduced compared to bare hands (2.7 times less sensitive). However, compared to conventional MIS instruments, the prototype performed better (den Boer *et al.* 1999).

A laparoscopic grasper designed by Balázs *et al.* (1998) and a kidney manipulator designed by Kota *et al.* (2005) do not contain bolt joints but have elastic jaws, so friction can be neglected. Unfortunately, no tests with these instruments could be found.

Mechanically efficient instruments are not always beneficial. For example, improving mechanical efficiency did not necessarily lead to decreased pinch forces, depending on the task. Mechanically efficient graspers can even increase the maximal excessive force, compared to normal graspers (90% efficiency compared with 30%) depending on the task. For tasks requiring little instrument movement, such as grasping and holding tissue, a low mechanical efficiency was sufficient, whereas tasks with repeated motion (feel tissue) required high mechanical efficiency. A holding task showed twice as much force necessary to prevent slip, and no difference occurred between novice and experts, probably because no practicing was involved before the start of the test (Heijnsdijk *et al.* 2004c). Additionally, the lack of endoscopic-visual feedback resulted in more slips (Heijnsdijk *et al.* 2004b).

Sensory substitution

Sensory substitution was used in most studies, using the electromechanical approach, to improve haptics. A thorough overview of different types of available tactile displays was made by Wall *et al.* (2006). These different types of displays can be used to improve haptics during MIRS and VRT as well.

The electromechanical approach uses sensors to measure forces applied to the tissue, and/or distract tactile tissue information, to reflect them electronically to the surgeon using a haptic, auditory or visual display. Auditory and visual displays depict a force distribution, or tactile information, using an auditory signal or respectively a graphical representation. Several kinds of haptic displays exist, kinesthetic (force plus position), vibro-tactile, relief-tactile, stretch-tactile, and electro-tactile displays.

A kinesthetic display uses an array of forces and positions that counteract the operator's manipulation forces and positions. Less sophisticated are force displays (sometimes only displaying forces in certain dimensions) and position displays that are often used instead of a full kinesthetic display. A vibro-tactile display uses an array of vibrating pins where the amplitude or the frequency of vibration becomes bigger with larger measured forces. A relief-tactile display uses an array of movable pins placed on the skin: The larger the measured force, the larger the deflection of the pin. A stretch-tactile display presents information through spatiotemporal patterns of mechanical skin stretch. An electro-tactile (or electro-cutaneous) display uses an array of electrodes placed on the skin to create touch sensation (Lundborg *et al.* 1998).

Schostek *et al.* (2006) developed a tactile sensor, integrated into a laparoscopic grasper jaw, to obtain information about shape and consistency of tissue structures. The tactile data were wirelessly transferred (Bluetooth) and graphically displayed to the surgeon. The prototype of the system proved feasibility (in an experimental environment) and the tactile data supplemented the haptic feedback provided by conventional MIS instruments. However, tissue exploration time was longer compared to a conventional grasper.

Prasad *et al*. (2003) developed a 2-Degrees of Freedom (DOF) force-sensing sleeve fitting a variety of instruments. The sleeve was used passively to monitor intra-abdominal forces during a retraction task. An audio display was used relaying force information to the user. Frequency modulation was preferred to amplitude information, but surgeons were concerned about continual noise in an operating room setting.

Dargahi *et al.* (2004b) developed force sensors to fit in laparoscopic graspers, but the led device that provided visual force feedback on the handle was not tested with users. Nevertheless, this probably will not work since surgeons do not look at their hands during a procedure.

Fischer and Trapp (1996) developed a tactile optical pressure sensor to fit a laparoscopic grasper and a sensing rod. This optical sensor displayed indurations (spread in the tissue) graphically. The measured values served to activate a vibro-tactile display-unit at the surgeon's fingertip providing tactile feedback. In a later study they (Fischer *et al.* 1998) optimized the vibro-tactile display, but no results were presented.

Yao *et al.* (2005) developed a surgical probe with tactile and auditory feedback. Tactile and auditory reproduction was established by detecting and magnifying the acceleration signal resulting from instrument-surface interaction. Subjects used the probe to detect cuts under four conditions: no amplification, tactile feedback, sound feedback, and passive touch. Tactile and auditory feedbacks showed significant improvements in performance. Unfortunately, the probe was not used through a trocar, so no interference factors were discounted for.

Bicchi *et al.* (1996) placed a force and position sensor in a conventional MIS Instrument and displayed the information graphically (position versus force), showing that subjects could discriminate between objects of different materials.

Two experiments were performed by Ottermo *et al.* (2006): a hardness and size discrimination task (rubber balls hidden in pig's intestine) using gloved fingers, a conventional laparoscopic instrument, or a laparoscopic instrument with a sensor array. A visual display provided tactile information (pressure distribution). Gloved fingers were better at differentiating hardness and size compared with the conventional instrument and the instrument with the sensor. There was no significant difference between the conventional instrument and the instrument with the sensor. This indicated that visual presentation might not be an ideal way of presenting tactile information. The authors indicated that the presence of the array does not make the task more difficult.

Fischer *at al.* (2006) studied a totally different approach of sensory substitution. They used sensors that could sense tissue oxygenation next to translational forces. The principle they used was based on the fact that when tissue oxygenation decreases below a certain value, trauma will occur. If oxygenation values are displayed to the user, grip forces can be controlled.

Several groups developed sensors to implement into instruments, for example tri-axial force sensors (Valdastri *et al.* 2006), tactile sensors to detect arteries (Beasley and Howe 2002), piezoelectric tactile sensors to detect compliance and total applied force (Sedaghati *et al.* 2005) and vibro-tactile sensors, where vibration is applied to the tissue, and different tissue properties are determined by the resonance range (Plinkert *et al.* 1997). However, how feedback is provided is not clear.

2.2.3.2. Haptic sensation in Minimally Invasive Robotic Surgery (MIRS)

In MIRS the instrument (slave) and handgrip (master) are physically disconnected, called a Master-Slave system Figure 2.2.3. The Master is held by the surgeon and dictates movements to the Slave that controls the instrument via an electromechanical device. The advantage of this system is that it compensates for some of the interference factors described earlier. An example is the simplicity to neutralize the mirroring effect by software. However, the mirroring does not seem to be a enormous problem because it is easy to get used to (Tendick and Cavusoglu 1997).

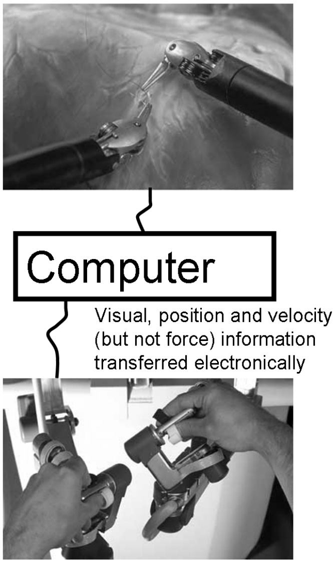


Figure 2.2.3. Schematic representation of robotic surgery. The handgrip (master) are physical disconnected from the special designed laparoscopic instruments at the slave side. The interaction between master and slave is controlled by a computer. Forces at the instrument tip are not measured in current systems.

When forces are measured, it is relatively easy to neutralize the scaling disturbance factor by applying a scaling factor between the master and the slave. In the same way, the interference from trocar friction can be neutralized by directly sending the tip force information to the handle of the master. Research showed that it is possible to measure forces (grip and tip force sensors) at the tip of the instrument and reflect them to the master (Fischer and Trapp 1996, Fischer *et al.* 1998). In spite of these technical possibilities, haptic feedback is still rare in MIRS (Wagner *et al.* 2002, Hu *et al.* 2004, Okamura 2004, Tholey *et al.* 2005, Wagner 2006), because adding force feedback is expensive and technically difficult (changes of instability). Currently there is no commercially available robotic system with haptic feedback (Grimbergen and Jaspers 2004, Sim *et al.* 2006, Wagner 2006). Position feedback is supported, and forces and positions are bounded to prevent excessive forces. Several research groups have addressed design issues for ideal kinesthetic control master/slave-mechanisms (Yokokohji and Yoshikawa 1994, Tavakoli *et al.* 2004) and listed requirements for MIRS systems (Brooks 1990).

2.2.3.2.1 Technical improvement aids

Because haptic feedback is not yet commercially available in MIRS, many research focused on evaluation and technical improvement by augmented force information feedback. Numerous reviewed studies used the Personal Haptic Interface

Mechanism (PHANToM Sensable Technologies, Inc., Woburn, MA, USA). The PHANToM was the first commercially available force feedback device that presented the illusion of contact with a rigid virtual object using programmable constraint forces supplied to an end-effector such as a handle or stylus (Massie and Salisbury 1994).

Tholey *et al.* (2005) researched the capability of tissue characterization during grasping with a Master-slave prototype (PHANToM used as a master device). Providing both visual and force feedback led to better tissue characterization (varied stiffness) than only visual feedback or only force feedback for both experts and novices. However, based on vision alone, experts were much better than novices, probably due to their experience with vision feedback in conventional MIS. The drawback was that subjects were not activating the grasper themselves (one of the test leaders was); they were only feeling the feedback by the PHANToM.

Wagner *et al.* (2002) analysed advantages of force feedback during a blunt dissection task (Novices used a laparoscopic hook on a clay tissue model). Addition of force feedback (using the PHANToM) resulted in more precise dissection, fewer errors (factor 3), lower applied peak and average forces (50% lower) at the instrument tip and shorter duration of high forces, compared to less or no force feedback. The addition of force feedback did not reduce the time required to accomplish the task.

Kazi (2001) investigated the benefits of force feedback (using a modified DISTEL Master-Slave system) during a catheter insertion task and found that peak forces were 40% higher without force feedback than with it.

Hu *et al*. (2004) researched the ability to give realistic kinesthetic sensation, experienced through conventional MIS Instruments to a Master-Slave system. The slave consisted of a commercially available disposable grasper equipped with position and force sensors in the handle, operated by a human slave. The information retrieved from the sensors transmitted force feedback to the master (PHANToM-stylus). Experts and novices alike were able to quantify stiffness of different tissue samples grasped by the slave with a high degree of accuracy. (The slave was operated by an other human instead of electronically.)

Rosen *et al*. (1999a) developed a master-slave grasper (FREG) with bilateral force feedback. Subjective tests of ranking stiffness of silicone materials, without visual feedback, using the FREG showed significant improvement in the performance compared to a standard grasper. Moreover, the FREG performance was closer to performance of the human hand (latex gloved) than a standard grasper. There were no differences in performance of experts and novices (MacFarlane *et al.* 1999).

Demi *et al.* (2005) presented a prototype of a force-reflecting MIRS system and evaluated the importance of force feedback. The prototype was actually suited to reduce unintentional injuries when appropriate force feedback was available, although the operating time increased compared to a manual intervention. However, for experts in conventional MIS, skills were not transferred to robotic surgery.

De Gersem *et al*. (2005) described a possibility to enhance sensitivity of stiffness by optimization of a control concept for a master-slave system based on human perception capabilities. Stiffness perception could be enhanced from 8-12% (revealed in an earlier study (de Gersem *et al.* 2003)) to 6% JND (just noticeable difference) compared to a probing task (using a PHANToM interface).

Several other groups have designed experimental haptic master-slave devices (Fritz *et al.* 2004) , but they are in a developmental stage, and no tests of haptic performance have been published yet.

Sensory substitution

Morimoto *et al.* (1997) developed a prototype force sensor system provided as an in-line transducer with six DOF's to fit current robotic-Babcocks. Force data were graphically presented. A three phase experimental trial, using a living pig, showed that force information could be used to minimize tissue trauma during laparoscopic surgery.

Kitagawa *et al.* (2004, 2005) studied the effect of substituting direct haptic feedback with visual and auditory cues using the da Vinci robotic system (Intuitive Surgical Inc., Mountain View, CA). They observed the difference between applied forces, during a knot tying procedure, for four different feedback scenarios: no feedback, auditory feedback, visual feedback, and a combination of auditory and visual feedback. Visual feedback, which provided continuous force information, could improve robot-assisted performance during complex tasks such as knot tying. Discrete auditory feedback gave additional useful support.

Akinbiyi *et al.* (2005) developed an augmented reality system (integrated with the da Vinci) presenting force information via a graphic display that overlays a visual representation of force levels on top of the moving instrument tips. During a knot-tying task, the system decreased the number of broken sutures, decreased the number of loose knots, and resulted in more consistent application of forces.

Judkins *et al.* (2006) showed that after adding feedback on grip force information graphically, for a short training period (10 trials using the da Vinci) and then removing it, users still used less force during several tasks (Bimanual carrying, needle passing and suture tying).

Bethea *et al.* (2004) showed (with a modified da Vinci) that visual sensory substitution permitted the surgeon to apply more consistent, precise, and greater tensions to fine suture materials without breakage during knot tying.

Tavakoli *et al*. (2006a) developed a prototype of a master/slave system (haptic interface and end-effector sensors) with kinesthetic feedback in 5DOFs (described in (Tavakoli *et al.* 2005, Tavakoli *et al.* 2006b). The Master looked like a conventional

MIS instrument handle. They compared force information feedback in one direction with visual and kinesthetic feedback in a (blind) lump detection task. Visual feedback showed longer task completion times but task accuracy was the same.

Sensor-actuator asymmetry

Due to costs and practical application of force feedback in MIRS, it may not be possible to match the number of DOFs of position sensing and control with the degrees of freedom of force sensing and feedback. Almost all MIRS systems presented in this article have more DOFs to manipulate than force sensing and feedback (up to 7 DOFs: 3 translational forces, 3 torque forces, and 1 pinch force). Verner and Okamura (2006) presented dynamic models of sensor-actuator asymmetries in master-slave systems and showed that asymmetries demonstrate challenges in creating practical, force-reflecting master-slave systems. Some preliminary research has been conducted to see whether this sensor-actuator asymmetry affects performance.

Semere *et al.* (2004) determined the affect of such sensor-actuator asymmetry during bilateral MIRS. In a task where users had to push a cup through a series of poses and in a blunt dissection task using phantom tissues, three different force feedback conditions were applied to a 3-D master-slave system: 3-D force feedback, force feedback without the axial forces measured on the slave tool, and no force feedback. The tasks were also performed manually using a hand-held stylus. The absence of measured axial forces did not create difference in applied force levels, in comparison with complete 3-D force feedback. In addition, this partial force feedback was a significant improvement over MIRS with no force feedback.

Verner *et al.* (2005) studied the effect of sensor-actuator asymmetry where users performed standardized tasks with varying force feedback conditions included: no forces, grip forces only, translational forces only, or grip and translational forces (sensor-actuator symmetry). Force feedback lowered error rates and force rates but full-force feedback was not always preferable above partial force feedback. In a later study, Verner and Okamura (2007) determined the effect of grip force feedback in relation to translational force feedback when users performed a soft peg-in-hole task with various DOFs of force feedback: full force feedback, translational force feedback only, grip force feedback only, and no force feedback. The level of force applied in the translational and gripping DOFs were decoupled by the subjects. They explain that this is likely due to the decoupled dynamics of internal and external hand forces.

2.2.3.2.2 Conventional and Robotic Minimally Invasive Surgery compared

Some studies compared MIS and MIRS. For example, Cao *et al.* (2003) compared a line drawing task conducted with MIS (limited haptic feedback) and MIRS (no haptic feedback). MIS performance was faster and extra visual force information was beneficial for both MIS and MIRS task performance. The number of errors was bigger in MIS probably because there were fewer DOFs than in MIRS. Berguer *et al.* (2006) compared mental and physical workloads during conventional MIS and MIRS without augmented haptic feedback. MIRS appeared slower and less precise than MIS for simple tasks, but equally fast and possibly less stressful for complex tasks. Previous experience in MIS had a complex influence on the physical and mental adaptation to MIRS.

Research showed that despite reduced haptic feedback in MIS compared to bare hands, it is possible to determine consistency of tissue with a laparoscopic grasper (Hu *et al.* 2004, Lamata *et al.* 2006b). Some new designs, including force feedback, for master–slave systems performed better on this task (Rosen *et al.* 1999a).

2.2.3.3. Haptic sensation in Virtual Reality Training (VRT)

VRT is used to train surgeons in all kinds of procedures. A well-designed VRT-system should provide realistic feelings of real-life surgery. Thus, a simulator without kinesthetic feedback does not train the student to cope and master the disturbance and interference factors that occur during MIS. Considerable interest exists in developing haptic-VRT-systems, even though the importance of haptic feedback remains poorly understood (Ottensmeyer *et al.* 2000, Dubois *et al.* 2002, Lamata *et al.* 2006b). A schematic drawing of a VRT system with haptic feedback is given in Figure 2.2.4.

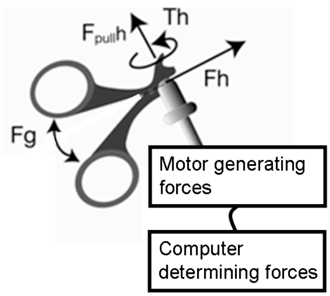


Figure 2.2.4. Schematic representation of a virtual reality training simulator with haptic feedback. Forces are generated by a motor and determined by a computer.

To produce realistic tissue and instrument behaviour, it is important to have information on the mechanical properties of organs. However, this is difficult to achieve because solid organs (e.g., liver, spleen and pancreas), hollow organs (e.g., gall-bladder, stomach, bowel), sick and healthy tissue behave different when manipulated and have non-linear stress-strain behaviour (Carter *et al.* 2001, 2005). Some researchers have tried to obtain these mechanical properties, for example on bowel tissue (Morimoto *et al.* 1997, Carter *et al.* 2001). Some instruments were developed to obtain in-vivo linear tissue compliance and geometry change (Ottensmeyer *et al.* 2000, Brouwer *et al.* 2001), but there is still much unknown. This lack of knowledge in combination with technical difficulties makes it difficult to realize realistic tissue behaviour in VRT-systems. Several articles (Cavusoglu and Tendick 2000, Basdogan *et al.* 2004) gave an overview about the technical problems, and important aspects that occur with haptic rendering.

Tissue consistency perception is mainly based on haptic information (Lamata *et al.* 2006b). Lamanta *et al* (2006b) showed that by seeing the tissue, experts could recall the consistency of tissue, because they had a kind of tactile memory built up. In VRT especially novices needed haptic information, when consistency information had to be delivered (Lamata *et al.* 2006b) (2005).

Schijven and Jakimowicz (2003) gave an overview of the most important VRT-systems available at that moment, and concluded that from the 12 systems, 6 contained force feedback and 3 provided an option to implement force feedback; However, they were expensive and the quality was not satisfactory.

2.2.3.3.1 Performance with augmented haptic information feedback

Is it possible to improve performance when haptic information is displayed to the users in a VRT system? Not much research found answered this question.

Wagner *et al.* (2005) demonstrated that force feedback can provide physical constraints to an operator’s motion, passively restraining the hand and reducing error even before the operator could voluntarily respond to the force stimulus. The magnitude of unwanted incursions into a virtual wall were reduced up to 80%, compared to no force feedback. Feedback through a kinesthetic display reduced errors within 150 ms of encountering the virtual wall while feedback using a vibration display took longer.

Ström *et al.* (2006) analysed whether the addition of force feedback in VRT, early in the training phase, improved performance in a diathermy task. They concluded that haptic feedback could be important early in the training phase of skill acquisition.

In a virtual computer movement task, augmented force feedback presented via a mouse helped to perform better (Houtsma and Keuning 2006) (the closer the mouse reached the target the more resistance the user got to move the mouse).

2.2.3.3.2 Technical improvement aids

Some studies have been done in the field of improvement of haptics in VRT-systems. For example, Acosta *et al.* (2005) developed a haptic skill-based laparoscopic simulator called LapSkills that aimed to provide a quantitative measure of the surgeon's skill level and to help improve their efficiency and precision. It is not clear how haptics were displayed to the user and if more than translational force feedback was displayed.

Some groups have developed haptic interfaces for VRT systems, but no literature could be found about user tests. Chou and Wang (2003) developed a VRT-system for MIRS neurosurgery, which included collision detection, deformation of soft tissue and kinesthetic rendering. During needle insertion, the brain was displayed, and the resistance force between the needle and organs were reflected to the surgeon by a 3-DOFs force feedback device. Maass *et al*. (2003) developed a flexible interface that could control several different force-feedback hardware systems, including the PHANToM, the Laparoscopic Impulse Engines from Immersion, and the VS-One virtual endoscopic surgery trainer. Several groups have developed VRT-systems with force feedback displays (Ottensmeyer *et al.* 2000, Aschwanden *et al.* 2005, Wu *et al.* 2006)

Sensory substitution

In VRT-systems the image of the surgery field often serves as a sensory substitution device itself. In a VRT needle task, force feedback in combination with visual feedback of needle position resulted in better performance than one of the two feedback systems alone (Gerovich *et al.* 2004).

Sensor-actuator asymmetry

The same perception problems that occur with sensor-actuator asymmetry in MIRS are applicable for VRT. For example, sensor-actuator asymmetry can cause non realistic feedback in VR, especially when one of the 3 translational forces is not displayed to the user (Barbagli and Salisbury 2003).

2.2.4. Discussion

The purpose of this review was to give an overview of the current knowledge of haptics in MIS. MIS instruments do, in fact, provide surgeons with haptic feedback. Although bare hands performed better, texture, shape, and consistency of objects can be perceived. Research showed that using minimally invasive techniques haptics are reduced considerable. But sensitivity qualities are highly variable, depending on the instrument. Perceived haptics are interfered by indirect tissue contact, trocar friction, resistance of the abdominal wall, scaling and mirroring of tip forces, and friction in the system mechanics. These interference components of haptic sensation during MIS can be as big as the interaction forces with the organs themselves. Currently, there are no commercially available MIS instruments, MIRS systems, and VRT-systems with adequate haptic information feedback. However, haptic feedback during MIS is needed (den Boer *et al.* 2001).

Many research groups claim to have developed haptic information feedback systems, but in fact they mean force information feedback. Commercially available MIRS systems only provide position feedback because of high cost and instability problems that still exist with the implementation of force and tactile information feedback in these complicated systems. Surgeons have to estimate applied contact forces by visual observation of tissue deformation and color change during MIRS. Especially when there are a lot of instruments inserted during a complex procedure, it is possible that some of them are out of sight while holding tissue. In such a case, force feedback could be helpful to control the grasp. The available VRT-systems provide no or non- realistic haptics because, next to technical difficulties and render realistic haptics, not much is known about the mechanical properties of living tissue.

Surgeons will benefit from extra information regarding the levels of force applied to tissues. Although reasonable research has been done on the displaying of translational forces, studies about information feedback of grip forces and slips are rare. Many high-degree-of-freedom haptic devices and master-slave systems either do not have grippers or do not provide force feedback in the gripper DOF. Ideally, MIS instruments should have full-haptic feedback, meaning that force feedback is provided in all DOFs of manipulation, and slippage and texture information is presented to the operator. This way the surgeons can feel as though they are directly manipulating the tissue. Full-haptic feedback as described above is not available because it is technologically still not possible. A solution might be to provide partly haptic information feedback, but this will result in a sensor-actuator asymmetry that might be a problem. However, it has been shown that information on grip force and translational forces do not interfere with each other, so they can be displayed separately without causing confusion.

Reducing the interference factors using mechanically more efficient instruments is not always preferred, depending on the task. A better approach seems an augmented haptic information display. However, additional feedback signals are only desirable when no extra mental workload is added. Force feedback reduced errors without requiring the cognitive attention of the user in a cannulation task (Wagner and Howe 2005). In the non-medical field, force feedback can indeed reduce mental workload in master-slave tasks (Lessard *et al.* 1995, Oakley *et al.* 2000, Chou and Wang 2001). Haptic displays, even if they do not present information in all DOF's, can enable passive strategies that would not be possible with only force information, such as with sensory substitution. However, a haptic information display that uses sensory substitution is much cheaper and easier to implement. When it is implemented correctly, haptic information displayed by sensory substitution is able to improve the surgeon's performance compared to no haptic information feedback at all. In non-medical fields, force information, displayed by sensory substitution, aids performance, for example combined auditory and vibro-tactile displays (Massimino and Sheridan 1993, Massimino 1995), or only vibro-tactile display (Debus *et al.* 2004). Sensory substitution can only partly improve haptic feedback, because it is very difficult or even impossible to provide "full"-haptic information feedback (force in all

DOF’s and tactile information on slips) without adding unwanted extra mental workload.

Further, haptic feedback alone might not be enough to guarantee unnecessary tissue trauma. Different sensing modalities, or multi-modal sensory input, may be required to prevent tissue trauma. Complementary studies in a non surgical VR task (Richard and Coiffet 1995) showed that multi-modal feedback of force information (auditory combined with force feedback) performed better than no force feedback and the two modalities on their own. In an additional study (Richard and Coiffet 1999) (in a VR manipulation task), it was shown that in addition to kinesthetic feedback, auditory or visual displayed force information even performed better than kinesthetic displayed, force information alone.

Augmented feedback of force information is beneficial for both experts and novices, even though experienced users are trained to cope with little haptic feedback. They are trained to use visual feedback to constrain their movements and avoid large forces. However, the aid of augmented force feedback can decrease errors even for experts.

Almost all reviewed studies were performed in a non-clinical setting. In order to give the surgeon extra haptic information, not only during simulated training settings, but also during clinical surgery, the availability of this information is a prerequisite. Therefore, sensors must be applicable in wet and warm environments, and be able to be sterilized. During experimental surgery on animals some studies showed that it is possible to get this information from living tissue with sensors implemented in the instruments (Morimoto *et al.* 1997, Dubois *et al.* 2002, Picod *et al.* 2005, Lamata *et al.* 2006a). Because of this, our research group (at TU Delft) will focus on improvements of haptic perception in conventional MIS, especially on the perception of slips and applied excessive forces during grasping, in order to prevent tissue trauma and improve patient safety during MIS.

2.2.4.1. Conclusion

Augmented force information can aid performance in all fields of minimally invasive surgery, and surgeons benefit from the additional feedback of force information. This information should be presented by a haptic display because of its intuitive nature, but a multi-sensory display might be preferable. In general, little research has been done in the field of augmented haptics during MIS. Especially when it comes to grasping forces and the perceiving of slips, little is known about the advantages additional haptic information can give to prevent tissue trauma during manipulation. Improvement of haptic perception by means of augmenting haptic information feedback to MIS might be promising for patient’s safety.

2.3. The Opinion and Experience of Surgeons with Laparoscopic Bowel Grasper Haptics

Background: In order to develop new and better laparoscopic bowel instruments, that reduces patient risks, the opinions and experience that surgeons have with current laparoscopic bowel grasper haptics is important. In this study we explored this by means of a questionnaire,

Method: A total of 386 online-questionnaires, were sent to laparoscopic surgeons working in European hospitals. They were all members of the European Association of Endoscopic Surgery and perform laparoscopic obesities or bowel surgery. Surgeons where divided into different age and experience groups..

Results: A total of 174 completely filled out forms were analyzed. In total, 16% of the surgeons cannot prevent damage when they pinch too hard, although they (10%) might have seen or felt it. Seven percent of the respondents were not able to see or feel tissue slippage. Whereas 31% can see or feel slippage they cannot do anything to prevent it. Overall, most of the respondents would appreciate technical changes in the laparoscopic bowel graspers to reduce tissue damage. Of all the respondents, 79% maintain that it is necessary to have a new laparoscopic grasper with augmented feedback. The majority of the respondents (77%) would like to have tactile feedback as an indication of the level of pinch force. There are not many differences in the opinions of surgeons at different skill levels.

Conclusion: From the results of the questionnaire and the other comments made by respondents it is evident that research and developments in the field of new laparoscopic graspers should continue.

2.3.1. Introduction

Laparoscopic surgery has many benefits for the patient, such as fewer traumas, shorter hospital stays and reduced recovery times (Cuschieri 1995, Moreno-Egea *et al.* 2005, Roumm *et al.* 2005, Dedemadi *et al.* 2006, Stefanoni *et al.* 2006). However, this technique gives rise to difficulties for the surgeon such as reduced haptics and indirect vision (Stassen *et al.* 2001), which in turn may lead to a higher rate of adverse events (Dankelman *et al.* 2003). During laparoscopic bowel surgery stress injury, which leads to tissue damage (e.g. perforation), pathological scar tissue formation, bleeding, adhesions, and loss of bowel motility may occur when the instrument is pinched with excessive force or when tissue slips from the grasper (Heijnsdijk *et al.* 2002, Westebring-van der Putten *et al.* 2009b).

Many studies are currently being performed to establish the best way of reducing tissue damage during laparoscopic procedures (for a review of this see (Westebring-van der Putten *et al.* 2008b)). One of our own projects concerns laparoscopic grasp control. There we are trying to determine whether augmented feedback in relation to excessive pinch force and tissue slippage during laparoscopic grasping may improve performance. Preliminary tests with augmented feedback containing grasp force information have shown that the accuracy/level of grasping forces has indeed increased. The main aim of the project is thus to find the best kind of augmented feedback in relation to grasp force during laparoscopic grasping. Laparoscopic obesities and bowel surgery is chosen as the applicable field, as the tissue of the bowel is very delicate. Good grasp control is therefore a prerequisite in the correct performance of bowel surgery.

Apart from gaining results from experiments, we are interested in surgeons' opinions and experience with the current laparoscopic graspers during bowel surgery. This way, researchers can develop instruments that fulfil the demands and wishes of the surgeons who are going to use the instruments. Current literature does not provide us with information retrieved from large groups of surgeons. Individual surgeons are asked to provide research groups with their opinion and experiences, although, these opinions are useful they might not represent the opinion of the whole user group. The amount of research done in the field of improving haptics suggest that this need is obvious, however, this has not been confirmed by large user groups. To collect this information, we compiled a questionnaire, which was first approved by the technical committee of the European Association for Endoscopic Surgery (EAES). The questionnaire was distributed to surgeons who use laparoscopic techniques. It included questions on laparoscopic surgery in general, laparoscopic bowel surgery, (augmented) feedback on pinch force information during laparoscopic grasping, involvement in hospital innovation and awareness and participation in research projects devoted to augmented feedback. This article will present the findings of that questionnaire.

2.3.2. Methods

In total, 386 surgeons from different European hospitals (members of the EAES who perform laparoscopic bowel and obesities surgery), were approached by email and asked to fill in a questionnaire via the Internet (developed using NET Questionnaires 6.0).

Apart from the overall opinions of the whole group we were also interested to see whether there were differences in the answers given by surgeons of different ages or levels of experience. We therefore distinguished three categories based on experience in terms of number of operations, experience in terms of years and age. All the surgeons were divided into one of the four levels given within each category (see Table 2.3.1 in the Result section).

The collected data was exported and processed into SPSS 16.0 for Microsoft Windows XP. The questions asked can be found in the appendix. Most questions had a one-answer option. Questions 6, 7, 8 and 10 allowed several answers. With each question it was possible to give additional comment.

To make sure that each respondent used the same definitions, we used the following explanation for tactile and proprioceptive feedback. Tactile perception relates to the perception of pressure, vibration, and texture (also sometimes called discriminative touch or cutaneous sense), and relies on different receptors in the skin (cutaneous mechanoreceptors). Proprioception (haptics) concerns the perception of posture and the position of the limbs, body and head in space and their positioning relative to each other, including the vestibular system, cutaneous sense and kinaesthesia (Widmaier *et al.* 2004).

2.3.3. Results and discussion

A total of 281 surgeons responded. Of the 281 respondents, 174 submitted a completely filled-in questionnaire. This resulted in a completely filled out rate of 45%. The experience level of the surgeons ranged from 80 to more than 10.000 operations and from <5 to 15-20 years of experience. The age of the surgeons ranged from 29 to 69 years. The amount of surgeons that responded is enough to make rough conclusions about their opinion. Although, each new development in this field should check its specific need with the user group. The results can be biased, as it is possible that the surgeons that did not fill the questionnaire are indifference for the topic.

Table 2.3.1. Division in groups of the 174 respondents.

	Respondents (%)	
Experience (no. of operations)	<500	30
	500-1000	17
	1000-2000	20
	>2000	33
Experience (years)	<5	9
	5-10	22
	10-15	28
	15-20	41
Age (years)	< 40	6
	40-50	26
	50-60	40
	>60	28

2.3.3.1. Results from the complete group of respondents

Forty-six percent of the respondents use grasper 1 to grasp bowel tissue, followed by 24% who use grasper 2. Graspers 3,4 and 5 where used by 10,10 and 3% of the respondents respectively and only 7% of the respondents reported using another type of grasper. Grasper 1 was used in our previous studies (Westebring-van der Putten *et al.* 2009a, Westebring-van der Putten *et al.* 2009b, Westebring-Van Der Putten *et al.* 2009c). The answers to this question confirmed that this choice of bowel grasper was suitable for representing the bowel graspers used in practice.

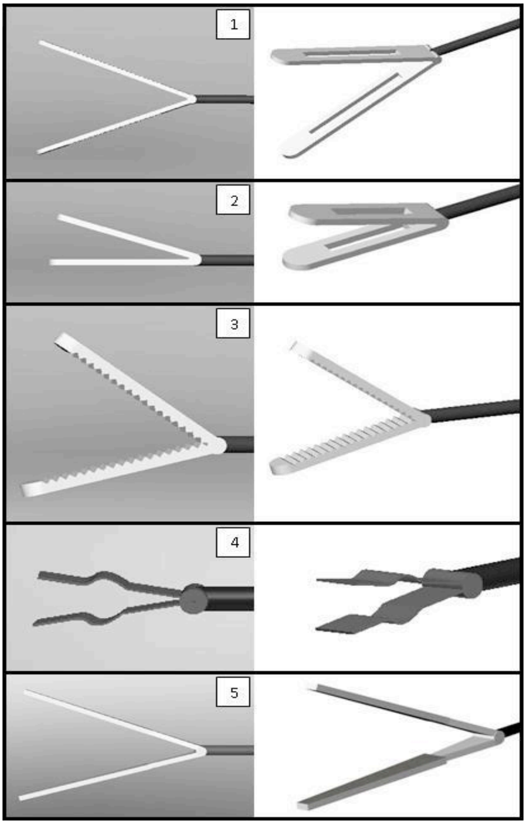


Figure 2.3.1. Images of laparoscopic graspers (see question 2).

From Figure 2.3.2 it can been seen that 51% of the respondents can feel when they apply excessive pinch force to the tissue and are able to adjust the pinch force to prevent damage. In total, 33% of the respondents can see when they apply excessive pinch force and are able to prevent damage. Six percent of the respondents cannot see or feel when they apply excessive pinch force to the tissue. Finally 16% of the surgeons cannot prevent damage although 10% might see or feel it.

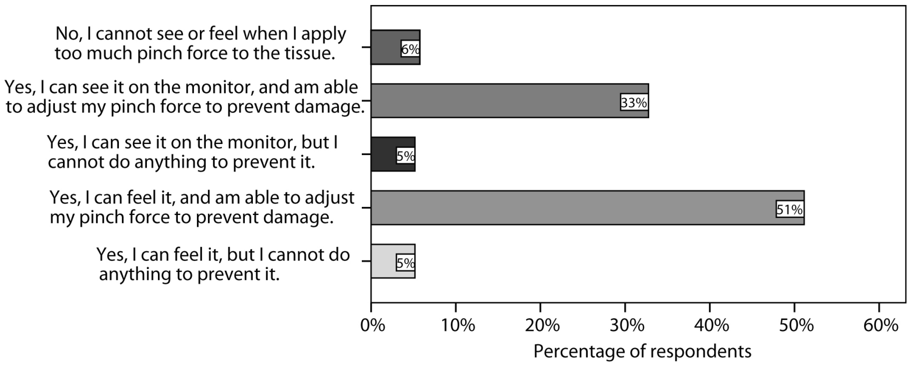


Figure 2.3.2. Respondent awareness of excessive pinch force usage. Answer on question 3. “Do you notice when you are about to apply too much pinch force on the tissue?”

Figure 2.3.3 shows that 32% of the respondents can feel and that 30% can see tissue slippage and are able to prevent it. In total, seven percent of the respondents cannot see or feel when tissue is about to slip. Some 31% of the respondents can see or feel slippage but they cannot do anything to prevent it. The results state that 94% of the respondents indicate that they notice tissue slippage, however, 38% of the respondents indicate that they cannot prevent it. These results show that there is a high percentage of the surgeons who cannot prevent tissue damage through slip. Heijnsdijk *et al.* (2002) discovered during a study carried out during 10 laparoscopic colectomies and 15 cholecystectomies conducted by experienced surgeons that the bowel slipped out of the grasper in 7% of the grasp actions, whereas the gallbladder slipped out in 17% of cases. Thus, it seems that even experienced surgeons have difficulty maintaining an accurate pinch force.

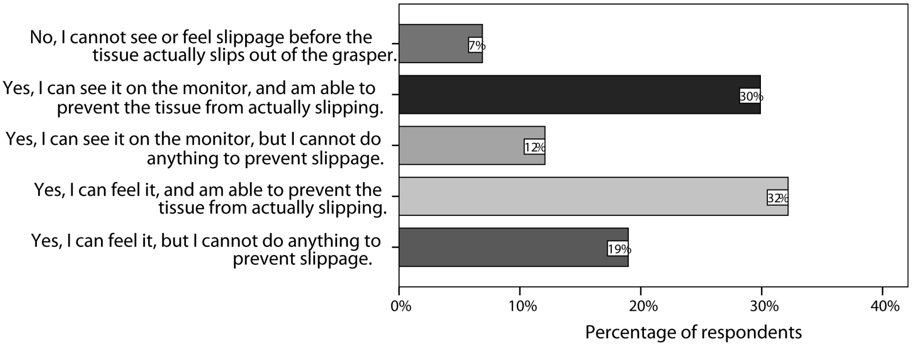


Figure 2.3.3. Respondent awareness of tissue slippage. Answer on question 4. “Do you notice when tissue is about to slip?”

In total, 32% of the respondents are aware of the existence of research projects linked to augmented feedback on pinch force information within laparoscopy and 4%

of the respondents took part in them. For 68% of the respondents this questionnaire was the first time they heard anything about it. This could indicate that surgeons are not concerned about this issue. However, if we look at the questionnaire response rate, we see that surgeons are concerned. Further research into this topic is therefore important. In addition, the results of these studies should be made easily accessible to surgeons.

Ultimately 12% of the respondents had experience with some form of augmented feedback regarding pinch force within laparoscopy. Table 2.3.2 shows, which form of augmented feedback these surgeons, had experience with. Some respondents had experience with more than one form of augmented feedback. The majority used visual (95%) or tactile feedback (81%).

Table 2.3.2. The form of augmented feedback regarding pinch force that respondents had experienced within laparoscopy.

Form of additional feedback	Number of respondents*	% of respondents
Visual feedback	20	95
Audible feedback	0	0
Tactile feedback	17	81
Proprioceptive feedback	7	33
Otherwise, (open response)	0	0

**Twelve percent of the total number or respondents answered question 6 with 'yes'. The number and percentage of respondents out of this twelve percent who used this form of augmented feedback during laparoscopy is indicated.*

Note that some respondents had experienced multiple forms of augmented feedback.

In total, 18% of the respondents had used a form of augmented feedback on pinch force information, during their virtual reality training. Table 2.3.3 shows the form of augmented feedback that the respondents used during virtual reality training. Some respondents had had experience with various forms of augmented feedback during their virtual reality training. However, the majority used visual or tactile feedback.

Table 2.3.3 The form of augmented feedback regarding pinch force that respondents had experienced during virtual reality training.

Form of augmented feedback	Number of respondents*	% of respondents
Visual feedback	19	61
Audible feedback	6	19
Tactile feedback	19	61
Proprioceptive feedback	5	16
Otherwise, (open response)	2	6

**Eighteen percent of the total number or respondents answered question 6 with 'yes'. The number and percentage of respondents out of this eighteen percent who used this form of augmented feedback during laparoscopy is indicated.*

Note that some respondents had experienced multiple forms of augmented feedback.

The results of questions six and seven show that tactile and visual augmented feedback is used in research much more frequently than audible and proprioceptive feedback. This can be explained by the fact that additional audible signals in the operating room will distract the surgeon, as there are so many other sounds already. Augmented proprioceptive feedback is technically more difficult to implement and it will be hard for the surgeon to interpret unless a natural reaction is provoked.

The questionnaire gave the respondents the opportunity to indicate their preferred augmented feedback form as an indication of the levels of pinch force. Figure 2.3.4 shows the preferences of the respondents. Most of the respondents would prefer to use tactile feedback as an indication of the level of pinch force (77%), followed by visual feedback (39%). Only 7% of the respondents do not like to use augmented feedback as an indication of the level of pinch force.

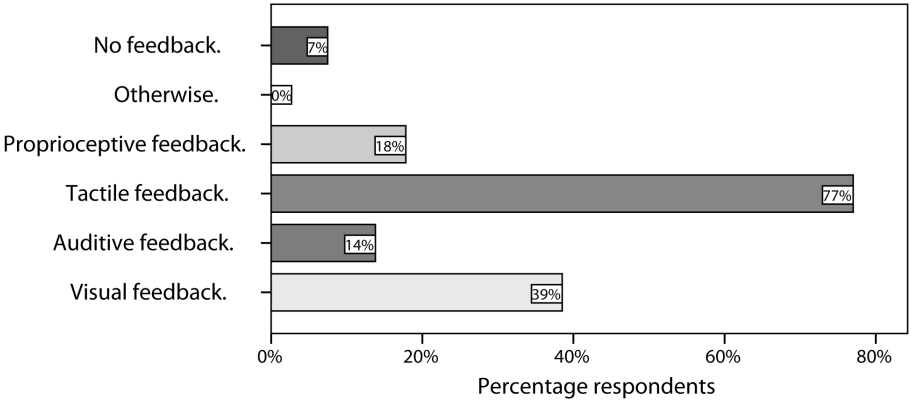


Figure 2.3.4. Preferred form of augmented feedback as indication of the levels of applied pinch force. Answer on question 8. “Which form of feedback would you like to use as an indication of the levels of pinch force ?”

During laparoscopic procedures, 64% of the respondents do not look at their hands while performing laparoscopic surgery, while 7% do look several times, 9% look frequently and 20% regularly look at their hands. When the respondents look at their hands, 30% (n = 19) of them look at the hand position on the handle, 24% (n = 15) look at the fingers on the handle, 49% (n = 31) look at the position of the handle and 21% (n = 13) look at other things, for example the hand position relative to the abdomen, angle of instrument to the abdomen and the open or closed position of the handle. These results show that the handle is not the most suitable place to position a visual augmented feedback display but that it might be appropriate to have a tactile or proprioceptive display on the handle.

Twenty-one percent of the respondents have taken part in the modification and/or development of laparoscopic instruments. Twenty surgeons of that group (56%) initiated the innovations themselves, and 25% (9) of them indicated that a colleague instigated the developments. Manufactures were cited in 19% (7) of cases as being responsible for the modification and/or development of laparoscopic instruments. None of the modifications or developments was enforced by the hospitals. This means that surgeons will use/develop new instruments when they are convinced of the added value with respect to the old instrument.

The respondents were asked if a new atraumatic grasper with additional haptic feedback is necessary. This question was answered with a ‘yes’ by 79% of the respondents. In their reply the respondents emphasized the safety of the grasper and the fact that it will prevent damage. The respondents who indicated that a new atraumatic grasper is not necessary are satisfied with the current laparoscopic instruments. Even though some of the respondents indicated that they notice when tissue is about to slip and that they can prevent it happening, 93 percent would like to have a laparoscopic instrument that provides some form of augmented feedback for slipping tissue. The conclusion therefore is that a new atraumatic grasper with augmented haptic feedback might help to reduce tissue damage.

Finally, 99% of the respondents are open to technical changes in the field of laparoscopic instruments; only 1% of the respondents was not open to changes and indicated that the current laparoscopic instruments are fine. Should this research be continued, 95% of the respondents declared themselves willing to participate in follow-up studies. This could mean that when a new laparoscopic instrument is introduced which contains augmented haptic feedback, a high proportion of the surgeons will want to use it.

2.3.3.2. Results of the categories

There were no major differences in the response between the twelve groups (4 levels in each category). However, there were some minor differences and these are listed below.

Experienced surgeons (1000-2000 operations), use grasper 1 (62%) more frequently than the less experienced ones (33%). More experienced surgeons (>2000 operations or 15-20 years of experience) indicate more frequently (63 and 61% respectively) than surgeons with less than 5 years of experience (19%) that they can feel when they are applying excessive pinch force to the tissue. Regarding the use of visual verification to determine whether they are about to apply excessive pinch force, the difference between these categories is minimal. Less experienced surgeons find it more difficult to prevent tissue damage than experienced surgeons (>2000 operations, 15-20 years experience and >60 age). This means that experience leads to a better interpretation of the task-intrinsic feedback. However, the learning curve for laparoscopic grasp control is long and even experienced surgeons do have difficulty using task-intrinsic feedback.

Surgeons of 60 years and older are not always the persons with the most experience in laparoscopic procedures. In contrast to the others, the category over the age of 60 does not have experience (0%) with virtual reality training regarding augmented feedback on pinch force. This is probably due to the fact that these techniques did not exist when they where being educated. In addition, this category of surgeons looks more at their hands during any given procedure (50% in this category as opposed to 30% in the categories >2000 operations or with 15-20 years of experience). The last minor difference is that less experienced surgeons (<500 operations, <5 years experience or <40 years) indicate not having been involved in new developments compared to the other categories. This is obviously attributable to the fact that less experienced surgeons might think they do not have enough experience to innovate change.

2.3.3.3. Conclusion

The aim of this study was to estimate the opinions and experiences of surgeons with the use of laparoscopic bowel graspers from the point of view of haptics. Thanks to the large number of respondents research and development of new instruments can now address the needs of the surgeons themselves.

In 38% of the cases the damage, according to the respondents, emanates from slip and in 16% of cases damage is attributable to excessive pinch force. This kind of tissue damage has to be reduced, possibly by using a laparoscopic instrument with augmented feedback on the levels of pinch force. The outcome of this study indicates a clear need for research and for the development of a new instrument with augmented feedback on force information and slippage.

2.3.3.4. Appendix: Questionnaire

Laparoscopic operations in general

1. How many years have you been using laparoscopic surgery?
2. Which of the pictures below best represents the laparoscopic grasper you use to grasp bowel tissue? The pictures are presented in Figure 2.3.1.
3. Do you notice when you are about to apply too much pinch force on the tissue?
    - *Yes, I can feel it, but I cannot do anything to prevent it.*
    - *Yes, I can feel it, and am able to adjust my pinch force to prevent damage.*
    - *Yes, I can see it on the monitor, but I cannot do anything to prevent it.*
    - *Yes, I can see it on the monitor, and am able to adjust my pinch force to prevent damage.*
    - *No, I cannot see or feel it when I apply too much pinch force to the tissue.*
4. Do you notice when tissue is about to slip?
    - *Yes, I can feel it, but I cannot do anything to prevent slippage.*
    - *Yes I can feel it, and am able to prevent the tissue from actually slipping.*
    - *Yes, I can see it on the monitor, but I cannot do anything to prevent slippage.*
    - *Yes, I can see it on the monitor, and am able to prevent the tissue from actually slipping.*
    - *No, I cannot see or feel slippage before the tissue is actually out of the grasper.*

Laparoscopic surgery and augmented feedback

5. Are you well informed on research into augmented feedback on pinch force information within laparoscopy?
   - *Yes, I have read studies.*
   - *Yes, I take/took part in similar research.*
   - *Yes, (open response).*
   - *No, (open response).*

The following definitions are used in questions 6 ,7 and 8: Tactile perception relates to the perception of pressure, vibration, and texture (also sometimes called discriminative touch or cutaneous sense), and relies on different receptors in the skin (cutaneous mechanoreceptors). Proprioception (haptics) concerns the perception of posture and the position of the limbs, body and head in space and their positioning relative to each other, including the vestibular system, cutaneous sense and kinaesthesia

6. Do you have experience with a form of additional feedback regarding pinch force within laparoscopy?
   - *Yes, from another research project. This research is about:*
     - *Visual feedback.*
     - *Auditive feedback.*
     - *Tactile feedback.*
     - *Proprioceptive feedback.*
     - *Otherwise, (open response).*
   - *No.*
7. Have you used a form of additional/alternative feedback on pinch force information, during a virtual reality training exercise?
   - *Yes, what kind of feedback have you used?*
     - *Visual feedback.*
     - *Auditive feedback.*
     - *Tactile feedback.*
     - *Proprioceptive feedback.*
     - *Otherwise, (open response).*
   - *No.*
8. Which form of feedback would you like to use as an indication of the levels of pinch force?
   - *Visual feedback.*
   - *Auditive feedback.*
   - *Tactile feedback.*
   - *Proprioceptive feedback*
   - *Otherwise, (open response).*
   - *No feedback.*
9. Do you look at your hands while performing laparoscopic surgery?
   - *Yes, several times (once or twice every 10 minutes) during surgery.*
   - *Yes, frequently (once or twice during every surgical procedure).*
   - *Yes, regularly (but not during every surgical procedure).*
   - *No, never.*
10. When you look at your hands what do you look at?
    - *My hand position on the handle.*
    - *My fingers on the handle.*
    - *The position of the handle.*
    - *Otherwise, (open response).*

Laparoscopic surgery and involvement

11. Have you taken part in the modification/development in laparoscopic instruments?
    - *Yes.*
    - *No.*
12. Who was responsible for the initiation of these changes?
    - *Self initiated.*
    - *Instigated by a colleague.*
    - *Enforced by the hospital.*
    - *Enforced by the manufacturer.*
13. Do you think a new atraumatic grasper with additional haptic feedback is necessary?
    - *Yes, because (open response).*
    - *No, because (open response).*
14. Are you open to technical changes in the field of laparoscopic instrumentation?
    - *Yes, I am open to changes and their applications.*
    - *Yes, I am open to changes, will probably continue to use the current laparoscopic instruments.*
    - *Yes, (open response).*

      No, I am not open to changes, the current laparoscopic instruments are working fine.
    - *No, (open response).*
15. Are you willing to take part in follow-up research, possibly including a test with a prototype?
    - *Yes, you may contact me in the future.*
    - *No, I am not interested.*

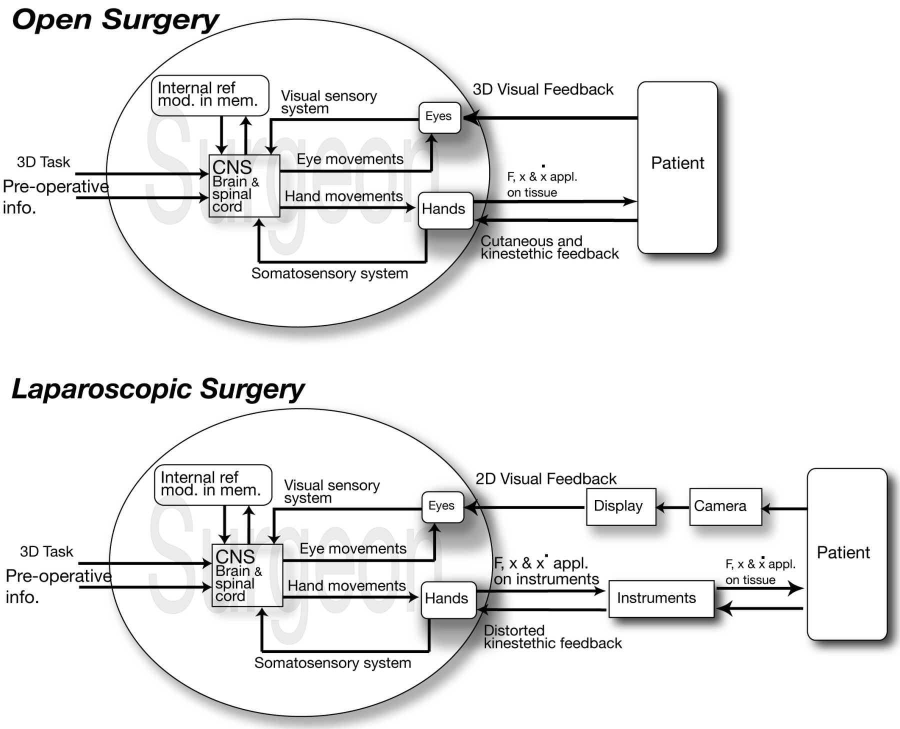


Figure 3. Simplified closed-loop control diagram of a surgeon performing open and laparoscopic surgery. It can be seen that intrinsic feedback is reduced

Chapter 3. Barehanded compared to tool grasping

This chapter provides insight into how accurately a human can sense forces and tactile information through a laparoscopic instrument during a tissue-grasping task. At present, it is not clear which factors are used to control the force applied to the tissue by the instrument. Unlike in the case of barehanded grasping, this chapter provides insight into the factors that influence the amount of force applied to the tissue by use of laparoscopic instruments.

On the basis of the information given in Chapter 2, a schematic representation of a surgeon performing open and laparoscopic surgery can be given in the way depicted in Figure 3. The surgeon controls the forces applied to the tissue via a closed–loop control system.

Section 3.1 is published as:

” Effect of laparoscopic grasper force transmission ratio on grasp control. Surgical Endoscopy and Other Interventional Techniques 2009: 23(4): 818-824.”

Section 3.2 is published as:

”Force feedback requirements for efficient laparoscopic grasp control. Ergonomics 2009:52(9): 1055-66.”

3.1. Effect of Laparoscopic Grasper Force Transmission Ratio on Grasp Control

Surgeons may cause tissue damage as a result of incorrect laparoscopic pinch force control. Unpredictable tissue and grasper properties may cause slips or ruptures. This study investigated how different forms of haptic feedback influenced the ability to generate a safe laparoscopic grasp while pulling tissues of variable stiffness using graspers with different force transmission ratios. The results will help define design requirements for training facilities and instruments.

Ten participants lifted an object either barehanded, with tweezers, or with one of two laparoscopic graspers until they where able to complete 5 consecutive safe lifts under different tissue stiffness conditions. Participants were presented with indirect visual feedback of pinch force, object-location and target-location..

Lifting with instruments (tweezers or graspers) required 4.5 to 14.5 times as many practice trials than barehanded lifts, where no slips were recorded. Additionally, slips occurred more often with decreasing force transmission ratio of the graspers, and with increasing tissue stiffness. Maximal pinch force when lifting with instruments was higher than lifting barehanded (26-60%), irrespective of stiffness conditions. Using a grasper, the slip-margin was often not high enough in the stiffest condition resulting in slippage of up to 84%.

Without the direct tactile feedback, which occurs with normal skin-tissue contact, participants using graspers have trouble anticipating slippage when lifting tissue with variable stiffness. Performance drops with decreased force transmission ratio of the instrument and increased tissue stiffness. Furthermore, the pinch forces are not adapted to the variable stiffness conditions; the same pinch force is applied irrespective of tissue stiffness. It takes participants longer to learn a safe laparoscopic grasp compared to barehanded lifts. Additionally, to perform safe laparoscopic surgery, care should be taken when using graspers with a low force transmission ratio.

3.1.1. Introduction

During Laparoscopic tissue manipulation, surgeons have to grasp organs and tissues with variable properties, one of which is stiffness. Stiffness is important as it determines the magnitude of the force required by a surgeon to pull and pinch to manipulate the tissue. Incorrect pinch force control causes tissue slippage and or damage (Westebring-van der Putten *et al.* 2008b). Heijnsdijk *et al.* (2002) found that during a study of 10 laparoscopic colectomies and 15 cholecystectomies, the bowel and the gallbladder slipped out of the grasper in 7% and 17% of the grasp actions respectively. Thus, it seems that even experienced surgeons have difficulties maintaining an accurate pinch force.

Accurate pinch force control relies to a great extent on haptic perception, the combination of tactile perception (through tactile mechanoreceptors in the glabrous skin of our fingers) and kinesthetic perception (through muscle, tendons and joint sensory receptors). If an unpredictable load force (unknown tissue stiffness) occurs when grasping barehanded, humans are able to adjust their pinch force to prevent slip while avoiding exceedingly large forces (Johansson and Westling 1987a, Winstein *et al.* 1991, Johansson *et al.* 1992, Cole and Johansson 1993, Jenmalm and Johansson 1997, Turrell *et al.* 1999, Jenmalm *et al.* 2000, Monzee *et al.* 2003).

During laparoscopic surgery the surgeon's hands are not directly in contact with the tissue, but with the handle of the laparoscopic grasper. Therefore, next to visual cues, the only way to receive information about applied pinch forces is through the forces and positions transmitted to the grasper handle. The transmission of forces from the tip of the instrument to the handle is limited and significantly disturbed, depending on the type of grasper and the kind of manipulation action (e.g. trocar friction, abdominal wall resistance, scaling factors, mechanical construction and efficiency) (Tendick *et al.* 1993, Sjoerdsma *et al.* 1997, Picod *et al.* 2005, van den Dobbelsteen *et al.* 2007, Westebring-van der Putten *et al.* 2008b, Zhou *et al.* 2008).

It is unclear which factors contribute to the surgeon's ability to appropriately adjust pinch force using a laparoscopic grasper if the load force is unpredictable. A safe grasp can be maintained if the internal mental reference model about the instrument and its interaction with the grasped object is correct. Mental models are used to estimate the input and output relations of systems and transform sensory signals into motor commands. Mental models have been generated for all motor actions and can be modified as new environments (for example new tools) are encountered (Witney 2004). The level of haptic feedback is thought to play a role in generating a correct mental reference model.

Therefore, the aim of this study is to investigate how different levels of haptic feedback influence a participant's ability to generate a laparoscopic grasp with no excessive force and no slip while pulling an object of unknown stiffness. To compare, different levels of haptic feedback, the experiment will test grasp control using two commercially available laparoscopic graspers, anatomical tweezers, and bare hands. The laparoscopic graspers have different frictional losses and different force multiplication factors. Inexperienced participants were used, as they have no preconceived mental model for laparoscopic tissue handling. This research contributes to the knowledge about the effects of limited and distorted force transmission of laparoscopic graspers on grasp control and will help define requirements for training facilities and instruments.

3.1.2. Method

Participants

Ten right-handed participants with no laparoscopic experience aged 21-41 were recruited for this study. The participants were not aware of the purpose of the experiment.

Task

Participants had to grasp an object either barehanded between thumb and index finger (H), with tweezers (T), or with one of two laparoscopic graspers (G_{HFTR} and G_{LFTR}) and move it to a predefined target location.

Experimental setup

A robotic device OMEGA (Force Dimension, Switzerland) was used to generate computer-controlled load forces to the object to be grasped to simulate stretching of different tissue types. The object was randomly subjected to three different stiffness profiles of 80, 120 and 160N/m. In human tissue elasticity only becomes noticeable once stretched, so the object was attached to a slack wire (Figure 3.1.1) in order to better simulate tissue grasping. Therefore, when moving the object, the wire first had to be tautened before the object was subjected to the different forces.

The object used was an aluminium wedge (17x 30 mm with an angle of 15°) in order to generate pinch-surfaces parallel to the jaws of the graspers and tweezers. The wedge was covered with a layer of rubber (0.5mm) and attached, with the wire, to the endplate of the Omega Figure 3.1.1 and Figure 3.1.2). To measure pinch forces, two thin (0.2 mm) FlexiForce force sensors (Tackscan, South Boston, MA, USA) were inserted into the pinch-surfaces between the aluminium and rubber. The sensors were covered with a thin steel plate (0.1mm) in order to ensure an even distribution of the pinch force.

The participant had no sight of the object in order to generate similar visual feedback in all four test-conditions. A curtain was used to prevent the participant from seeing the object in condition H and T and a Pelvi-trainer in condition G_{HFTR} and G_{LFTR} (Figure 3.1.2). Visual feedback on both the object and target locations was graphically presented to the participant on a monitor. A blue dot (diameter 20 mm) represented the grasped object and a red dot represented the target location.

The laparoscopic graspers were placed through a trocar (type Xcel 5, Ethicon ENDO-Surgery Inc., Cincinnati, Ohio) with low friction to minimize the disturbance of forces caused by other elements (van den Dobbelsteen *et al.* 2007). Figure 3.1.1 shows the experimental set up for the condition of a laparoscopic grasper.

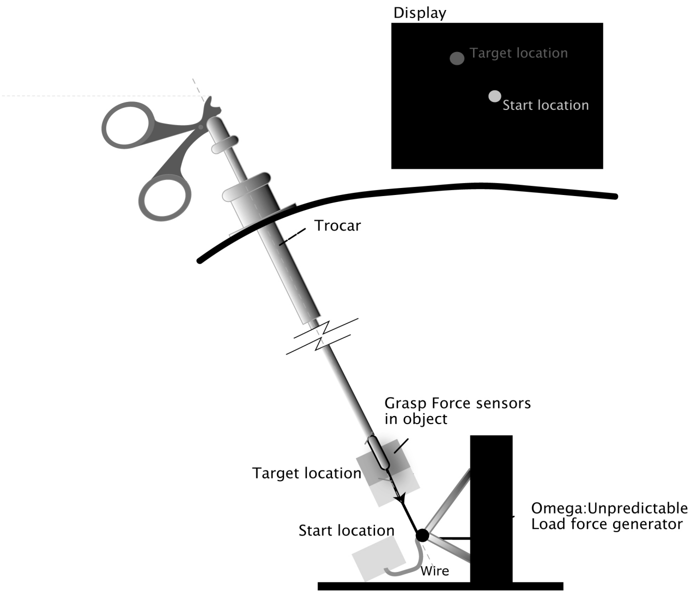


Figure 3.1.1. Experimental setup and feedback screen for the condition of a laparoscopic grasper.

Figure 3.1.2. Omega used to simulate different tissue stiffness conditions. The object to be grasped was attached to the endplate (A) with a slack wire.

Instruments used

Two reusable Laparoscopic graspers (type 33321 MH and 33321 C Karl STORZ) and a pair of anatomical tweezers were used. The force transmission ratios (combination of frictional losses, force multiplication factors and hysteresis) of each grasper were determined by measuring pinch force at the tip when handle forces were varied (with a fixed jaw opening of 15 degrees). Figure 3.1.3 shows that there were large differences in the force transmission ratio of the two laparoscopic graspers. In order to generate the same tip force, the grasper with a high force transmission ratio

(G_{HFTR}) required less effort from the participant than the grasper with a low force transmission ratio (G_{LFTR}). The surface areas of the instrument tips were approximately the same for all instruments (tweezers or laparoscopic graspers).

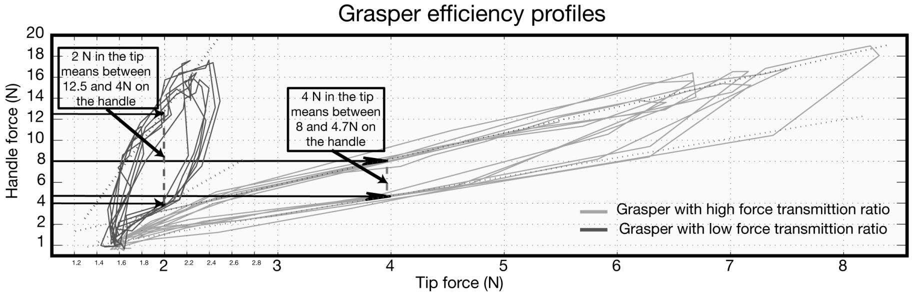


Figure 3.1.3. Tip and handle forces of the graspers with a high force transmission ratio (33321 MH) and with a low force transmission ratio (33321 C). Tip and handle forces were measured during several cycles of squeezing and releasing of the handle (with a fixed jaw opening of 15 degrees).

General procedure

The experimental setup was individually ergonomically adjusted to the participants. The participant stood in front of the setup and grasped the object either barehanded (H) (thumb and index finger), with tweezers (T) or with one of the two laparoscopic graspers (G_{HFTR} and G_{LFTR}) and moved it to a predefined target location Figure 3.1.1). After the lift, they had to keep the object at the target location for 2 seconds before releasing the object. To guarantee that the pinch-surface was at the predefined starting position before the participant pinched and pulled, the experimenter placed the object in the participant's instrument or hand each time the participant had to re-grasp it.

In order to make the movement in this experiment realistic, the target location was placed in such a way that the object had to be moved over a distance of 50 mm along a travel-path 60 degrees relative to the horizontal plane which is similar to reported pull directions of the colon (de Visser *et al.* 2002). To prevent the participants from automatically moving to the target location, the target location was changed randomly during the trials (0 mm, 5 mm to the left, or 5 mm to the right relative to the sagittal plane). The different pull forces required for reaching the target location were 4, 6 and 8 N, respectively.

The participants were instructed to handle the object as if it were very delicate tissue. In order to prevent damage, the participants had to lift and pinch the tissue with the minimal force required to prevent slippage. To prevent the participant from adapting a strategy of applying as much force as possible to prevent slippage, a maximum pinch force level of 10 N was allowed. This was the level at which Heijnsdijk *et al*. (2003) found perforation forces of a small human bowel of 10.3 +/-

2.9 N. Visual feedback indicated whether the pinch force was approaching 10 N by changing the colour of the dot representing the object gradually from blue to white with increasing force.

It was assumed that a correct mental model had been generated after a participant had performed five safe lifts in a row. A safe lift was defined as a lift without slip and without exceeding 10N of pinch force. The task had to be repeated till five consecutive safe lifts were performed. The four different grasp conditions were performed randomly with a resting period of five minutes in between.

Analyses

For each of the four conditions, the number of safe and unsafe lifts performed by the participant before completing five consecutive safe lifts were counted and defined as the number of attempts. The number of slips were also noted. In order to see whether the variable tissue stiffness influenced the number of slips, the percentage of slips within the attempts were calculated for each stiffness condition.

To estimate the pinch force used by the participant, the output of the two force sensors were averaged. The inaccuracy of the combined output of the two sensors was about 5%. To determine the maximal force levels used by the participants, the average peak pinch force during the 5 safe lifts was calculated.

Statistics

A Friedman test was used to compare the number of required attempts and the percentage of slip during the trials between the different conditions. The influence of the variable tissue stiffness was tested as well. A two-way ANOVA was used to compare the mean maximal pinch force used during the five consecutive safe lifts and the influence of the variable tissue stiffness. Multi-comparison procedures using Tukey's honestly significant difference criterion were preformed to see which pairs of means were significantly different, and which were not. Significance was set at p=< 0,05. If the data was not normally distributed, medians were used and otherwise the average and standard deviation were calculated for each condition.

3.1.3. Results

3.1.3.1. Influence of instrument type

Compared to lifting barehanded (H: 0 attempts (median)), the participants required significantly more attempts using one of the three instruments (T: 4,5, G_{HFTR}: 10, and G_{LFTR}: 14.5 attempts (median)) before performing 5 consecutive safe lifts (Friedman Chi^2=18.09, df=3 and p<0.001). In condition G_{LFTR} the participant required significantly more attempts than in condition T (Figure 3.1.4).

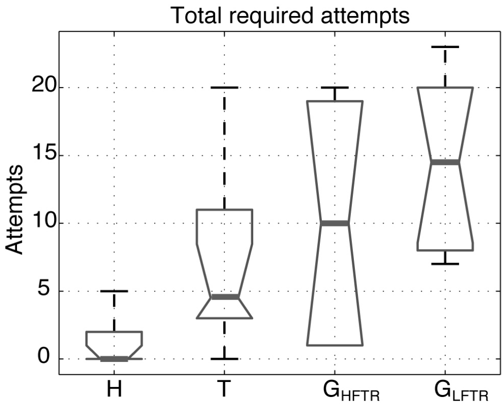


Figure 3.1.4. Total required attempts during the practice period. Data are presented as notched box and whisker plots, where every box has a line at every quartile, median, and upper quartile values. The whiskers are presented as lines that extend from each end of the box in order to show the extent of the rest of the data. The notches represent the 95% confidence interval for the median. Boxes whose notches do not overlap are significantly different ($p<0.05$).

The participants experienced significantly more slips using one of the three instruments (T: 4.5%, G_{HFTR}: 28%, G_{LFTR}: 51% of the total attempts required (median)) (Friedman $Chi^2 = 20.7$, df=3 and $p<0.001$), than when lifting barehanded (H: 0%). In condition G_{LFTR} the participants had significantly more slips than in condition T. (Figure 3.1.5).

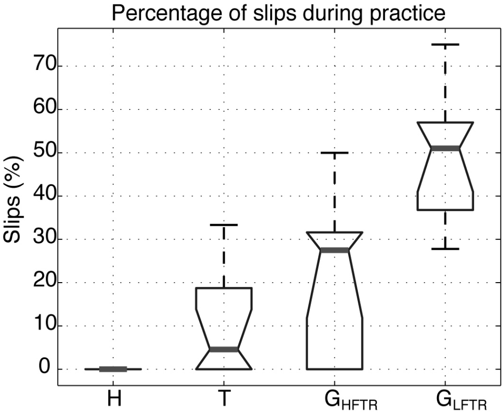


Figure 3.1.5. Percentage of slips during the practice period. Data are presented as notched box and whisker plots, where every box has a line at every quartile, median, and upper quartile values. The whiskers are presented as lines that extend from each end of the box in order to show the extent of the rest of the data. The notches represent the 95% confidence interval for the median. Boxes whose notches do not overlap are significantly different ($p<0.05$).

3.1.3.2. Influence of the variable stiffness

The influence of the variable stiffness conditions on the percentage of slips and on the average maximal pinch force applied to the object during the 5 safe lifts is presented in Table 3.1.1. The maximal forces did not significantly differ between the objects with different simulated stiffness conditions. Pinch forces used during condition G_{HFT_R} and T were significantly higher than in condition H (F=8.2 p<0.001).

Table 3.1.1 Influences of the variable tissue stiffness on the average maximal pinch force during the five safe lifts and the percentage of slips during the required attempts.

	Condition	***H***	***T***	G_{HFTR}	G_{LFTR}
Average maximal pinch force N(sd)	80 N/m	3.5(0.7)	5.1(2.1)	5.6(1.7)	4.4(1)
	120 N/m	3.9(1.2)	5.6(1.8)	5.1(1.2)	4.6(0.9)
	160 N/m	5(1.4)	5.1(1.3)	5.6(1.5)	5.2(0.9)
Average percentage of slips during practice	80 N/m	0%	0%	11%	14%
	120 N/m	0%	3%	27%	61%
	160 N/m	0%	35%	41%	84%

For condition T and G_{HFTR} the percentage slips during the pulls of the stiffest object differed significantly from the pulls of the object with the lowest stiffness (p=0.024 and p=0.018 respectively). The percentage slips during the lifts of the object with a stiffness of 120 N/m did not differ from the other two. For condition G_{LFTR} the percentage of slips during the pulls of the object with a stiffness of 120 and 160 N/m significantly differed from the pulls of the object with the lowest stiffness (p<0.001).

3.1.4. Discussion

The aim of this research was to investigate how different forms of haptic feedback influence the ability to generate a safe laparoscopic grasp while grasping an object of unpredictable stiffness. The type of instrument (barehanded, tweezers or laparoscopic graspers with a high and low transmission ratio) used to lift the object and the different stiffness profile influenced slip occurrence and the amount of force applied. Results show that the number of trials required to perform 5 consecutive safe lifts was higher when using instruments than when lifting barehanded. Furthermore, slips occurred more often when the force transmission ratio of the laparoscopic grasper was lower. No slippage occurred when lifting barehanded; when using an instrument, more slips occurred as the stiffness of the object increased.

We defined slip margin as the difference between the exact slip force and the force used to prevent slip. The amount of force used to prevent slips compared to the slip force was higher when lifting with the aid of instruments than when lifting barehanded (26-60%). This did not differ for the different stiffness conditions. The fact that the slip margin was not adjusted to the variable object stiffness demonstrates that when grasping an object with the aid of instruments (tweezers or laparoscopic graspers) load force is not taken into account: however much load is applied, the pinch force remains the same. The slip margin, therefore, was often not great enough in the stiffest condition and resulted in slippage of up to 84% of the required attempts during condition G_{LFTR}.

The results of condition H are consistent with results from studies in which objects were lifted barehanded and where load forces were changed to induce pinch force modifications. The pinch force modifications were in phase with the changes in load force (Flanagan and Tresilian 1994); slips rarely occurred as the pinch force exceeded the minimum required force to prevent slippage by a slip margin determined by the skin object friction (Johansson and Westling 1984). Literature shows that a lack of cutaneous sensation of applied pinch force generally results in a higher slip margin. However, the pinch force is reduced during a static hold period (Augurelle *et al.* 2003). The cause of the slips in this study where partly due to this reduction in force during the static hold period. In general, a high slip margin can lead to unacceptably high forces being applied to the tissue during laparoscopic surgery, or to unwanted slips resulting from the reduction in force during the static hold period.

This study suggests that, as haptic perception is distorted by instruments (tweezers and laparoscopic graspers), it is more difficult to control a safe grasp. Haptic feedback can be divided in kinesthetic feedback and tactile feedback. All three instruments used in this study considerably disturb tactile feedback, as there is no contact between tissue and the cutaneous sensors in the skin. As the hands are in contact with the instrument handle, slippage has to be detected by movements, forces and vibrations distributed by the instrument handle as a result of object movement in the tip of the instrument. The cutaneous sensors in the skin can detect pressure and vibrations of the handle, and sensors in the muscles and joints can detect force and position changes. However, the results show that the participants could not timely react to this limited amount of haptic feedback and could often not prevent slippage using an instrument (tweezers or laparoscopic grasper).

Kinesthetic feedback distortion can be attributed to the following disturbance factors: trocar friction, abdominal wall resistance, scaling factors, mechanical construction and efficiency (Westebring-van der Putten *et al.* 2008b). From the three instruments used in this experiment, tweezers caused the least kinesthetic distortion. However, the maximal pinch force, the number of attempts required, and the percentage of slips resulting from the use of tweezers was similar to that of the grasper with a high force transmission ratio. This shows that the effect of haptic distortion on performance using these two instruments is comparable. In real surgery, however, the distortion of the transmission of haptic information for laparoscopic graspers is greater than for tweezers. The reason for this is that tweezers are used in an open setting without disturbing factors such as abdominal wall thickness, which can vary enormously in laparoscopy. Compared to the other instruments, the grasper with a low force transmission ratio provided less feedback on force, therefore it was even more difficult to control pinch forces.

These results lead to the expectation that the slip margin would be higher in condition G_{LFTR} than in condition G_{HFTR} and T. This, however, was not found as in condition G_{LFTR} it was almost impossible to exceed the 10N of pinch force: to achieve a force of 10 N in the tip extreme force (~133N) on the handle is required (see Figure 3.1.3). As a result of these extreme forces on the handle, it is possible that minor changes in handle position (due to slippage) were not noticed. Additionally, pain sensation could be the cause of disregarding tactile information provided through the handle, due to the inhibition of cutaneous sensors. In condition G_{LFTR}, participants complained of sore hands due to high handle forces, even after a holding period of only two seconds.

Heijnsdijk *et al.* (2004b) evaluated the effects of differences in force transmission ratio of laparoscopic forceps and concluded that the efficiency is dependent on the task being performed. While a low force transmission ratio is sufficient for tasks requiring little movement of the forceps such as grasping and holding tissue, a high force transmission ratio is required for tasks requiring repeated movement of the forceps. In our experiment, the G_{LFTR} grasper caused a significant amount of slippage when the participant had to make a lift, however, the maximum pinch force applied was acceptable. In a time-action analysis study in real surgery Heijnsdijk et al (2002) found that in 89% of time, the colon was clamped for less than 1 min. The maximum clamping time was 7 min for the colon, and 55 min for the gallbladder (often using an instrument handle with ratchet). This suggests that graspers with a low force transmission ratio are suitable in situations where the tissue is very elastic, as the tissue does not have to be moved and the tissue is not held for a lengthy period. Literature shows that these conditions are rare during surgery (Heijnsdijk *et al.* 2002). Therefore, to perform safe surgery, the use of these laparoscopic graspers should be avoided. As wear can cause the force transmission ratio of laparoscopic graspers to decrease, extra care should be taken when using older non-disposable laparoscopic graspers.

In this study we did not provide the participant with a direct view of the instrument tip whilst holding the object. In surgery, the surgeon can view the instrument tip holding the tissue on a monitor, and tissue deformation can help the surgeon determine the pinch-force required. However, if the tip is not visible the surgeon has to rely on haptic information to control pinch forces. Inexperienced surgeons find it difficult to use visual cues because they have not been trained to use these as an indication of pinch force, as the endoscopic view differs from the view in an open setting.

These findings are of value when designing new graspers or developing training facilities. This study demonstrates that the greater the amount of haptic feedback (as in tweezers and the grasper with a high force transmission ratio) the quicker the development of a mental model required to apply a safe grasp; this results in less practice time. In order to prevent slippage, improved feedback on the minimal force required might also help to reduce practise time.

3.1.4.1. Conclusion

When grasping tissue with a variable stiffness, participants need 10 to 14.5 times more trials to achieve a safe grasp with a laparoscopic grasper, than barehanded. Without tactile feedback, which results from normal skin-tissue contact, participants have trouble anticipating slippage during lifts of tissue with variable stiffness. Furthermore, when using a laparoscopic grasper, the pinch forces applied are not adjusted to suit the variable stiffness conditions. This is why the same pinch force is applied irrespective of the tissue stiffness. Applying these results to the field of laparoscopic surgery, these experiments demonstrate that to improve laparoscopic surgery safety, care should be taken when using graspers with a low force transmission ratio.

3.2. Force feedback requirements for efficient laparoscopic grasp control

Statement of relevance

Much is known about grasp control during barehanded object manipulation, especially the control of pinch forces to changing loading, whereas, little is known about force perception and grasp control during tool usage. This knowledge is a pre-requisite for the ergonomic design of tools, which are used to manipulate objects.

During laparoscopic grasping, tissue damage may occur due to use of excessive grasp-forces and tissue slippage, whereas in barehanded grasping, humans control their grasp to prevent slippage and use of excessive force (safe-grasp). This study investigates the differences in grasp-control during barehanded and laparoscopic lifts. Ten novices performed lifts in order to compare pinch-forces under four conditions: barehanded, using tweezers, a low-efficient grasper, and a high-efficient grasper. Results showed that participants increased their pinch-force significantly later during a barehanded lift (at a Pull-force level of 2.63N) than when lifting laparoscopically (from Pull-force levels of 0.77 to 1.08N). In barehanded lifts all participants could accomplish a safe-grasp, whereas in laparoscopic lifts excessive force (up to 7.9N) and slippage (up to 38% of the trials) occurred frequently. For novices, it can be concluded that force feedback (additional to the hand-tool interface), as in skin-tissue contact, is a pre-requisite to maintain a safe-grasp.

3.2.1. Introduction

During laparoscopy (Minimally Invasive Surgery in the belly alcove), grasping different tissue types may result in stress injury, which leads to tissue damage (e.g. perforation), pathological scar tissue formation, bleeding, adhesions, and loss of bowel motility (Kalff *et al.* 1998, Anup and Balasubramanian 2000, Marucci *et al.* 2000b, Heijnsdijk *et al.* 2002). In the past decade, the number of laparoscopic procedures has increased significantly. By using long and slender laparoscopic instruments, surgeons can operate through small incisions in the skin reducing both risk of infection and recovery time (Cuschieri 1995, Moreno-Egea *et al.* 2005, Dedemadi *et al.* 2006). Despite these advantages for the patient, laparoscopic surgery also brings difficulties for the surgeon (Stassen *et al.* 2001) that can lead to a higher degree of errors and complications (Westebring-van der Putten *et al.* 2008b). One of the issues is the lack of haptic feedback the surgeon receives. Slip and excessive pinch force are the main causes of injuries induced by graspers. The ideal grasping instrument holds tissue securely without damaging it (a safe grasp). In order to design instruments and training facilities to improve surgical safety, it is important to understand how humans control their laparoscopic grasp.

Grasping is defined as a pinch and pull combination. In order to safely grasp tissue, the combination of the pinch and pull force levels applied by the instrument to the tissue should be within a certain safe area (de Visser 2003). This safe area is different for each instrument and tissue combination as they each have their own mechanical properties (Figure 3.2.1). The boundaries of the safe area are formed by the damage-line and the slip-line. The damage-line is the boundary above which a certain pinch/pull force combination damages the tissue. The slip-line is the boundary below which a certain pinch/pull force combination causes the tissue to slip. A surgeon should therefore, stay within the safe area when grasping tissue. Factors that contribute to a safe grasp include: jaw properties, the mechanical properties of the tissue grasped, and pressure applied to the tissue through the instrument.

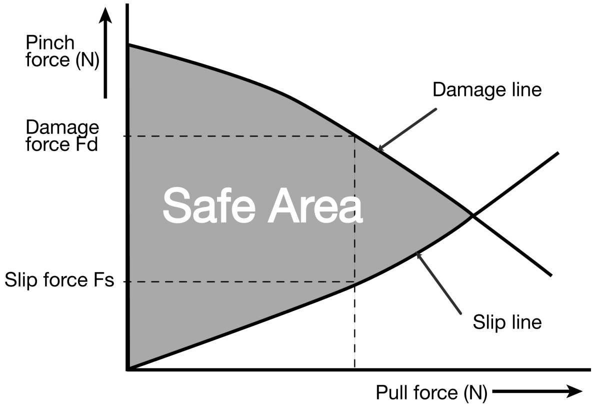


Figure 3.2.1. Safe area bounded by slip and damage forces. Figure adapted from de Visser (2002).

Much research has been carried out on jaw design (Frank and Cuschieri 1997, Marucci *et al.* 2000a, Shakeshaft *et al.* 2001, de Visser 2003, Heijnsdijk *et al.* 2005) showing how jaw design can contribute to increase the safe area. A number of factors are known to influence the size of the safe area: an increase in the area of contact contributes to grip security, hence fenestration of the jaws does not contribute to a more secure grip (Heijnsdijk *et al.* 2005); wave patterns on jaws produce less tissue trauma then teeth (Marucci *et al.* 2000a); and curved edges moderate high tip pressures (Shakeshaft *et al.* 2001).

Mechanical properties of tissues also differ greatly from each other; tissue stiffness in particular can vary enormously. In addition, some tissues, like bowel tissue, are more vulnerable than others and therefore have to be handled with extreme care.

A surgeon can adjust the pressure applied to the tissue through the instrument; however, the accuracy of this action depends on the surgeon's ability to perceive force exerted on the tissue. In an ideal situation surgeons are able to perceive whether or not they are in the safe area when grasping tissue laparoscopically. However, the skin of the fingers (with tactile mechanoreceptors that encode the load rate in barehanded grasping) is not directly in contact with the tissue but with the handle of the laparoscopic instrument. Therefore, the only way to receive information from the grasped tissue to control the grasp, are forces and positions translated to the instrument handle. According to the percentage of slippage (7 to 17%) (Heijnsdijk *et al.* 2002) and amount of tissue damage (Kalff *et al.* 1998, Anup and Balasubramanian 2000, Marucci *et al.* 2000b, Heijnsdijk *et al.* 2002) reported in the literature, it seems that surgeons have difficulties determining the safe area and controlling pinch forces during laparoscopic grasping. Distortion of haptic information feedback is responsible for a lack of perception. Tactile perception is distorted as a result of indirect tissue contact, and kinesthetic feedback is distorted by factors like trocar friction, abdominal wall resistance, scaling factors, mechanical construction and efficiency of the instrument (Westebring-van der Putten *et al.* 2008b).

Research shows that during barehanded tissue grasping people unconsciously perceive the safe area and are able to maintain a safe grasp automatically (Johansson *et al.* 1982, Westling and Johansson 1984, Westling and Johansson 1987, Johansson and Westling 1988, Forssberg *et al.* 1991, Johansson *et al.* 1992, Johansson and Cole 1994, Johansson 1998). Using somatosensory information related to the pulling forces the pinch force can be modulated automatically during an object lift. It is clear that when the pull force is increased during an object lift, the pinch force also has to increase to prevent slippage. In order to stay in the safe area the amount of maximum pinch force allowed decreases when pull force increases as can be seen in Figure 3.2.1. When cutaneous sensors in the fingertips are blocked (as in local ring-block anaesthesia of the index and thumb) humans can no longer control their grasp efficiently, and slippage occurs frequently during barehanded object lifts (Augurelle *et al.* 2003).

Typical trajectories of the changes in pinch forces during a barehanded object lift have been reviewed (Johansson and Westling 1984, Johansson and Westling 1987a, Johansson and Westling 1987b, Cole and Abbs 1988). Pinch force responses are initiated after a brief delay. The response to the increasing pull force is characterized by an initial fast pinch force increase termed the 'catch-up' response, which compensates for the response delay (Johansson *et al.* 1992, Cole and Johansson

1993). The pinch force adequately matches load demands by the end of the catch-up response. In lifts with longer lasting pulling phases (amplitude greater than or equal to 2 N), the catch-up response is followed by a 'tracking' response, during which the pinch force increases in parallel with the pull force and maintains an approximately constant force ratio that prevents frictional slips (Johansson *et al.* 1992, Cole and Johansson 1993). The pinch force during the hold phase is linearly related to the load force, with an intercept close to the pinch force used prior to the loading (Johansson *et al.* 1992, Cole and Johansson 1993). Whether our ability to actively adjust a stable grasp during barehanded tissue lifts is still present during lifts with the aid of a laparoscopic grasper is unknown. Therefore, it is valuable to compare important parameters of the trajectories of the changes in pinch forces during a laparoscopic object lift with a barehanded lift.

The aim of this study was to investigate the trajectory of the changes in pinch force during object lifts conducted with the aid of laparoscopic graspers, and compare them with the trajectory of changes in pinch forces during a barehanded lift. Furthermore, the influence of the mechanical efficiency of the laparoscopic grasper on performance was investigated, as different instruments transmit haptic information differently.

3.2.2. Method

Participants

Ten right handed participants (5 male and 5 female) without laparoscopic experience (employees and students of the Technical University Delft) participated in this study. Their ages ranged from 21-41 years. The participants were naïve with respect to the purpose of the experiment. Data of one participant had to be excluded as data was not collected properly due to technical issues.

Task

Each participant had to grasp an object, either barehanded between thumb and index finger (H), with tweezers (T), or with one of two laparoscopic graspers, and move it to a predefined target location. The participants were instructed to handle the object as if it was very delicate tissue and move the object with as little pinch force possible, to prevent slippage.

Experimental setup

Computer-controlled load forces acting on the object to be grasped were generated using a robotic device, OMEGA (Force Dimension, Switzerland). To simulate stretching of different tissue types, the Omega generated an unpredictable, force (to simulate different stiffness profiles) for the participants. The object was randomly subjected to three different stiffness profiles of 80, 120 and 160N/m. In order to simulate the grasping of human tissue, where elasticity only becomes noticeable once stretched, the object was attached to a slack wire (Figure 3.2.2). Therefore, when moving the object, the wire had to be tightened before the object was subjected to the different forces.

The object used was a wedge constructed of aluminium (17x 30 mm with an angle of 15°) in order to generate pinch-surfaces parallel to the jaws of the graspers and tweezers. The object was covered with a layer of rubber (0.5mm) and attached, with the wire, to the endplate of the Omega (Figure 3.2.2 and Figure 3.2.3). To measure pinch forces, two thin (0.2 mm) FlexiForce force sensors (Teckscan, South Boston, MA, USA) were inserted into the pinch-surfaces between the aluminium and rubber. The sensors were covered with a thin steel plate (0.1mm) in order to distribute the pinch force evenly.

In order to generate similar visual feedback in all four test-conditions, the participant had no sight of the object. To prevent the participant from seeing the object, a curtain was used in condition H and T, and a Pelvi-trainer in condition LG and HG (Figure 3.2.3). Visual feedback on object and target locations was graphically presented to the participant on a monitor. A blue dot (20 mm diameter) represented the grasped object and a red dot represented the target location.

To minimize the disturbance of forces caused by other elements than the laparoscopic graspers, the graspers were placed in a low friction trocar (type Xcel 5, Ethicon ENDO-Surgery Inc., Cincinnati, Ohio) (van den Dobbelsteen *et al.* 2007). Figure 3.2.2 and Figure 3.2.3 show the experimental setup for the laparoscopic grasper.

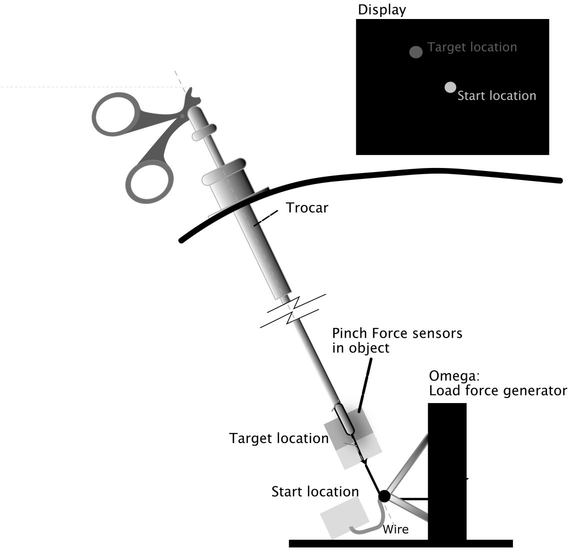


Figure 3.2.2. Experimental setup and feedback screen in the condition of a laparoscopic grasper.

Figure 3.2.3. Omega used to simulate different tissue stiffness conditions. The object to be grasped was attached to the endplate (A) with a slack wire.

Instruments used

Two reusable Laparoscopic graspers (type 33321 MH and 33321 C Karl STORZ) and a pair of anatomical tweezers were used. The mechanical efficiency (i.e. the force transmission ratios resulting from a combination of frictional losses, force multiplication factors and hysteresis) of each grasper was determined by measuring pinch force at the tip when handle forces were varied (for a full description see (Westebring-Van Der Putten *et al.* 2009c). In order to generate the same tip force, the high-efficient grasper (GH) required less effort (the force transmission ratio during a squeeze and release action is 2.0 and 1.2 respectively) from the participant than the low-efficient grasper (GL) (the force transmission ratio during a squeeze and release action is 6.3 and 2.0 respectively). The surface areas of the instrument tips with which the object was pinched during the lifts were approximately the same for all instruments (tweezers or laparoscopic graspers).

General procedure

The participants stood in front of the experimental set-up, with their right upper arm slightly abducted (about 20 degrees), elbow flexed and their forearm extended anteriorly. The grasping height was individually adapted so that the task could be performed with a natural wrist angle. The participant task was to grasp the object either barehanded (H) (thumb and index finger), with tweezers (T) or with one of the two laparoscopic graspers (GH and GL) and move it to a predefined target location. After the lift, they had to keep the object at the target location for 2 seconds before releasing the object. To guarantee that the pinch-surface was at the predefined starting position before the participant pinched and pulled, the researcher positioned the object in the participant's instrument or hand each time the participant had to re-grasp it.

In order to make the movement in this experiment realistic, the target location was placed so that the object had to be moved over a distance of 50 mm along a travel-path 60 degrees relative to the horizontal plane. This trajectory was chosen as pull forces applied to the colon in bowel surgery are applied at an angle of about 40 to 70 degrees relative to the horizontal plane (de Visser *et al.* 2002). To prevent the participants from automatically moving to the target location, the target location changed randomly during the trials (0 mm, 5 mm to the left or 5 mm to the right relative to the sagittal plane). The different pull forces required to reach the target location were 4, 6 and 8 N, corresponding to stiffness of 80, 120, and 160 N/m, respectively.

Before the experiment started, the participants were allowed to practice till they could perform 5 consecutive safe lifts. The learning curve for this task has previously been investigated by (Westebring-Van Der Putten *et al.* 2009c). A Safe lift was defined as a lift without slip and which did not exceed 10N of pinch force. In the practice period, visual feedback was provided in order to indicate to the participant whether the pinch force was approaching 10 N. This was done by changing the colour of the dot representing the object gradually, from blue to white with increasing force.

During the trial, no visual feedback was provided about the magnitude of the pinch force (no colour change of the dot). The four different grasp conditions (H, T, GH and GL) were performed in random order with a resting period of five minutes. In each condition 27 lifts had to be performed without slippage (three times three different positions at three different stiffness profiles). If slip occurred, the lift had to be repeated until successfully lifted. Therefore, in each condition the total number of started lifts could be greater than 27.

Data acquisition and analyses

Pinch and Pull force data were sampled at 1000Hz during the 972 lifts (4 conditions containing 243 lifts each, conducted by 9 participants). To estimate the pinch force applied by the participant, the output of the two force sensors was averaged. The inaccuracy of the combined output of the two sensors was approximately 5% (confirmed in a pilot study). Data was analysed using MATLAB R2006b. A curve was fitted to the raw data of the pinch force using a local regression with weighted linear least squares and a 2nd degree polynomial model that assigns lower weight to outliers in the regression. The method assigned zero weight to data outside six mean absolute deviations. The span (a percentage of the total number of data points less than or equal to 1) was set to 10%. (MATLAB function yy = smooth (y, 0.1, rloes)). Figure 3.2.4 shows the fitted curve and the data parameters analysed.

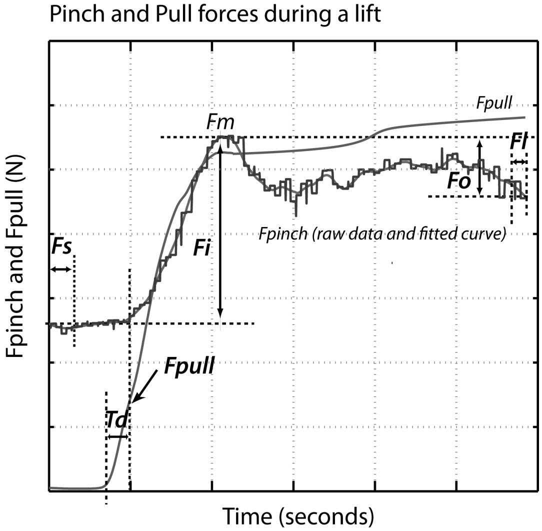


Figure 3.2.4. Parameters of the pinch force trajectory analysed during a lift. Maximal pinch force (Fm), Mean start pinch force (Fs). Increase in pinch force (Fi), Time delay between start pull force and start of increment in pinch force (Td). Mean pinch force during the last 0.1 seconds (Fl). Overshoot of the pinch force (Fo). Pull force at which the pinch force starts to increase (Fpull).

Several parameters were determined to investigate the differences in the trajectory of the changes in applied pinch force, during the lifts in the four conditions. These parameters were: Mean start force (*Fs*), defined as the mean pinch force during the first 0.1 seconds of the lift; the time delay (*Td*), defined as the delay of the start of the increment of pinch force on the start of the increment of the pull force; and the pull force (*Fpull)* at which the participant started to increase their pinch force. The other parameters (*Fi* and *Fo*) are described by the following equations: the increment of pinch force during the lift (*Fi*) as in (1), is defined as being the maximal pinch force (*Fm*) minus the start pinch force (*Fs*), where *Fm* is defined as the maximal pinch force during the lift calculated as a mean of 0.05 seconds before and after the maximal value of the pinch force in the raw data.

$$Fi = Fm - Fs \qquad (1)$$

The overshoot in pinch force (*Fo*) as in (2), is defined as being the amount of pinch force decline after the increment of pinch force. *Fl* is defined as the mean pinch force during the last 0.1 second of the lift.

$$Fo = Fl - Fm \qquad (2)$$

The raw data of the pinch force was plotted against the pull force after which it was interpolated in steps of 0.1 N of pull force.

During surgery, surgeons apply, on average, 2.5 N and maximally 5 N of pull force to the colon to stretch the mesocolon for dissection (de Visser *et al.* 2002). To investigate parameters at pull force levels that are common in surgery, the pinch force was determined in the data at these two levels of pull force: 2.5 and 5 N respectively. In addition, these pull forces were used in each lift, with an exception of the pull force of 5 N in the stiffness condition of 80 N/m where the maximal pull force was 4 N. The pinch forces applied during these two pull forces were determined by averaging the pinch forces applied from 2.4 to 2.6 N and from 4.9 to 5.1 N of pull force respectively. Individual and group average as well as the minimum, maximum and range of the pinch force applied at the two pull forces were determined. Actual slip forces were estimated by analysing the trials where slip occurred. Slip ratio was defined as the minimal ratio necessary between the slip force and pull force that prevents slippage. The slip margin was defined as the difference between slip ratio and force ratio, where the force ratio was defined as the ratio between the applied pinch and pull force.

In order to see whether the variable tissue stiffness influenced the applied pinch forces during the lifts, all values were calculated and evaluated for each stiffness condition.

Statistics

Differences between the test conditions H, T, GH and GL, and the influence of the three different stiffness conditions of the object were analysed with a MANOVA to see whether the dependent variables were unrelated to each other. As appropriate, the variables were subjected to separate repeated measures two-way ANOVAs. The interactions between the independent variables were evaluated. Position was not considered as an independent variable as the differences in the target positions showed only small deviations from the basic position described in section 2.5. The variables were the different parameters of the pinch force trajectory (*Fs, Fi, Fo, Fpull* and *Td*), and the mean, maximum, minimum and range of the pinch forces used at 2.5 and 5 N of pull force. To analyse which pairs of means were significantly different, post hoc tests were performed by a multi-comparison procedure using Tukey's honestly significant difference criterion. Significance was set at $p < 0.05$. To visualize significances between the four conditions during pull force levels of 2.5 and 5 N, notched box and whisker plots were used, where every box has a line at every quartile, median, and upper quartile values. The whiskers are presented as lines that extend from each end of the box in order to show the extent of the rest of the data. The notches represent the 95% confidence interval for the median. Boxes where notches do not overlap are significantly different ($p<0.05$).

3.2.3. Results

3.2.3.1. Differences in trajectory of the pinch force

Figure 3.2.5 shows a typical plot of lifts of an object with a tissue stiffness of 120 N/m, either barehanded (a), with the aid of a high-efficient grasper (b), with the aid of a low-efficient grasper (c) and with the aid of tweezers (d). The pinch and pull forces are plotted against time. A number of representative features of the force trajectories can be seen in the Figure. A MANOVA showed that the four groups (H, T, GH, GL) differed significantly from each other. There were no interactions between the values of the dependent variables.

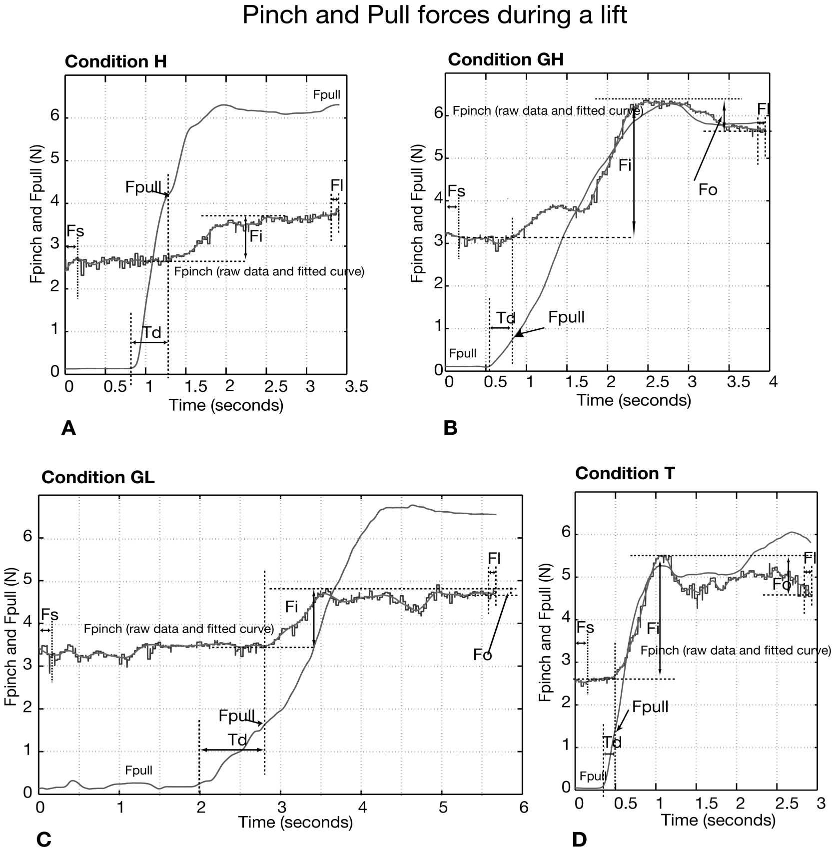


Figure 3.2.5. Typical data for applied pinch and pull forces during a lift. A) Lifting barehanded (H), B) Lifting with the aid of a High-efficient Laparoscopic grasper (GH). C) Lifting with the aid of a Low-efficient Laparoscopic grasper (GL). D) Lifting with the aid of Tweezers (T). Fs is defined as the mean pinch force during the first 0.1 second. Fi is defined as the increase of the pinch force during a lift. Fl is defined as the mean pinch force during the last 0.1 second. Fpull is defined as the pull force at the start of the increase of the pinch force. Td is defined as the time between the start of the increase of the pull force and the start of the increase in pinch force.

Differences in lifting an object with a different stiffness only occurred in conditions H (Fi, p=0.001 and Fpull, p=0.04) and T (Fi, p=0.03). With increasing object stiffness the rise in pinch force increases (Table 3.2.1). Table 3.2.1 shows average values if the different stiffness did not result in significantly different values of the variables

An important parameter is the height of the pull force at which the pinch force starts to increase during a lift. The pull force (Fpull) at which participants start to increase their pinch force was significantly higher when lifting barehanded than lifting with the aid of an instrument (Table 3.2.1 and Figure 3.2.6C) ($F_{(3,96)}$= 31.3, p<0.001). Participants lifted significantly more slowly with the aid of low-efficient graspers than barehanded or with the other instruments. Therefore, Td is greater in Condition GL than in Condition H, GH and T (Table 3.2.1).

Table 3.2.1. Differences between the trajectories of the applied pinch force during the lifts in the four conditions.

Condition	**H**			**GH**			**GL**			**T**		
Stiffness N/m	*80*	*120*	*160*	*80*	*120*	*160*	*80*	*120*	*160*	*80*	*120*	*160*
Mean Fs (sd) N	2.38(0.1)			3.39(0.97)			2.98(0.7)			2.60(0.3)		
p	<0.001*											
Mean Fi (sd) N	0.64(0.3)	1.44(0.8)	2.49(1.3)	2.71(1.0)			1.45(0.6)			2.39(1.3)	2.91(1.1)	3.94(1.2)
p	<0.001*											
Mean Fo (sd) N	-0.22(0.11)			-0.66(0.4)			-0.49(0.2)			-0.99(0.8)		
p	<0.001*											
Mean Fpull (sd) N at start of increase pinch force	1.95(0.9)	2.95(1.1)	2.98(0.8)	1.08(0.8)			0.77(0.5)			1.30(0.77)		
p	<0.001*											
Mean Td in sec.	0.65			0.66			1.81			0.63		
p	<0.001*											

** See Figure 3.2.6. to see which conditions differ significantly from each other.*
H: Hand, GH: High-efficient Grasper, GL: Low-efficient grasper, T; Tweezers, Fs: mean pinch force during the first 0.1 second, Fi: increase of the pinch force during a lift, Fpull: pull force at the start of the increase of the pinch force, Td: time between the start of the increase of the pull force and the start of the increase in pinch force.

Figure 3.2.6A and Table 3.2.1 show that lifts conducted with the aid of each of the graspers (GH and GL) induced a significantly higher applied pinch force at the start of the lift (*Fs*) than when lifted barehanded ($F_{(3,96)}$=13.5, p<0.001). Figure 3.2.6B and Table 3.2.1 show that the increase of pinch force during a lift was significantly higher when lifting the object in condition GH and T than in condition H. ($F_{(3,96)}$=20.08, p<0.001). The overshoot of the pinch force was significantly higher in the static hold period after a lift with the aid of a high-efficient grasper or with tweezers than after a barehanded lift ($F_{(3,96)}$=14.45, p<0.001) (Figure 3.2.6D and Table 3.2.1).

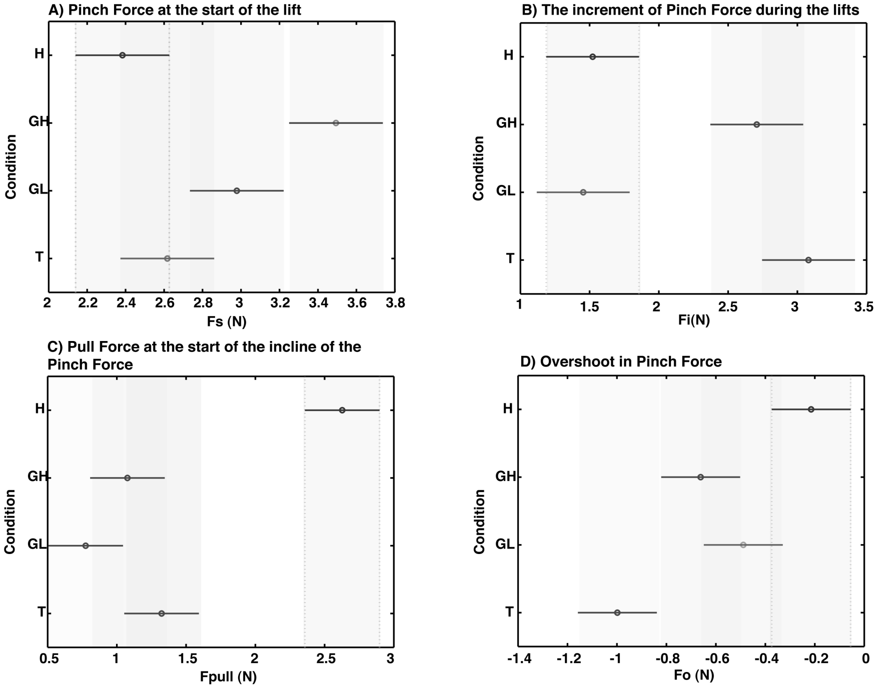


Figure 3.2.6. Differences in properties of the pinch force trajectories. Conditions: Hand (H), Tweezers (T), High-efficient grasper (GH) and Low-efficient grasper (GL) A) Differences in applied pinch force, at the start of the lift. B) The increment of pinch force during the lift. C) Difference in Pull Force (Fpull) at the start of the incline of the pinch force during a lift. D) The overshoot in pinch force. Differences are significance in those conditions, which do not overlap.

A small number of participants performed lifts where, after the start of the lift, no increment in the pinch force occurred. In other words the pinch force at the start of the lift was high enough to perform the lift without increasing the pinch force any further. As this happened only 10 out of 243 lifts (during one condition), no conclusions can be derived from these values.

3.2.3.2. Pinch forces used at pull force levels of 2.5 and 5 N

Figure 3.2.7 shows a plot of the interpolated pinch force plotted against pull forces for all participants. In order to be clear, only the data of lifts for an object with a stiffness of 160 N/m are shown for each condition. This is legitimate, as no significant differences were found between the lifts of objects with different stiffness, irrespective of condition (H, GH, GL and T). In Figure 3.2.7 the safe-area is shown bounded by the slip-line and damage-line. As can be seen the damage-line is often exceeded. Figure 3.2.7 does not show the trial results where slippage occurred and pinch force values were below the slip-line. The occurrence of slippage in condition

H was 0% of the trials, in condition T 7%, in condition GH 8%, and the slippage percentage in condition GL was 38% of the trials. Using a Two-way ANOVA, differences were tested in average, minimal, maximal and range of the pinch force, at both pull force levels of 2.5 and 5 N.

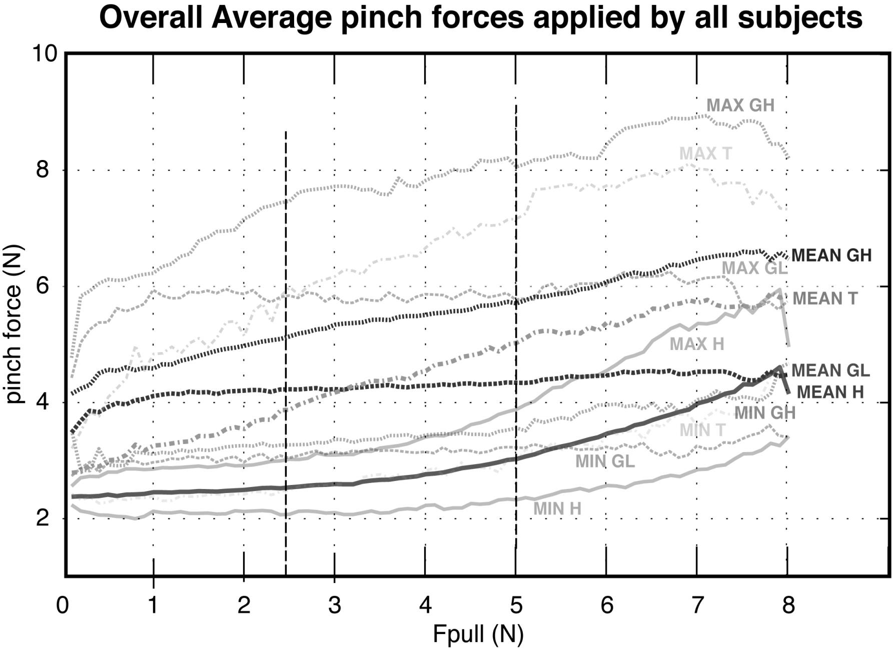


Figure 3.2.7. Overall average pinch forces applied by all the participants. Pinch force is plotted against the pull force for the lifts of the objects with stiffness condition of 160 N/m. The plot represent the data in condition H (bare hand), T (tweezers), GH (high-efficient grasper) and GL (low-efficient grasper) of the group average maximum applied pinch forces (MAX), group average applied mean pinch force (MEAN) and the group average minimal applied pinch force (MIN). Vertical lines are drawn at pull forces of 2.5 and 5N. The shaded area is the safe area bounded by the slip line and the damage line (derived from the human small bowel perforation forces mentioned by (Heijnsdijk *et al.* 2003))

For all instruments the slip ratio at pull force levels of 2.5N was 0.77 and at a pull force level of 5N the slip ratio was 0.44. The slip ratio for the bare hand is an average slip ratio, as the subjects all had different finger-object contact areas. At a pull force level of 2.5N the slip ratio was 0.76 and at a pull force level of 5N the slip ratio was 0.42. Slip Margins were calculated and are displayed in Table 2. As can be seen, the safety margin at pull force levels of 2.5N is much higher than at pull force levels of 5N. This holds for all conditions. For condition H the safety margins are significantly lower than in the conditions of the instruments.

At a pull force level of 2.5 N, the average, minimum and maximum pinch force applied by the participants were significantly higher using one of the three instruments (Conditions GH, GL and T) than barehanded (Condition H) (Table 2) ($F_{(3,96)}$=22.48 and p<0.001, $F_{(3,96)}$=18.3 and p<0.001 and $F_{(3,96)}$=23.52 and p<0.001 respectively). In condition GL and T the participants applied a significantly lower average, minimum and maximum pinch force compared to condition GH. At a pull force level of 5 N, the average, minimum and maximum pinch force participants applied were significantly higher using one of the three instruments compared to barehanded (Table 2) ($F_{(3,64)}$=17.39 and p<0.001, $F_{(3,64)}$=10.48 and p<0.001 and $F_{(3,64)}$=17.17 and p<0.001 respectively). Additionally, in condition GL the participants applied a significantly lower average and maximum pinch force compared to condition GH and T. The minimum pinch force applied during condition GL was significantly higher than in condition GH.

Table 3.2.2 shows that the range of pinch forces used, at a pull force level of 2.5 and 5 N, were significantly greater using instruments compared to bare hand ($F_{(3,96)}$ =17.9 and $F_{(3, 64)}$=11.6 and p<0.001) respectively. In condition GL a smaller range of pinch forces was used compared to condition GH.

Table 3.2.2. Pinch forces applied during pull forces of 2.5 and 5 Newton.

	H		**GH**		**GL**		**T**	
Pull Force	*2.5 N*	*5 N*	*2.5 N*	*5 N*	*2.5 N*	*5 N*	*2.5 N*	*5 N*
Slip Ratio	*0.76*	*0.42*	*0.77*	*0.44*	*0.77*	*0.44*	*0.77*	*0.44*
Mean pinch force N (sd)	2.5(0.2)	3.1(0.4)	4.9(1.4)	5.4(1.4)	3.8(0.9)	4.1(0.9)	3.9(1.2)	4.9(1.2)
Mean Slip Margin	0.24	0.2	1.52	0.64	0.75	0.38	0.79	0.54
Average Minimum pinch force N (sd)	2.1(0.2)	2.3(0.4)	3.1(0.5)	3.5(0.6)	2.9(0.8)	3.0(0.8)	2.3(0.4)	3.1(0.7)
Minimal Slip Margin	0,08	0,04	0,47	0,26	0,39	0,16	0,15	0,18
Average Maximum pinch force N (sd)	3.1(0.3)	3.9(0.7)	7.2(2.5)	7.9(2.5)	5.3(1.5)	5.7(1.6)	5.8(2)	7.1(1.7)
Maximal Slip Margin	0,48	0,36	2,11	1,14	1,35	0,7	1,55	0,98
Average Range of pinch forces N (sd)	0.9(0.3)	1.6(0.7)	4.1(2.2)	4.3(2.2)	2.4(1.4)	2.7(1.4)	3.2(1.9)	4.0(1.4)

H=Bare hand, GH=high-efficient grasper, GL= low-efficient grasper and T=tweezers.

3.2.4. Discussion

The aim of this study was to compare and investigate the trajectory of the changes in pinch force, during lifts of objects with a variable tissue stiffness, performed barehanded and with the aid of laparoscopic graspers. Furthermore, the influence on performance of the mechanical efficiency of the laparoscopic grasper was investigated, as different instruments transmit haptic information differently.

The most important difference between the trajectories of the changing pinch force during a lift was the pull force (*Fpull*) at which participants started to increase their pinch force. Lifting barehanded (H), participants started to increase their pinch force significantly later than lifting with the aid of an instrument (tweezers (T) or laparoscopic graspers (GH, GL)). Compared to barehanded lifts, participants used 1.5 to 2 times as much pinch force on average when using an instrument (T, GH, GL). The range of pinch forces used was 1.7 to 2.7 times greater than in a barehanded (H) lift. The area of the tip of the instruments and the area of the fingertip differ, which could explain some of these differences in pinch force levels.

The results imply that when lifting barehanded, participants waited until it was necessary to increase pinch force, whereas when lifting with the aid of an instrument; participants increased their pinch force in advance. However, participants applied pinch forces with a large safety margin at pull force levels below approximately 2.6N in the barehanded condition (H). This lasted until the increase in pinch force occurred. From this point further the pinch force increased in parallel with the pull force increment. In studies by Johansson *et al.* (1984), pinch forces in barehanded lifts changed in parallel with the changing pull forces after a much shorter delay than in our study. This can be explained by the differences in experimental setup. In our setup, pull forces were only measured after the wire was tightened and gravity of the object was overcome. In the experiments by Johansson *et al.* load forces were measured from the onset of the grasp and ended when gravity was overcome. The pinch forces measured at the onset of the increase of the pull force in our experiment contain pinch forces necessary to overcome the gravity of the object and therefore contain a safety margin. When the participants started to pull the object with a tightened wire, they apparently waited with increasing their pinch force until the safety margin approached zero. The safety margin above the actual slip line was very small during the barehanded lifts.

When lifting barehanded, cutaneous sensors in the skin are in contact with the object and detect, together with mechanoreceptors in the muscles and joints, whether the pinch force is sufficient. In this way humans can efficiently adapt their pinch force to the force needed to generate a safe grasp. During laparoscopic grasping, the hands of the surgeon are not in contact with the tissue grasped. Therefore, no tissue information and forces acting on the tissue are transmitted to the surgeon by the cutaneous sensors. Position and forces of the handle are the only information sources surgeons can use to base their actions on. Apparently, this kinesthetic feedback is insufficient to adapt pinch force efficiently when manipulating tissue with the aid of an instrument. Therefore, participants start to increase their pinch force at the first moment they feel a pull force, in order to prevent slippage during laparoscopic grasping. The safety margin during laparoscopic lifts was therefore excessive.

During lifts, at pull force levels of 2.5 and 5 N, the height of the pinch forces in condition T did not significantly differ from condition GH. Both conditions caused the participant to use more pinch force than when lifting barehanded. In condition GL participants were able to pull the object with less pinch force than during lifts with the aid of one of the other two instruments. However, using this low-efficient grasper, slippage occurred 5 times more often and participants lifted significantly slower.

The two laparoscopic graspers disturb force feedback similarly as there is no direct skin contact with the object. The disturbance of kinesthetic feedback differed between instruments depending on the mechanism. In condition GL the majority of the participants complained about not feeling anything but painful hands. Especially when lifting objects with the stiffest tissue properties, they chose the strategy to pinch as hard as possible to prevent slippage as they were not able to feel whether they were in the safe area or not. Handle forces can be much greater than tip forces as the force transmission ratio is often greater than 1 (6.3 for grasper GL) In this condition (GL) handle forces greater than 63.6N occurred which could easily block cutaneous sensors in the skin, resulting in a continuous sensation of pain.

In this study, mean pinch forces applied to the handle, in condition GH, calculated during pulling with a force of 5 N, varied between 7.3 and 11.3 N (depending on opening or closing of the handle) and maximal handle forces varied between 11.9 and 17.6 N. In order to check whether these values are realistic for surgery, they were compared to pinch forces used in surgery. Brown et al (2004) measured, *in vivo* pig surgery, pinch forces at the handle of a laparoscopic grasper during bowel and stomach manipulation tasks, by means of a tracking system known as the Blue DRAGON. Their results show mean pinch forces on the handle of 8.5 N +/- 2.8N and maximal pinch forces of 24.9N+/- 8.1 N. Unfortunately, the actual tip pinch forces could not be calculated as the mechanical efficiency of the several different instruments they used was not mentioned. Additionally, it was impossible to define whether their participants could cause tissue damage as no pull forces related to the pinch forces were mentioned. As the handle forces in condition GH seem similar to the values seen by Brown *et al*. (2004), we can presume that they used a mechanically similar grasper. Based on these findings, the forces mentioned in the results of this study are comparable with surgery. However, this does not imply that our results would have been the same if experienced surgeons participated in the study.

Relating the results to surgical practice, if the grasped object in this study had been human small bowel tissue, it would have frequently been perforated in condition T and GH, as pinch forces at which human small bowel is perforated are approximately 10.3 +/- 2.9 N (Heijnsdijk *et al.* 2003). These perforation forces were measured with no pull force, meaning that adding a pull force would result in lower perforation forces. The damage line in Figure 7 is an estimate based on Heijnsdijk's study. In our experiment this estimate was exceeded. Our subjects practiced the task before they participated in the experiment. However, more practice might have improved their grasp control.

Besides the difference in applied pinch forces during the lifts in the four conditions, differences in the amount of slippage were recorded as well. The occurrence of slippage in condition T (7%) and GH (8%) can be compared to the values found by Heijnsdijk et al (2002): for all clamping actions, bowel slipped out of the grasper in 7%, whereas the gallbladder slipped in 17%. The slippage percentage in condition GL (38%) was higher, which can be explained by the inferior mechanical efficiency of the instrument. During barehanded lifts, no slippage occurred. The results of Heijnsdijk *et al.* (2002) show that even experienced surgeons have trouble controlling their grasp forces laparoscopically (resulting in slippage), and are not as dexterous as in barehanded grasp control. Further research is therefore required to see if experienced surgeons have the same force profiles during a laparoscopic lift as novices. According to Forssberg *et al.* (1991) it takes 8 years to develop bare handed grasp control.

In this study all factors, besides the mechanical construction of the instrument, which can influence haptic perception, were set to a minimum (e.g. thin artificial abdominal wall, low-friction trocar, ideal placement of the trocar). Therefore, in surgery haptic perception could be even worse than measured in this study. Additionally, with use, the wear and tear of laparoscopic graspers will result in a decreasing mechanical efficiency and, as a result, haptic perception will also decrease.

Lifting objects with the low-efficient grasper used in condition GL resulted in poor performance as a result of a poor mechanical efficiency (~10%). These kinds of instruments, however, are commercially available and widely used. In a study of force transmission in laparoscopic instruments by Sjoerdsma *et al.* (1997), instruments with even less mechanical efficiency profiles were seen (8 %). Additionally, these low-efficient instruments have a high hysteresis, resulting in a greater uncertainty of the pinch force information in the surgeon's hand. In practice surgeons change instruments during surgery, therefore, they have to cope with different mechanical efficiency profiles during a single procedure, which makes it even more difficult to maintain a safe grasp.

3.2.4.1. Conclusion

During laparoscopic tissue grasping, novices have trouble efficiently applying pinch forces. The main difference between barehanded grasping and use of a laparoscopic grasper is the pull force at which pinch force is increased. The increase in pinch force during a barehanded lift is significantly later than when lifting with the aid of a laparoscopic grasper. This means that during a barehanded lift, people wait until it is necessary to increase the pinch force to prevent slippage, whereas lifting laparoscopically, they increase their pinch force in advance. In barehanded lifts all participants could accomplish a perfect and safe grasp, whereas in laparoscopic object lifts excessive force and object slippage occurred frequently. Therefore, it can be concluded that force feedback, as in skin-tissue contact, is a pre-requisite for novices to maintain a safe laparoscopic grasp.

Acknowledgments

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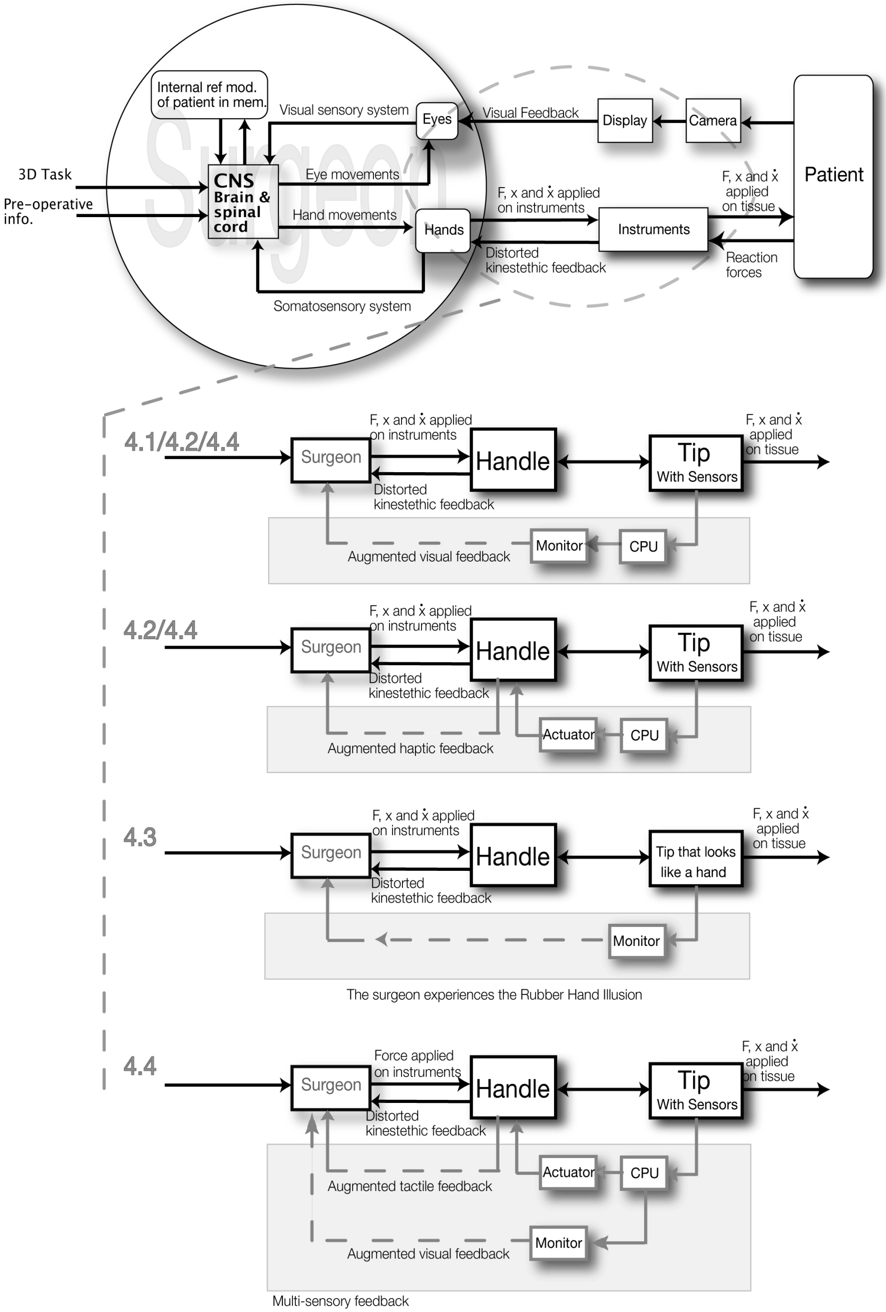


Figure 4. The four different Control diagrams for Laparoscopic Surgery with improved information feedback that are discussed in Chapter 4. 4.1/4.2/4.4 Augmented Visual feedback, 4.2/4.4 Augmented haptic feedback, 4.3 Rubber hand Illusion and 4.4 a combination of Visual and haptic feedback.

Chapter 4. The augmented feedback possibilities

The fundamentals of human grasp control that were discussed in Chapter 2 show that haptics and vision are important in the controlling of hand forces. These principles are the same as those that apply to the safe controlling of instruments in MIS but, as seen in Chapter 3, the instruments disturb the available tissue information. Visual and kinesthetic feedback are available although disturbed and tactile information is not present.

The numbers of consequential and inconsequential errors that are made, due to insufficient grasp force control, indicate that the currently available combination of visual and haptic feedback is not sufficient to perform safe tissue manipulation. It was shown in Chapter 2 that augmented feedback could aid performance in several tasks other than grasping. Whether augmented feedback can aid performance in laparoscopic grasping will be tested and discussed in this chapter. Several augmented feedback modalities will be considered. Just how they fit into the control diagram, which was derived after Chapter 2, can be seen in Figure 4.

Section 4.1 is published as:

"Differences between operator reactions on of visual feedback of haptic stimuli, in a crossed or uncrossed position of laparoscopic tools. Lecture Notes in Computer Science. Madrid. 5024 LNCS 2008: 400-408."

Section 4.2 is published as:

"Tactile feedback exceeds visual feedback to display tissue slippage in a laparoscopic grasper. Studies in Health Technology and Informatics 2009 142: 420-425."

Section 4.3 is published as:

"Bodily Self-attribution Caused by Seeing External Body-Resembling Objects and the Control of Grasp Forces. Lecture Notes in Computer Science; EuroHaptics 2010. A. M. L.Kappers . e. a.. Berlin Heidelberg, Springer-Verlag. Part II: 263-270."

Section 4.4 is published as:

"*The Effect of augmented feedback on grasp force in laparoscopic grasp control.*" *IEEE Transactions on Haptics* 3(4) 2010: 280-291.*"*

4.1. Differences between Operator Reactions on Positions of Visual Feedback of Haptic Stimuli, in a Crossed or Uncrossed Position of Laparoscopic Tools.

At present Laparoscopic surgeries are performed regularly. In practice, no augmented feedback on pinch force is currently available. However, research has proven this to be useful. This research explored the location of a visual feedback signal on pinch force. The reaction time and amount of errors of two different positions of a feedback signal was studied. Firstly, the feedback signal was placed next to the endoscopic view and secondly, it was placed near the tips. Each experiment contained a crossed and an uncrossed tool configuration and was performed with and without view of the tips. It was expected that in the crossed tool conditions problems could occurred as a result of the (non) existence of spatial compatibility between feedback stimulus and response goal. Based on reaction time, it can be concluded that the best position for a visual feedback signal on pinch forces is on top of the instrument tip.

4.1.1. Introduction

During the past decade, the number of laparoscopic procedures (Minimally Invasive Surgery in the belly alcove) has increased significantly. Because of the long and slender laparoscopic instruments, surgeons can operate through small incisions in the skin. With this, both risks of infection and recovery times are reduced (Cuschieri 1995, Moreno-Egea *et al.* 2005, Dedemadi *et al.* 2006). Despite these advantages for the patient, laparoscopic surgery also brings severe difficulties for the surgeon (Stassen *et al.* 2001) that can lead to a higher degree of errors and complications (Westebring-van der Putten *et al.*). One of these difficulties is reduced haptic information, as a result of friction between trocar (cannula used as access port) and instrument shaft, resistance of the abdominal wall, scaling and mirroring of tip forces, and the mechanism of the instruments (Fischer and Trapp 1996).

It is common that slips and excessive forces during grasping pass unnoticed by the surgeon, especially when the instrument tip is out of view. Research shows that augmented feedback on grip force benefits the surgeon in maintaining a safe grip. Haptic display is the most natural way to feedback haptic information. However, at this moment a full haptic display, combining force and tactile, is not yet available as the development of such a display is costly and technically challenging. A good, less costly, alternative could be visual feedback of haptic information. This research focused on visual feedback.

Some studies e.g. (Akinbiyi *et al.* 2005, Ottermo *et al.* 2006, Schostek *et al.* 2006) use visual feedback to inform the user of pinch force levels. These studies show that the user could benefit from this extra information. However, none of these studies explore the type of visual feedback, like appearance, colour and position on screen. These factors are important, as the signal should not interfere with the main task information (view of the operating field). However, the signal must be noticeable when required. Therefore, it is to be expected that the kind of feedback signal will influence performance. To address one of these issues we examined the positioning of the visual feedback signal displayed on the screen. It is unknown whether a surgeon performs better when the feedback signal is positioned left and right of the main endoscopic view or on top of the instrument tips. Especially in those cases where laparoscopic tools are crossing, (for instance during stitching) or when the instrument tips are out of sight, it is unclear where to best position the visual feedback signal.

A lot of research has been done to examine whether a crossed or uncrossed position of hands has an effect on the reaction time to the stimuli on the left vs. right side (Fitts and Seeger 1953, Wallace 1971, Brebner *et al.* 1972, Wallace 1972, Brebner 1973, Anzola *et al.* 1977, Nicoletti *et al.* 1982, Nicoletti *et al.* 1984, Riggio *et al.* 1986). In all studies a certain stimulus was shown to the participants. They had to react to the stimulus by pressing a response key. In general, 3 different configurations were examined (Figure 4.1.1). Firstly, in an uncrossed position of the hands, a left (right) stimulus had to be followed by pressing the left (right) response key by the left (right) hand (Figure 4.1.1A). Secondly, in a crossed position of the hands, a left (right) stimulus had to be followed by pressing the left (right) response key by the right (left) hand (Figure 4.1.1B). Thirdly, in a crossed position of the hands, a left (right) stimulus had to be followed by pressing the right (left) response key by the left (right) hand (Figure 4.1.1C).

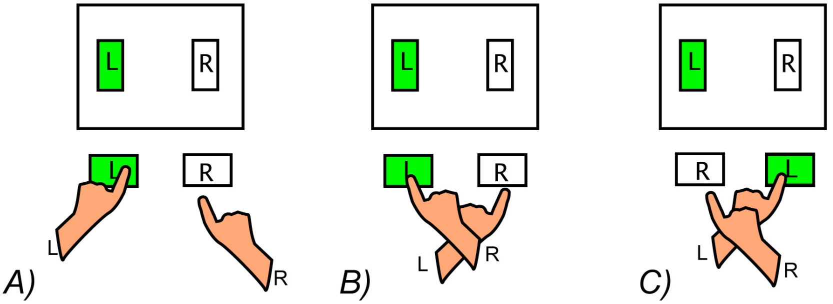


Figure 4.1.1. In an uncrossed position of the hands, a left (right) stimulus had to be followed by pressing the left (right) response key by the left (right) hand (A). In a crossed position of the hands, a left (right) stimulus had to be followed by pressing the left (right) response key by the right (left) hand (B). In a crossed position of the hands, a left (right) stimulus had to be followed by pressing the right (left) response key by the left (right) hand (C).

Several researchers found that spatial compatibility of the location of the stimuli and response goal is more important to the reaction speed than the location of the specific part of the body that has to respond (Figure 4.1.1 A and B) (Fitts and Seeger 1953, Wallace 1971, Brebner *et al.* 1972, Brebner 1973, Anzola *et al.* 1977). In the study of Riggio *et al.* (1986), it seemed that in a crossed position of the hands, the reaction time became slower because of a mismatch between the responding hand and the locus of the response goal. The conclusion of this research was that there seemed to be a natural propensity of the hand connected to the right half of the body to act on the right side and of the hand connected to the left half of the body to act on the left side. The study of Tlauka (2004) confirmed this finding.

Mistakes occur more often when hands are in a crossed position (Shore *et al.* 2002) (Figure 4.1.1 B) than in a parallel position. One obvious explanation for the performance decrement in the crossed hands position of the present study relates to the possibility of a response coding conflict between the responding hand's anatomical label (as a 'left' or 'right' hand) and its spatial position (left versus right) relative to the other hand (Nicoletti *et al.* 1984, Shore *et al.* 2002). Research showed that performance could be improved by training. However, the crossed-hand deficit will never completely disappear (Craig and Belser 2006).

Some studies explored the effect of operating on the response goal with tools instead of hands (Maravita *et al.* 2002, Tlauka 2004). Tlauka (2004) compared both the configurations of Figure 4.1.1, B and C (hands holding sticks that where crossed). The main conclusion of these two experiments was that the sticks are used as an extension of the body, wherefore the behaviour becomes the same as when the hands were crossed.

Based on these findings, the aim of this study is to examine whether the position of the visual feedback signal on grip force, has an effect on the reaction time of the crossed or uncrossed position of laparoscopic tools either with or without endoscopic vision of the tools. This is a step towards the optimisation of visual feedback of haptic information in order to develop a credible alternative to a full haptic display.

Firstly, it was hypothesised that with the use of laparoscopic tools, the location of a visual feedback signal would influence the reaction time more than the position of the tools, which are crossed or uncrossed. Secondly, compared to the situation where the right (left) hand has to react to the left (right) visual feedback signal, it was hypothesised that the reaction time would be longer, and that more mistakes would be made in a crossed position of the laparoscopic tools when the right (left) hand has to react to the right (left) visual feedback signal. This situation occurs when the feedback signal is at the side of the main screen in the crossed position, as at that moment no spatial compatibility exists between the response goal (tool tip) and the feedback signal.

4.1.2. Method

Participants.

Twenty-one students (range: 20 - 25) of Delft University of Technology participated in this research. Eleven (8 male and 2 female) participated in the first experiment and ten (6 male and 4 female) in the second. In each experiment there was one left-handed participant. Data derived from one participant in the first experiment was not analysed, as the tasks were not performed correctly. The participants were unfamiliar with the purpose of the experiment.

Apparatus and Materials.

Participants were positioned at a table in front of a box trainer in a well-lit room with, in each hand, a laparoscopic grasper (type 33321 MH Karl STORZ) holding a sponge. This is shown in Figure 4.1.2. A laptop provided visual feedback on pinch force, which instructed the participants to increase or decrease their pinching force. The laptop was positioned at eye height. The intensity of squeezing in each tool was measured by two thin (0,08 mm) flexi force-sensors (Tack scan) that were placed within the sponge. These sensors were connected electronically to a measurement device (LabJack) and a desktop computer, in which data was recorded. During some of the tasks, a life webcam image of the tips of the laparoscopic tools was displayed to the participants.

Procedure.

Two experimental sessions were performed (Exp1 and 2). In these sessions, the position of the feedback signal on grip force was altered. Both experiments consisted of two different tool positions (parallel (Pa) and crossed (Cr)) and were performed with (On) and without (Off) webcam vision of the tool-tips. Therefore, each participant had to perform 4 conditions within experiment 1 or 2. The participant was always aware of the parallel or crossed position of the tools.

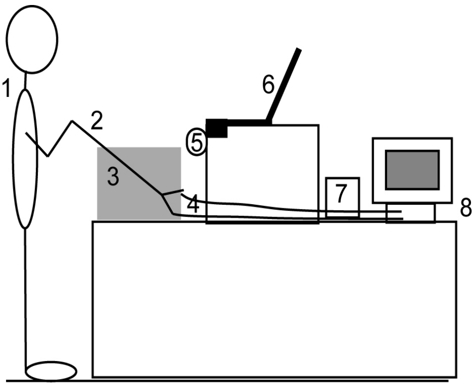


Figure 4.1.2. Position of the apparatus 1) Participant, 2) Laparoscopic tools, 3) Box trainer, 4) Sensors in sponge, 5) Webcam, 6) Laptop screen, 7) Electronic components including 'LabJack', 8) Desktop computer.

In experiment 1 the feedback signals were positioned next to the main endoscopic image (Figure 4.1.3 A-B and Figure 4.1.4 A-D). The left (right) signal was always corresponding to the left (right) hand. In experiment 2 the feedback signals were positioned as close to the tool-tips as possible (Figure 4.1.3 C-D and Figure 4.1.4 E-G). As a result of technical problems, it was not possible to position the feedback signals exactly on top of them. In Figure 4.1.3 the differences between the two experiments are illustrated.

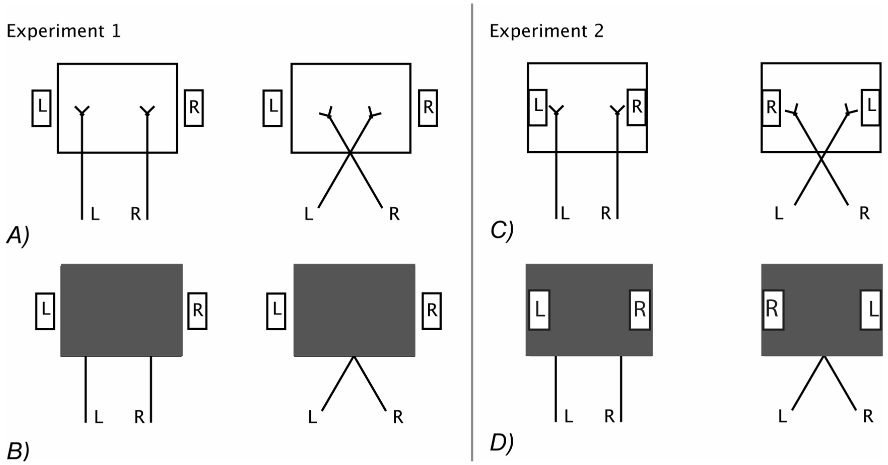


Figure 4.1.3. Layout of experiment 1 and 2: A and C) conditions with webcam view of the instruments, B and D) conditions without webcam view.

The task of the participant was to react as fast and as accurate as possible to the feedback signals. The feedback signalled with which tool the participant had to react and whether they should increase or release their grip. In both experiments with the tools in the parallel position, the participant had to use the left hand to react to the left feedback signal, and the right hand had to react to the right feedback signal. No differences were expected between these two situations. They merely served as a control. In the crossed position, the participants of experiment 1 still had to react with the left (right) hand to the left (right) feedback signal. The participants of experiment 2 had to react with their left hand to feedback on the right side on the screen, and their right hand had to react to feedback on the left side.

When the webcam image was switched on, the participants were told to focus on the tools and not on the feedback signal. When the webcam image was switched off, the participants had to focus on a fixed image. Before the actual test started all participants got four times three minutes to practice each condition (randomly ordered). They could ask questions and got tips to get better results. After this practicing period the real tests started immediately and each test took one minute. The practicing period and the tests were conducted without any resting periods in between. During the test 12 feedback signals were presented randomly. The tests always started with the signal to increase grip for both left and right tool. The test ended with a beep. Errors are defined as reactions with the wrong tool or wrong reactions to the signal (squeeze instead of release or vice versa). The reaction time is defined as the time between feedback signal and response of the tool.

The Feedback Signal.

The main conclusions of earlier pilot tests were that the feedback signals had to change from colour changing signals only, into colour and position changing signals (see Figure 4.1.4). As a feedback signal, coloured bars (yellow, red and green) with different positions were used. During the total duration of the test, the bar was coloured yellow in the middle and remained in the same position. A red signal appeared above the midpoint of the bar, informing the participant that the pinch force was too high and instructing the participant to release. A green signal always appeared below the middle of the bar, informing the participant of upcoming slip and instructing the participant to squeeze harder.

Feedback appeared randomly for the left or the right tool and was not linked to the actual force in the laparoscopic tools. The reason for this was that experiment focused on the reaction of the user to the feedback signal rather than the actual force itself.

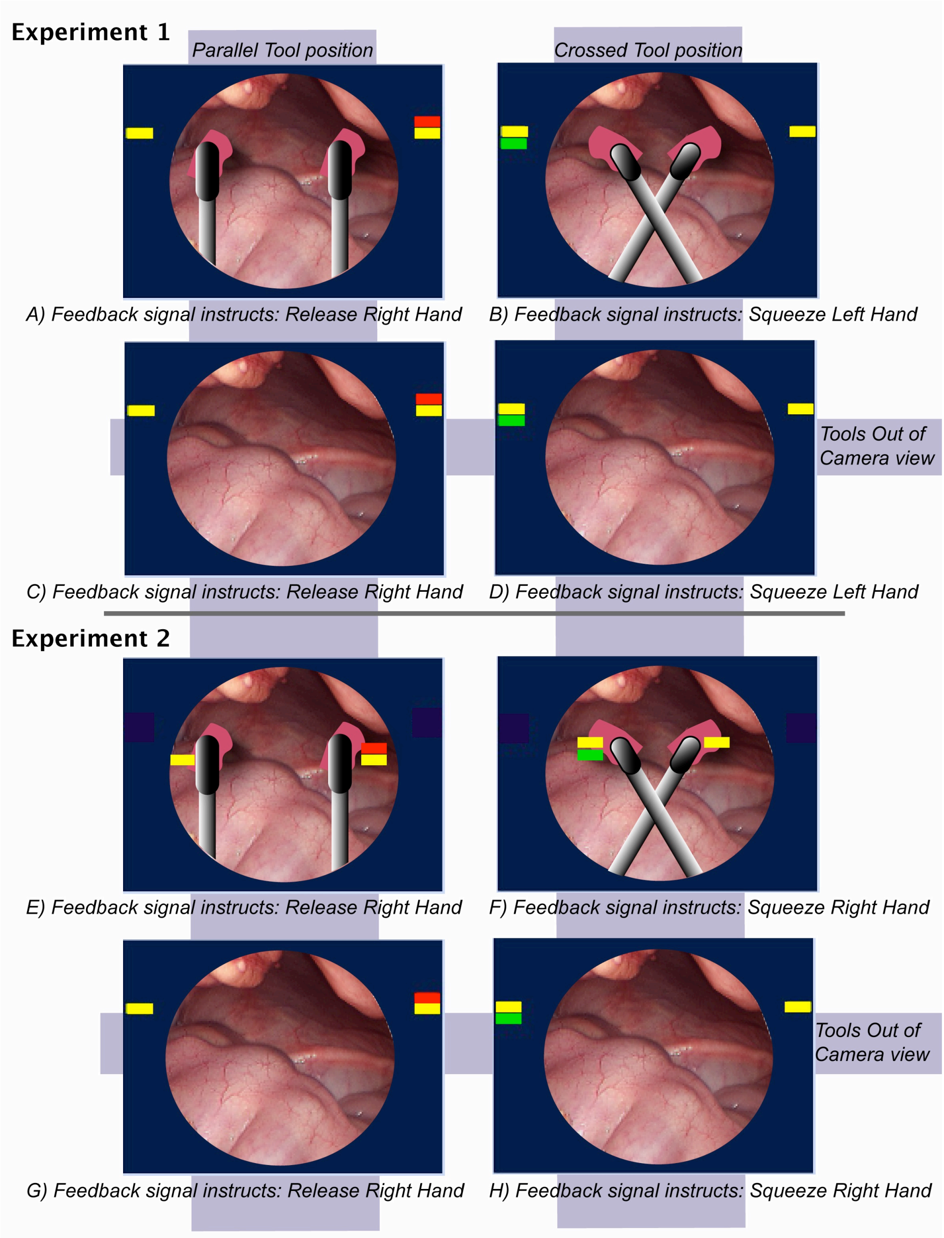


Figure 4.1.4. Layout of the screen participants looked at. Examples of feedback signals are shown. A) Exp1PaOn, B) Exp1CrOn, C) Exp1PaOff, D) Exp1CrOff, E) Exp2PaOn, F) Exp2CrOn, G) Exp2PaOff, H) Exp2CrOff

4.1.3. Results

In Figure 4.1.5 a typical plot is shown of the reactions to the feedback signal of one participant.

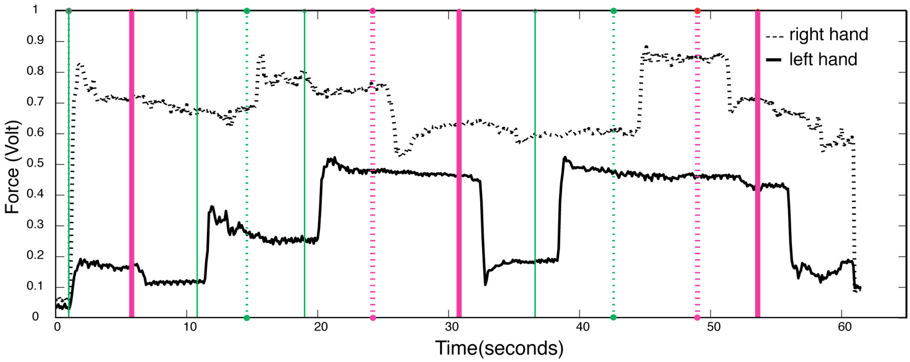


Figure 4.1.5. The results of Exp1PaOff of Participant 2 (no errors made): The dotted line is the output of the sensor of the tool in the right hand and the solid line is the output of the sensor of the tool in the left hand. The vertical lines are: dotted: green feedback signal and red feedback signal for right tool, solid: green feedback signal and red feedback signal for the left tool.

Number of Errors.

Based on the principle of spatial compatibility, it was expected that participants would make more errors during Exp1CrOn and Exp1CrOff than during test Exp2CrOn and Exp2CrOff. However, a Mann-Whitney test showed that there was no significant difference between the number of errors with crossed position of the tools during experiment 1 and experiment 2. See Table 4.1.1 for the results.

Table 4.1.1. Percentages of errors made and mean reaction time during both experiments 1 and 2.

	Exp1PaOn	*Exp2PaOn*	*Exp1PaOff*	*Exp2PaOff*	*Exp1CrOn*	*Exp2CrOn*	*Exp1CrOff*	*Exp2CrOff*
Mean % of Errors	3.33	9.17	11.67	7,50	5.80	10.83	7.50	5.00
p	0.284		0.279		0.078		0.797	
Mean reaction time (s)(sd)	1.15(0.35)	1.21(0.56)	1.03(0.21)	1.04(0.22)	1.13(0.51)	0.77(0.44)	1.12(0.25)	0.88(0.28)
p (1-taled)	0.613		0.539		0.057		0.033*	

**Significant*

Reaction time. Based on the principle of spatial compatibility, the reaction time was expected to be longer during test Exp1CrOn and Exp1CrOff than during test Exp2CrOn and Exp2CrOff. Student t-tests showed that the reaction time was slower in experiment 1. However, only significantly slower in de condition where there was no camera view on the tool-tip. See Table 4.1.1 for the results.

An ANOVA showed that there was no difference in reaction time when tool positions (crossed vs. parallel) were compared (F=2.48, p=0.12).

4.1.4. Discussion

In order to develop a credible alternative to a full haptic display this research helps to make a step towards the optimisation of visual feedback of haptic information. The aim of this study was to examine whether the position of the visual feedback signal on grip force, has an effect on the reaction time of the crossed or uncrossed position of laparoscopic tools either with or without endoscopic vision of the tools.

The results showed that with the use of laparoscopic tools, the location of a visual feedback signal would have more influence on reaction time than the position of the tools, which are crossed or uncrossed. This confirmed the first hypothesis. The second hypothesis was only partly confirmed. The results showed that there were no significant differences between the number of errors during experiment 1 and experiment 2. The results showed that compared to the situation where the right (left) hand had to react to the left (right) visual feedback signal, the reaction time was longer in a crossed position of the laparoscopic tools when the right (left) hand had to react to the right (left) visual feedback signal. This situation occurred in the crossed-tool position, when the feedback signal was positioned at the side of the main screen (Experiment 1). This was based on the fact that no spatial compatibility existed between the response goal (tool tip) and the feedback signal. However, compared to experiment 2, the reaction time in experiment 1 during the cross-tool condition was only significantly longer in the condition where there was no view of the tool tips.

An explanation for these results could be that when using a Laparoscopic Tool there are two possible positions for the response goal. In studies found in literature where participants used a stick to operate a response goal, the response goal was always at the tip of the stick (Maravita *et al.* 2002, Tlauka 2004). However, using a Laparoscopic tool, participants can either choose the tip (adjusting pinch force performed by the tip on the tissue) or the handle (adjusting the force performed by the hand on the handle) to be the response goal. This means that in experiment 1, where the feedback signal was positioned next to the main screen, spatial compatibility existed when the user defined the handle to be the response goal. In experiment 2, where the feedback signal was close to the tip, spatial compatibility existed when the tip of the instrument was seen as the response goal. It could be that participants choose between one of these two strategies.

Another explanation could be that the practicing period was long enough to learn to cope with spatial difference of stimuli and response goal. In other words, 3 minutes of practice was enough to get the same results, considering only the amount of errors made. A quick look at the number of errors made during the practising period shows that the number of errors made during Exp2CrOff was higher than during the other tests. An explanation could be that without practice and without seeing the tool-tips, the (user-set) response goal is shifted from the tip to the handle, so that there is no spatial compatibility. However, practice shifts the response goal back to the tip so that spatial compatibility exists. A second explanation for the fact that the amount of errors of Exp2CrOn and Exp2CrOff did not differ from the others is that some participants mentioned that they, contrary to the instructions, lost focus from the middle of the screen, to the stimuli. In real surgery this can never happen, as the surgeon has to focus on his operation field.

For future research in this area, certain aspects of the experiment can be improved. Firstly, one needs to be sure that the focus remains in the middle of the screen by giving the participants a certain task. Furthermore, the positioning of the feedback signals in experiment 2 can be improved by placing them exactly on the tips of the laparoscopic tools and by moving them along with the tool tips. Finally, the effect of the practice time on the results should be investigated.

4.1.4.1. Conclusion.

From the results it can be concluded that there is significant difference in reaction time between positioning visual feedback on haptic stimuli at the same side and at the opposite side of the instrument tip when tools are crossing each other. Focusing on reaction time, the results of these experiments indicate that the position of the feedback signal on top of the tool-tip was a better position. Furthermore, the location of a visual feedback signal will have more influence on reaction time than the position of the tools, which are crossed or uncrossed.

4.2. Tactile Feedback exceeds Visual Feedback to Display Tissue Slippage in a Laparoscopic Grasper

Virtual reality can help to learn basic laparoscopic tasks. However, no haptic feedback, which alerts for tissue slippage, is provided by most simulators, although, it might be of influence for the decrease of errors. This study explored whether visual or tactile feedback can be used to alert the surgeon of tissue slippage. Twenty-four participants performed a laparoscopic grasping task and where provided with either visual or tactile feedback about tissue slippage. The reaction time with the visual feedback was compared to the reaction time with tactile feedback signal. The results showed that when tissue slippage is simulated, tactile feedback shows significant faster reaction times (269ms) than visual feedback signals (398ms).

4.2.1. Introduction

Laparoscopy is Minimally Invasive Surgery (MIS) performed in the belly alcove. Compared to open surgery, this technique brings difficulties for the surgeon that can lead to a higher complication rate (Dankelman *et al.* 2003). Heijnsdijk *et al*. (2002) found that during a study of 25 surgical procedures, the bowel and the gallbladder slipped out of the grasper in 7% and 17% of the grasp actions respectively. In a study by Westebring – van der Putten *et al.* (2008) it was shown that slippage occurred (85%), more often when an object was held with graspers than with bare hands. This lack of grasp control is caused by the lack of direct tactile feedback and by several other haptic interference factors (Westebring-van der Putten *et al.* 2008b). When surgeons notice slip by watching the monitor, they often react too late and possibly damage the tissue by grasping the slipping tissue more firmly (de Visser 2003).

Research showed that augmented feedback on grip force is beneficial for maintaining a safe grasp (for a review see (Westebring-van der Putten *et al.* 2008b)). A safe grasp means holding the tissue without damaging it by excessive force. Further, studies show that grasping is more efficiently when control is based on a slip signal as opposed to a signal related to the force exerted by the fingers (D'Alessio and Steindler 1995). When novice surgeons learn to control their grasp they can make use of box-trainers and Virtual Reality trainers. However, none of these training methods provide additional feedback about slippage other than actual tissue slippage that can be seen on the monitor. If the surgeon was to be informed about upcoming tissue slippage the surgeon could prevent it. But what is the best way to present slippage feedback?

There are three possibilities to provide information on tissue slippage: auditory, visual and haptic. Auditory feedback is not the most effective way to communicate to the surgeon, as there are many other sounds in the surgeon's environment (Bethea *et al.* 2004). Adding visual features to the main endoscopic view can be used as visual feedback on slippage. Several studies make use of visual feedback to present forces (e.g. (Cao *et al.* 2003, Kitagawa *et al.* 2005, Schostek *et al.* 2006)). However, none of these present information on tissue slippage. To express tissue slippage by haptic feedback, tactile feedback is more natural than kinesthetic feedback, as slip is defined as the relative motion between a surface and the skin (Salada *et al.* 2004). Tactile feedback can be given in different ways. For example with exerting pins (Fisch *et al.* 2003), a rotating disk (Salada *et al.* 2004), a sphere (Webster *et al.* 2005), and a pinch grasp display based on magneto-rheological fluids (Scilingo *et al.* 2007).

Therefore, two sensory modalities seem to be appropriate for providing the surgeon with information on slippage; visual or tactile feedback. The surgeon will presumably benefit the most from the feedback signal that leads to the shortest reaction times and therefore leads to less damaged or lost tissue by the grasper. The feedback signal should be given before actual slippage occurs, otherwise a surgeon is still too late. The shorter someone's reaction time, the later the feedback signal can be given and the less force is needed to hold the tissue (D'Alessio and Steindler 1995).

This study explored which modality; visual or tactile, evokes the shortest reaction times. We hypothesize that during a laparoscopic grasping task where slippage occurs, the reaction time with a tactile feedback signal will be shorter than with a visual feedback signal. This was based on a study by Scott *et al.* (Scott and Gray 2008) where drivers with a tactile warning on upcoming collision had significantly shorter reaction times than drivers without a warning and had a significant advantage over drivers with visual warnings.

4.2.2. Tools and Methods

Participants

Twenty-four students aged 18 – 25 years, of the Delft University of Technology participated in this study; twelve (6 male and 6 female) participated in the condition with tactile feedback (TestT) and twelve (5 male and 7 female) in the condition with visual feedback (TestV). All participants performed the tests with their dexterous right hand, had normal or corrected vision and were familiar with the aim of the experiment.

Procedure

Participants were positioned in front of a table with a box trainer. The experimental set-up was individually adjusted to the participants. They held a laparoscopic grasper (type 33321 MH Karl STORZ, Tutlingen, Germany) in the right gloved-hand (surgical gloves), holding a wooden wedge (25 x 12.5 mm) containing an ultra thin (0.08 mm) pressure sensor (Flexiforce, Tekscan, South Boston, MA, USA). The instrument could be moved freely through a trocar (type Xcel 5, Ethicon ENDO-Surgery Inc., Cincinnati, Ohio) in the box trainer. The whole set-up is shown in Figure 4.2.1.

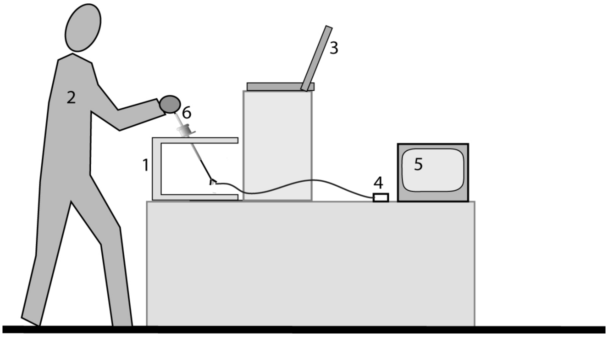


Figure 4.2.1. Experiment set-up. 1: Box trainer, 2: Participant, 3: Display, 4: Feedback Switch 5: Data recording laptop, 6: Trocar with Laparoscopic grasper and pressure sensor in wedge.

The task was to hold a wedge laparoscopically (with minimal force possible) while reading an on-screen-text out loud. During the task, the experimenter induced feedback signals, indicating that the wedge slipped, to the participants. Participants had to react as quickly and as accurately as possible to the signals, by pinching the handle of the grasper. The participants could not see the grasper-tip holding the wedge. Instead, they saw the on-screen-text. Reading the text out-loud prevented them to focus on an upcoming feedback signal and made sure that they where concentrating on the middle of the screen, just like a surgeon during surgery. The text was an explorative text about laparoscopic surgery. All participants wore earplugs; as a result, they were not able to react to the sounds produced by the switch that activated the feedback signals, or the sound of the spinning motor in condition TestT.

Before the actual test started, all participants were allowed to practice. During the practice period they were allowed to ask questions and received verbal advice to achieve a desirable result. Participants had to practice till they responded correctly to the given feedback signal. On average ten practice trials where needed. Immediately afterwards the test started. Each test condition contained 10 feedback signals (either tactile in TestT or visual in TestV), given at randomly chosen intervals varying between 3 to 10 seconds.

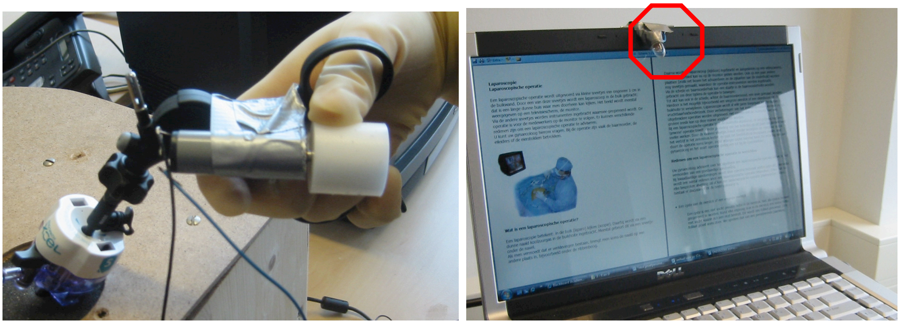
Feedback Signals

In condition TestT a slip sensation at the right thumb served as feedback signal to inform the participants of upcoming tissue slippage (Figure 4.2.2). The slip sensation was provided through a cylindrical rotating device placed perpendicular to the thump, since, the glabrous skin on the front of the hand contains the most nerve endings (Dargahi and Najarian 2004a). For realistic slip display, psychophysical experiments have proven this kind of feedback to be sufficient (Murphy *et al.* 2004). The tactile display rotated with a speed of 4 times/s by a small electric motor (16 mm Ø Maxon DC motor) with a speed reduction gearbox (16 mm Ø Maxon gear)(both Maxon Motor ag, Sachseln, Switzerland). The actual slip display consisted of a cylinder (length 25 mm, Ø 25 mm) made of the polymer POM attached to the shaft of the motor. The dimensions of the cylinder were based on research of Murphy *et al.* (2004), who used a sphere of 15 mm Ø. To be able to adjust the placement of the cylinder in relation to the surface of each thumb, 10 mm was added to the cylinder‘s diameter. Hereby, the thumbs of all participants were able to touch the cylinder. As the sensitivity to the perception of slip at the fingertip depends heavily on surface texture the surface of the cylinder should not be homogenous. Small features evoke more accurate perceptions than homogenously textured surfaces (Salada *et al.* 2004). Therefore, a sharp metal tip was used to texture the surface of the cylinder. Furthermore, research showed that the angle between the fingertip and feedback did not seem to be relevant (Webster *et al.* 2005). Therefore, it was justified to place the cylinder on the grasper in a way that it would tangentially touch the participant’s inner side of his or her thumb.

A light bulb (3.6V, 0.3A) was used as a visual feedback signal (Figure 4.2.2B) in Test V. The best placement for a visual feedback signal on screen is as close to the tip as possible (Westebring-van der Putten *et al.* 2008a). However, in this experiment, confusion between the feedback signals corresponding to the left or right instrument is not present as only one grasper is used. Therefore, the bulb was placed at the top-middle of the screen. Both visual and tactile feedback signals had the same connection in the experimental set-up and were powered by a power source, which could be manually switched on and off.

Data Analysis and Statistics

For both conditions the reaction times (RT) were recorded (500Hz) and errors were documented. The RT was defined as the time between start of the feedback signal and the moment the participant pinched the grasper and hereby the pressure sensor. For each participant mean RT was calculated. The Kolmogorov and Mann-Whitney tests were used to compare RT and number of errors of TestV and TestT. The significance level was set at $P <= 0.05$.



A B

Figure 4.2.2. a) Tactile slip display and b) Screen with text and light bulb used as Visual feedback signal.

4.2.3. Results

The data of two participants could not be analyzed due to technical problems within the data files. Figure 4.2.3 shows typical plots of a part of the data of two participants. The differences between the responses to the two different feedback signals can be seen clearly. Participants using the tactile display tend to pinch the grasper during the whole duration of the feedback signal whereas participants using the visual display tend to give a short pinch. No errors occurred in either TestT or TestV. The RT in TestT (mean: 0.2686s sd: 0.06s) was significantly shorter than the RT in TestV (mean: 0.3984s sd: 0.09s) (Z: -3.2176 rank sum; 77 and $p_{\text{two-tailed}}$: 0.0013).

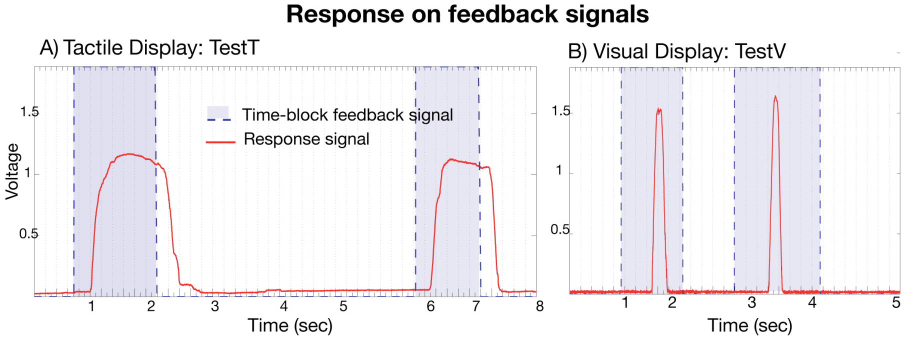


Figure 4.2.3. Typical results of A: a participant in the condition with a tactile feedback signal and B: a participants in the condition with a visual feedback signal B. The straight line represents the feedback appearance, given manually by turning the power on and off. The peaked line represents the reaction of the participant, squeezing the grasper and thereby the pressure sensor.

4.2.4. Discussion

The aim of this study was to examine whether visual or tactile feedback signals can be used as an effective way to communicate upcoming tissue slippage to the surgeon in laparoscopic grasping tasks. The results showed significant faster RT's responding to tactile feedback than responding to a visual feedback signal. This confirmed our hypothesis that the reaction time in TestT would be shorter than in TestV. During the experiments there were some interesting observations and remarks made by the participants. Participants attempted to stop the motor from rotating by pressing the thumb upon the tactile feedback display. This is exactly what a surgeon needs to do: pinching until tissue slippage stops. Participants also tended to pinch harder until the signal finally stopped. This suggests that the rotating device evoked an automated response.

In surgery, the surgeon holds two instruments. Therefore, both instruments need a feedback module. Two sources of visual feedback, one for each instrument separately, might be more confusing than two sources of haptic feedback, as the haptic feedback is directly linked to the hand, holding the instrument, while the visual feedback has to be translated into the appropriate left or right response. Another observation was that in TestV the visual feedback evoked brief pinch responses while in TestT participants pinched until the motor stopped (Figure 4.2.3). The magnitude of applied forces in response to the different types of feedback was not examined since the focus of this experiment was on RT. Therefore, the participants where not instructed to respond with a certain pinch force. The relationship between applied force and type of feedback should be explored in further studies.

The reaction times on the tactile feedback signal in the current experiment were not as fast as possible. The delayed response (~72ms) of the motor is a factor that increased the actual human reaction time. A faster responding motor could be used to reduce the time between the driving signal and the rotating movement of the shaft. Furthermore, the task of the participants, reading a text about laparoscopy out loud, isn’t the same type of task as performing surgery. No actions, other than reacting to the feedback signals with the hands, were performed. Reading a text out loud was an easy way to make sure that the participants were not constantly focusing on a possible feedback signal. The use of manipulation tasks may be more suitable in this context, however, this requires a more complex test set-up. For the tactile feedback display there are many variables still to consider: which is the best surface texture on the rotating cylinder, the best size of the display, the best speed of rotating, the best position of the display in relation to the fingertip and which fingertip or position on the hand is best?

In conclusion, when slipping of tissue is simulated, tactile feedback of tissue slippage information during laparoscopic grasping shows significant faster reaction times than visual feedback. Providing feedback on slippage can help the surgeon to keep a safe grasp during surgery and during training (both virtual reality trainers and box-trainers), which will improve patient safety.

4.3. Bodily Self-attribution Caused by Seeing External Body-resembling Objects and the Control of Grasp Forces

The brain localizes body parts in their perceived visual locations. The brain can, however, be easily fooled. By making use of the Rubber Hand Illusion (RHI), a feeling of ownership of the rubber hand can be evoked. The influence of this illusion on grasp force has not yet been researched, but it might well prove promising for grasp control during tool usage. This study explores whether the RHI can be used to give a person better control over grasp force when manipulating an instrument that makes use of the RHI than when using an instrument that does not. Ten participants performed grasp and pull tasks under three different conditions. They were required to grasp an object with their bare hands, with a rubber-hand, and with an instrument. After analysing grasp forces during maximal pulling loads (4.95N barehanded, 6.45N rubber-handed and 7.9N using an instrument), it may be concluded that the RHI can contribute to improved grasp control.

4.3.1. Introduction

During daily life we can simply feel and manipulate objects with our bare hands. We can rely on the tactile and proprioceptive feedback that the body provides, to control grasp forces. Differences in applied force and slipperiness can be naturally corrected without damaging the grasped object or having slippage. We do not have conscious control over grip force modulations (Johansson 1998). It is when we start to use tools to grasp objects that problems can occur as we do not touch the objects directly which means that cutaneous receptors are not in direct contact with the objects in question. Objects can therefore be damaged or broken due to excessive pinch force or slippage.

The literature suggests e.g. (Armel and Ramachandran 2003, Ijsselsteijn *et al.* 2006, Makin *et al.* 2007, Longo *et al.* 2008, Makin *et al.* 2008) that the brain constructs a sense of the body by combining the information received from sight, proprioception and touch. Vision is the most dominant modality in creating such body images. Proprioception is the perception of movement and body part spatial orientation derived from stimuli (detected by mechanoreceptors in muscle tendons and joints, the vestibular system and the cutaneous sense) within the body itself (Makin *et al.* 2007, Westebring-van der Putten *et al.* 2008b). In this way, the brain constructs a sense of the body by combining influences and information gained from sight, touch and proprioception, rather than just passively receiving it (Ernst and Banks 2002, Haggard *et al.* 2003). Modalities are weighted by the brain on the basis of the estimated reliability of the information (Ernst and Banks 2002). In cases where vision does not correspond with proprioception and touch the brain often gives more weight to visual information than to proprioception and touch because vision is more reliable and spatial acuity is greater (Lee and Aronson 1974, Armel and Ramachandran 2003). Body parts are traced to the apparent visual location, particularly when the visible location corresponds to the possible range dictated by proprioception (Armel and Ramachandran 2003). Even non-informative vision can improve the spatial resolution of touch; during non visible passive touching of a body, gazing in the direction of the touched body part (but not seeing the actual touching) enhances the spatial resolution of touch (Kennett *et al.* 2001).

The Rubber Hand Illusion (RHI) reported in the relevant literature amounts to a multisensory conflict between sight and touch. Touch is seen on the rubber hand, but felt at a different location (in the own hand). The spot and the way in which both hands are touched should be similar though if this effect to be optimally present. The body can resolve the conflict by representing the rubber hand as one's own hand (and part of the so-called bodily-self) and picturing the real hand being in the rubber hand's position (Botvinick and Cohen 1998, Tsakiris and Haggard 2005, Costantini and Haggard 2007). With RHI there is a drift of bodily awareness towards the rubber hand. An external object can be perceived as a body part thanks to the visual capturing of proprioceptive information. Due to the rapid decrease in proprioception when there is no direct view of the touched object, the body automatically allows the visual information to replace the lack of visually supported proprioception (Botvinick and Cohen 1998, Tsakiris and Haggard 2005). The key to all of this lies in touch, synchrony between the stimulation of the rubber and the real hand, and the hands being equally postured and laterally similar.

The rubber hand illusion is mainly allied to the 'Bayesian logic' underlying all perception. When two perceptions from different modalities co-occur with high probability, they are connected to each other. With the RHI the seen and the felt touching are connected because they occur synchronously (Armel and Ramachandran 2003). The illusion is not significantly influenced by differences in skin tone, hand size, or specific characteristics of the participant's hand that are not visible on the rubber hand (Armel and Ramachandran 2003). Holmes *et al.* (2006) concluded that the visual information from the rubber hand only needs to approximately resemble aspects of the real hand.

The RHI also influenced the felt position of one's own hand. This derives from three-way interaction between sight, touch and proprioception (sensory information coming from the skin, joints, muscles, eyes and even from the ears (Makin *et al.*

2008)); the visually captured touch results in the mis-localisation of one’s own (unseen) hand towards the position of the (visible) rubber hand. It is in combination with the misinterpretation of visually captured proprioception that RHI occurs (Tsakiris and Haggard 2005, Costantini and Haggard 2007). During the RHI the peri-hand space is shifted from the own hand to the rubber hand(Graziano 1999). The peri-personal space is the space closely surrounding the different body parts. It represents the separation zone between the external environment and the body. The neurons, which code this peri-personal space, combine the visual and proprioceptive information of the hand to estimate the hand’s position. If this information conflicts the movement of the hands can be disrupted (Makin *et al.* 2008).

With the RHI, when the rubber hand is placed outside the original peri-hand space the visual information near the hand is not represented by the peri-hand mechanism (Lloyd 2007). That is why the strength of the illusion decreases when the rubber hand is placed further away from the real hand. A rubber hand can be assimilated, with simultaneous touch, into both the real hand and the rubber hand up to a distance of 91cm (Armel and Ramachandran 2003). This shows that the brain is able to assimilate a rubber hand to anatomically impossible distances. The strength of the illusion decreases though when the distance between the real and the rubber hand is greater than 27.5 cm. (Lloyd 2007)

In this article, we investigate whether bodily self-attribution caused by the seeing of external body-resembling objects can improve the control of grasp forces in tool usage. In other words whether, for instance, visual feedback obtained from a dummy hand implemented with the instrument used, can sufficiently stimulate bodily self-attribution to create greater control of the instrument and to thus allow the user to apply force in a more controlled way. This is a field that has not yet been investigated in this setting, though it is interesting and full of opportunities, for instance for the medical design industry, especially in circumstances where indirect grasping instruments are used, like in the case of Minimally Invasive Surgery (MIS; surgery through small incisions, using elongated instruments).

With the information given above it is hypothesized that a human using a tool to grasp something, can mentally override the lack of direct touch when the grasper tip looks like a real hand. There is currently no instrument or system that uses the effects of RHI. Before actually performing research in a complete MIS setting we test to see if the RHI can aid grasp control during tool usage by actually allowing subjects to see the tool-tip via a screen. It is hypothesized that participants will view the Rubber Hand as their own and therefore it is hypothesized that grasp forces will be better controlled (less force, less slippage) with the tool that makes use of the RHI than with the normal tool.

4.3.2. Method

Participants

Ten right-handed participants, three male and seven female, aged between 19 and 23 years participated in this study. The participants were unaware of the purpose of the experiment. The task of the participants was to grasp an object in three states: with their Bare Hand, between their thumb and index finger (1), with a Rubber Hand (2) or with an Instrument (3). The object had to be grasped from an elevation and pulled in a straight line towards the participant until out of range of the camera. Afterwards it had to be put back on the elevation.

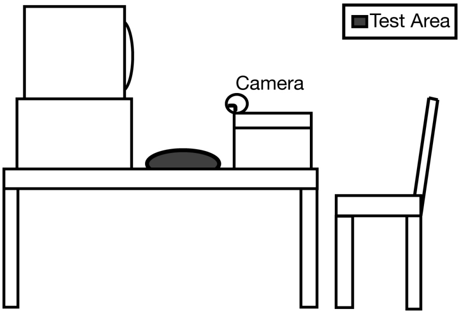


Figure 4.3.1. Schematic illustration of the experimental setup

Experimental set-up.

The object used was a cube (ten mm3, weighing 1.2 grams). To measure the pinch forces, a load cell (Futek WC1 USA, 245108-10LB) was attached to the top of the object. The pins of the load cell were the points where the object had to be grasped. The object was placed on an elevation that was 100 mm high. This was done to make the grasping of the object easier and to prevent the Instrument, the Rubber Hand and the real hand from touching the table and to thus, in that way, make it more difficult to successfully grasp the object.

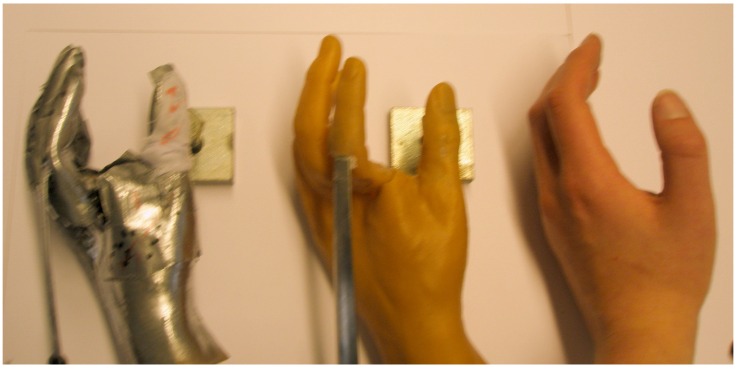


Figure 4.3.2. The Instrument, Rubber Hand, Real hand

In order to measure pull forces and ensure that the participants applied more grasp force than just the force needed to overcome gravity, a rubber band was attached to the object, which, in turn, was attached to a second load cell (50 N, 57250 type LCV-U). This second load cell was then attached to a fixed point.

In order to generate similar visual feedback in all three circumstances, a box was used to prevent the participant from directly seeing the object and hands. A camera (ELMO CCD AC-E31ZW) (see Figure 4.3.1) provided visual feedback on the object and Instrument/hands. The camera images were presented on a television screen that was positioned at eye level.

Two pairs of tongs (IKEA 365+ baking pincers) were used as instruments. One of the instruments was equipped with a fake rubber hand. We will refer to this instrument as the Rubber Hand. The other instrument was also equipped with a similar fake rubber hand, however it was painted and taped to make sure that, apart from its shape, it did not look like a real hand (see Figure 4.3.2). The object-contact places of the Instrument were not covered with paint or tape so that the material properties were similar to those of the Rubber Hand. We will refer to this as the 'Instrument'. The Instrument and Rubber Hand had to be similar in terms of shape and stiffness for the test results to be compared. A Left hand was used as no right Rubber Hands where available.

Procedure

The participants sat in front of the experimental set-up that was placed on a table in a well lit up room. The left hand of the participant was placed in the box while their other hand rested on their lap or on the table. The participants were instructed to grasp the object with the minimal degree of force required to prevent slippage. In each situation (1,2,3) the participant had to perform ten lifts. Before each new test, the participants were allowed to practice five times to be sure that they could perform the task that was required of them and to discover how to apply as little force as possible to prevent slippage. In total each participant performed fifteen practice lifts and thirty lifts in the three different situations. If slip occurred the lift had to be repeated. In between the different tests there was a break so that the procedure for the next test could be explained and the subjects had the chance to practice.

To prevent and exclude learning effects, the order of the tasks varied from participant to participant. There were six different orders, which were randomly assigned to the participants. The participant was provided with visual feedback through the screen about the movement made during the task. No feedback was given on the pinch and pull forces applied. After the experiment the participants were asked to rank the extent to which they agreed with three statements relating to their experiences during each of the tests. The following three statements were read aloud by the experimenter:

I. "I had the feeling that the force I had to apply to the object with my own hand matched the force that I had to apply with the Rubber Hand and the Instrument."
II. "I had the feeling that the Rubber Hand resembled my own hand when I looked at the television screen."
III. 'I had the feeling that the Silver Hand resembled my own hand when looking at the television screen."

The statements were translated into Dutch and the participants responded verbally using a ten-point scale with a score of 1 to show that they "strongly disagreed" and a score of 10 to indicate that they "very much agreed".

Data acquisition and analysis.

A descriptive analysis was used for the data obtained from the questionnaires to indicate whether the participants experienced the Rubber Hand as part of their own body. Further analysis of the data will reveal whether this feeling of the Rubber Hand belonging to one's self (the so-called Rubber Hand Illusion), gives the participant better control over his grasp force while using the Rubber Hand. The data acquired from the pull and pinch sensors was then processed in MatLab 2007b. The mean and standard deviation of pinch forces during the extreme pull, (mean pinch force at maximum pull forces) and maximum pinch force values during the movement were calculated. In this way it is possible to see if the forces using the Rubber Hand come closer to the forces used during a barehanded grasp than during a grasp with an Instrument. The number of times that slip occurred was counted during each condition. To ascertain if the data from the various conditions differed, a repeated measure ANOVA (SPSS 16) was carried out for all pinch force data. The number of times slip occurred was tested using the Wilcoxon Signed Rank Test. Posthoc tests were performed to see which condition differed. Significance levels were set at $p<0.05$.

4.3.3. Results

For technical reasons 36 out of 300 grasps contained incomplete data and were not therefore analysed. The score on the first question showed that (average 4.6) that the participants did not have the feeling that the force they had to apply with their own hands matched the force that they had to apply with the Rubber Hand or the Instrument. The scores on the second question showed (average 7.3) that the participants had the feeling that the Rubber Hand resembled their own hand. The score on the third question showed that (average 4.9) that the participants did not have the feeling that the Instrument resembled their own hand.

Table 4.3.1. Mean of the measured maximal pinch forces.

	Bare hand	Rubber hand	Instrument
Maximal pinch force during maximal pull force (N)	4.95	6.45	7.90
p	0.003*		
		0.006*	
		<0.000*	
Standard deviation of pinch force during maximal pull force (N)	0.22	0.15	0.09
p	0.35		
		0.48	
		0.006*	
Maximal pinch force during the whole movement. (N)	5.88	7.74	8.58
p	0.001*		
		0.288	
		<0.000*	

Table 4.3.1 shows the means of the maximal pinch forces for the three different situations. The mean maximal pinch force during the highest pull forces exerted with the Rubber Hand were significantly different when compared to the mean force exerted with the Instrument and the mean pinch force applied with the Bare Hand. The participants needed less pinch force to hold the object, while pulling hardest, with the Rubber Hand than with the Instrument. In addition, during the last pull phase there was no pinch force variation between the Bare Hands and the Rubber Hand whereas there was a difference between the Bare Hand and Instrument usage. If we look at the whole picture the Bare Hand circumstances demanded lower maximum pinch forces compared to both the other situations. The degree of slippage was significantly lower between the Bare Hand (median of zero times) and the Rubber Hand (median of two times) (p=0,02). The slippage shown while using the Instrument (median of one time) did not differ from the two other conditions.

4.3.4. Discussion

The purpose of this study was to establish whether bodily self-attribution caused by the sight of external body-resembling objects, improves the control of grasp forces during tool usage. The results of the questionnaire suggest that people do experience bodily self-attribution while using a Rubber Hand while that is not the case when using the Instrument. This was the expected outcome as the Instrument has the same form as a normal hand but not the same general appearance or skin colour resemblance.

It was expected that when using the Rubber Hand the participant would have a better control of his grasp forces than with the Instrument. The force applied when using the Rubber Hand would also be closer to what was exerted when using an own hand than the force exerted while using the Instrument. The participants needed less pinch force to pull the object with the Rubber Hand than with the Instrument. This could indicate that the Rubber Hand illusion was evoked and that the Rubber Hand was thus perceived as part of the participant's own body.

The participants used less force during the Rubber Hand experiment, especially during the high pull force phase of the movement, than when using the Instrument. They therefore used forces closer to slip forces (smaller safety margin) and as their own skin did not touch the object their cutaneous receptors are not able to detect slippage. With the Instrument they had a large safety margin, which was why slippage did not occur very often. Conversely, the results also showed that during the whole procedure the maximal pinch force exerted was lower, but not significantly lower when Rubber Hand use was compared to Instrument use. As the phase of the movement when this pinch force was exerted was not investigated it is difficult to compare the three conditions for this value. Part of the difference in force control between the conditions lies in the grip type that was used. Although the instruction was to hold the backing pincers with a precision grip they were grasped with a grip that looked more like a power grip (instead of the thumb and the tip of the index finger, the thumb and the side of the index finger where used) while the bare hand displayed a real precision grip. These grip types involve different neural structures with probably less fine control of force in the power grip.

The ideal situation during tool use would be for the user to feel as though he/she is actually touching the object with his/her barehands. It is not always possible to touch objects with one's bare hands, for example, during MIS. Our research showed that it might be possible for the sight of a hand touching tissue to evoke the RHI and a feeling of ownership over the Rubber Hand. Ideally the distance between the real hand and the Rubber Hand should not be greater than 27.5 cm (Lloyd 2007) because beyond that the illusion decreases significantly. The closer to the body the information is, the stronger the illusion will be. The relevant literature suggests that tool use can extend the peri-personal space (Tlauka 2004, Serino *et al.* 2007). This means that distance would not be an obstacle.

Making use of the Rubber Hand Illusion to innovate grasping tools may prove useful, since it will improve a users grasp force control by creating bodily self-attribution with his/her tools. If we look beyond the field of surgery, though, enhanced bodily sense would prove useful in generally evoking greater control over objects, for instance, in such areas as archaeology, production industries, the construction business, repairs, robotics and artificial limb creation.

Acknowledgements

We would like to thank the following students: Jael Nanarjain, Stephanie Kool, Mischa Meekes and Ingrid Verhoef for contributing to this research.

4.4. The Effect of augmented feedback on grasp force in laparoscopic grasp control

Little is known about the influence of augmented feedback, on laparoscopic grasp control. To gain more knowledge on the influence of this on the learning curve two experiments were conducted. In the first experiment, four groups learned a single-handed laparoscopic lifting task. Three groups received augmented feedback (visual, haptic or a combination of feedback modes) on slip and excessive pinch force. In the second experiment a two-handed task had to be accomplished to investigate whether paying reduced attention would influence grasp-force control. The surgeons and novices either received tactile feedback or no augmented feedback on grasp-forces. In both experiments learning sessions and a retention-test followed a pre-test. In the two-handed task, novices who received tactile feedback could control their pinch-force in order to remain within the required limits unlike participants who did not receive augmented feedback. Approximately one third of the participants who received augmented feedback became dependent on the signal. Regardless of their level of experience, participants benefited from augmented feedback. This research supports the claim that there is a need for augmented tactile feedback when learning laparoscopic grasp control. It enhances learning and goes beyond what could be achieved without.

4.4.1. Introduction

Laparoscopy is any Minimally Invasive Surgery (MIS), performed in the belly alcove. Compared to open surgery it is a technique that gives rise to difficulties for the surgeon (Stassen *et al.* 2001) and can lead to a higher rate of adverse events (Dankelman *et al.* 2003). One of the difficulties during MIS derives from grasp force control when manipulating tissue. Insufficient control of pinch and pull forces can lead to tissue slippage and to the use of excessive force. Both slippage and excessive force can damage the tissue being grasped. Tissue trauma caused by excessive grasp forces has been frequently studied (Cartmill *et al.* 1999, Heijnsdijk *et al.* 2003, De *et al.* 2006) and reported on (Reissman *et al.* 1996, Anup and Balasubramanian 2000, Marucci *et al.* 2000b, Heijnsdijk *et al.* 2002, De *et al.* 2006) . Both clinical and experimental data show that tissue slippage in laparoscopic grasping is common (occurring in 7% to 38% of all grasp actions) (Heijnsdijk *et al.* 2002, Westebring-van der Putten *et al.* 2009b). In addition, we showed in our previous work that during laparoscopic grasping excessive pinch force is applied and slippage occurs much more often than in barehanded grasping (Westebring-van der Putten *et al.* 2009b, Westebring-Van Der Putten *et al.* 2009c) . If surgeons can be taught to maintain a safe grasp faster and with greater accuracy then this will improve patient safety and reduce training costs.

Limited laparoscopic grasp control stems from a lack of direct tactile feedback (Westebring-Van Der Putten *et al.* 2009c), and from various haptic interference factors, such as the forces generated by the abdominal wall, reduced force transmission of the instruments and friction in the trocar (for a review see (Westebring-van der Putten *et al.* 2008b)). Further research carried out with handheld objects (D'Alessio and Steindler 1995) has suggested that in the interests of preventing slippage, grasp control can be more efficient when based on a slip signal generated by tactile sensors than on signals related to the force exerted by the fingers as in the case of laparoscopy. If there is no direct contact with the tissue the surgeon mainly has to rely on visual information about slip, but clinical data shows that they often react too late (Heijnsdijk *et al.* 2002, de Visser 2003).

Several studies have proven that augmented feedback on force information contributes to safe grasping (e.g. (MacFarlane *et al.* 1999, Bethea *et al.* 2004, Akinbiyi *et al.* 2006, Wagner 2006) for a review see (Westebring-van der Putten *et al.* 2008b)). However, none of these studies provide feedback on slippage. Augmented feedback is defined as feedback that is supplementary to the task-intrinsic (sensory) feedback naturally available while performing a skill. Augmented feedback comes from a source external to the person performing the skill and it helps him or her to learn the skill in question by enhancing or adding information to the task-intrinsic feedback. Augmented feedback enhances the task-intrinsic feedback when it provides information that the person’s sensory system can detect on its own but it adds information when a person cannot detect it with the help of his or her own sensory system (Magill 2006). Furthermore, providing augmented feedback enhances the danger of becoming dependent on augmented feedback. However, a study done by Judkins *et al.* (2006) has shown that when providing graphic augmented feedback on grip force information for short training periods (ten trials), users still use less force afterwards. This indicates that people did not become dependent on the augmented feedback. The specific contribution made by augmented feedback to the maintaining of a safe laparoscopic grasp has not been thoroughly studied.

The augmented feedback providing slip and grasp force information can be auditory, visual or haptic. Auditory feedback is not the most effective way of communicating with the surgeon, as there are many other noises in the surgeon’s environment (Bethea *et al.* 2004, Kitagawa *et al.* 2005). Several studies (e.g. (Bethea *et al.* 2004, Akinbiyi *et al.* 2006, Judkins *et al.* 2006)) showed that augmented visual feedback on force information can aid performance. However, there is some evidence that during palpation tasks (Ottermo *et al.* 2006), augmented visual feedback is not the most effective way of communicating force information. We also found that people reacted faster to a tactile stimulus than to a visual stimulus during a laparoscopic holding task in a box trainer (Westebring-van der Putten *et al.* 2009a). Augmented haptic feedback seems to be the most intuitive and natural way to present slip and force information, as this is the modality, which is distorted. Tactile feedback is the most natural way of expressing slip in terms of haptic feedback as slip is defined as the relative motion between a surface and the skin (Salada *et al.* 2004). However, the combination of haptic feedback with visual feedback as in a multi sensory display might be more effective than one of the modalities on its own. The aim of this study is thus to determine whether augmented feedback on slip and pinch force information can shorten the learning curve for laparoscopic grasp control and to then evaluate which kind of feedback is most suitable. This study also investigates whether this augmented feedback is necessary for maintaining a safe grasp or whether the augmented feedback can be dropped after the learning phase.

We conducted an initial experiment in which four groups of novices learned a single-handed laparoscopic lifting task. Three groups received augmented feedback (visual, haptic or a combination of the two) on upwards slip and excessive pinch force. The fourth group served as a control group and had to learn the lifting task without any extra feedback on slip or excessive pinch force except for verbal feedback during the learning phase. To test whether augmented feedback could aid grasp control in tasks when attention to the grasping hand was reduced we conducted a second experiment. In this experiment a dual handed task had to be learned with the aid of the kind of augmented feedback that helped the participants most in the first experiment. Experienced surgeons where included in the second experiment to see if augmented feedback could be helpful to them.

We had three hypotheses concerning the augmented feedback provided during dual handed laparoscopic grasping tasks; a) in two handed tasks, augmented feedback is more beneficial than in single handed tasks as participants have to divide their attention b) even experienced surgeons will use less force when they receive augmented feedback and c) participants will not become dependent on the augmented feedback containing pinch force information. Hence, after having provided augmented feedback in the learning phase, one is able to control grasp forces better when this feedback is not available anymore.

4.4.2. Method

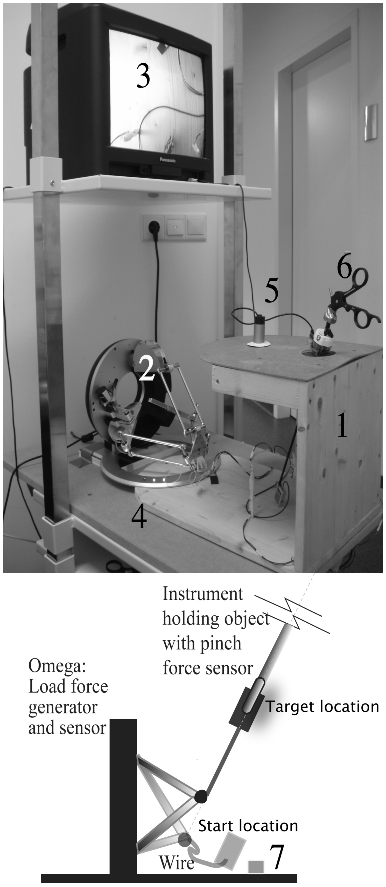


Figure 4.4.1. Experimental setup. 1: box-trainer, 2: haptic device, 3:working screen, 4: adjustable table, 5: camera, 6: trocar plus instrument, 7: movable push button (Experiment 2).

Task

The task in Experiment 1 (Exp1) was to lift (grasp and pull) an object to predefined target goals whilst exerting the minimum amount of force required to prevent slippage. In Experiment 2 (Exp2) an extra task was added. During the lifting phase participants had to push a button with the other tool. In order to learn the task, participants had to complete several learning sessions with several lifts. They also performed a pre-test and a retention test without any augmented feedback. The sessions are explained in the procedure sections of both experiments.

Apparatus and Instruments

Figure 4.4.1 gives a representation of the setup. The setup is described in brief. A thorough description of the experimental setup can be found in (Westebring-Van Der Putten *et al.* 2009c).

To measure pinch forces, a load cell (LSB200-10LB FUTEK) was attached to the tip of the laparoscopic grasper (type 33310 ON, Karl STORZ, Tutlingen, Germany) with a force transmission ratio that was comparable to the most efficient grasper used in our previous study (Westebring-Van Der Putten *et al.* 2009c). The pull force needed to lift the object, depended on the distance from the starting force and was generated by a robotic device OMEGA (Force Dimension, Switzerland). In order to simulate the grasping of human tissue, where elasticity only becomes noticeable once stretched, the object was attached to a slack wire (Figure 4.4.1). Therefore, when moving the object, the wire had to be tightened before the object was subjected to the different forces. As the aluminium object was covered with rubber the surface was not slippery.

Data on pinch and pull forces were sampled at 500 Hz. The target locations where indicated by LEDs on a pole. The LEDs were positioned in such a way that the object had to be moved over a distance of 50 or 62.5 mm. A Bullit-camera (type SecCam50, Nedis, s-Hertogenbosch, the Netherlands) was attached to the box-trainer and provided the participants with a real-time 2D view of their work area on a screen placed at eye level (comparable to a real surgery situation). The screen provided all participants in all conditions with normal visual feedback on the properties of the object.

Augmented feedback on excessive force and on a force 10% above the actual slip-force was given. (For the values see the procedure sections for each experiment). Augmented Tactile feedback on slippage was provided by means of a small electric motor with a speed reduction gearbox and a cylindrical piece (length 25 mm, diameter 25 mm) made of the polymer POM attached to the shaft of the motor. A description of the slip display can be found in (Westebring-van der Putten *et al.* 2009a). The slip display (see Figure 4.4.2) was attached to the grasper handle in an adjustable way so that it fitted into the hand as comfortably as possible and would touch the participant's thumb. A vibro-tactile display, to inform the participant about excessive pinch forces, was constructed out of a vibro-tactile cylinder covered with foam and an elastic sleeve. The display was attached to the palm of the participant's hand by means of an adjustable elastic band (see Figure 4.4.2).

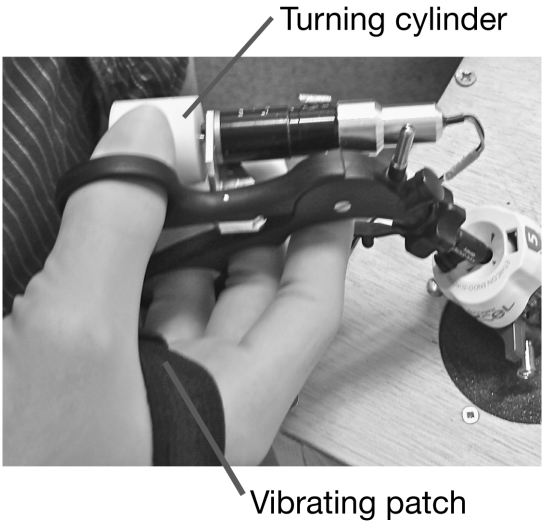


Figure 4.4.2. Hand placed on the handle with Tactile feedback.

Small LEDs (3mm) were placed on top of the object that had to be lifted and were used to provide augmented visual feedback on the forces exerted. A green LED was used to inform the participant of too low forces and a red LED to inform him or her of excessive force (Figure 4.4.3).

Both the Visual (V) and Tactile (T) feedback signals were programmed in such a way that feedback was only provided when the pinch force applied exceeded the safe area. This pinch force safe area, while pulling (grasping and lifting) tissue, has been explained by de Visser *et al.* (2003) and by Westebring-van der Putten *et al.* (2009c). The safe-areas used for these experiments are described in the procedure section of each experiment.

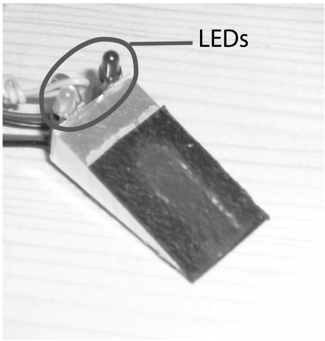


Figure 4.4.3. Object with augmented visual feedback LEDs The object had no LEDs in the conditions without augmented visual feedback

Data Analysis and Statistics

For both experiments (Exp1 and Exp2) the following performance measures were analysed in the pre-test, learning sessions and in the retention-test: percentage of safe-lifts (lifts within the safe-area) (*Safe*), percentage of lifts containing slippage (*Slip*), percentage of lifts where the pinch force exceeded the damaged-line (*Damaged*), the maximum pinch force (*Fmax*) applied during the lift and the standard deviation of the maximum applied pinch force (*SD*).

Overall, when the variable *Safe* increased over the course of time participants learned to control their grasp. When the variable *Damaged* decreased and the variable *Safe* increased participants produced fewer lifts with excessive force. When the variable *Damage* did not decrease while the variable *Safe* increased the participant experienced less object slippage. When the variable *Fmax* decreased it meant that the participant had learned to avoid peak forces when lifting. The variable *SD* is an indication of grasp force steadiness. The smaller the variable *SD*, the more stable the grasp force.

Comparisons Within Groups: For all the different feedback conditions in Exp1 and Exp2, pre-test performance (*Safe, Damaged, Fmax and SD*) was compared with performance in the last learning sessions and with performance in the retention test. The first comparison was made to determine whether a training period with augmented feedback can lead to better performance. The second comparison was made to see if the performance level after training with augmented feedback can be maintained, or whether augmented feedback is a prerequisite for better performance. In addition, in Exp2, these analyses were also made for the subgroups (different experience levels).

Comparisons Between Groups: In order to establish whether the different groups started with a comparable level of dexterity, the performance of the groups with different feedback conditions in the pre-tests where compared to each other. In the case of both experiments the last learning session and retention tests where compared in order to ascertain under which conditions, performance was best after learning. In Exp2 both the different conditions and the subgroups at the same experience levels, but subjected to different conditions, were compared to each other.

Data was analyzed using analysis of variance (ANOVA) and a Bonferoni correction as multiple analyses of variance had to be carried out (the significance was set at $p<0.0125$). When ANOVA showed significant differences, post hoc Holm-Sidak analyses were conducted. The data where percentages were analysed were not normally distributed so Krusskal Wallis ANOVA's and Wilkoxon rank sum tests were used in these cases. These test are applicable for smaller amounts of participants per group (Machin D *et al.* 1997). The MATLAB 2007b Statistical Toolbox was used to perform the statistical analyses.

4.4.3. Experiment 1

Participants Exp1

Twenty-eight medically trained participants (employees of the Catharina Hospital, Eindhoven, the Netherlands) with no previous laparoscopic experience (aged 20-46 years) participated in this experiment. Balanced for gender, the participants were randomly assigned to one of the four groups, each with a different feedback condition; group N had no augmented feedback (seven participants; four females (one left-handed) and three males), Group V had augmented visual feedback (seven participants; three females (one left-handed) and four males), Group T had augmented tactile feedback (eight participants; four females and four males) and Group VT had combined augmented visual and tactile feedback on applied pinch force (six participants; three females and three males). All participants signed an informed consent agreement.

Procedure Exp1

After lifting the object to the target location, the participants had to hold it there for 2 seconds and release the object gently to the start location. The set-up was adapted in case of left-handedness. To prevent the participants from automatically moving the object to the target position, they were asked to move it to one of two slightly different target locations in a smooth straight movement. The distance they had to lift the object and the object elasticity they felt while pulling were adjusted in such a way that the pull force needed to reach the target location was always 5 N. This was the pull force chosen because surgeons maximally apply 5 N of pull force to the colon to stretch the mesocolon for dissection (de Visser *et al.* 2002).

The participants were instructed to handle the object as if it was very delicate tissue. The participants were informed that they had to learn to apply the minimum required amount of pinch force and to prevent slippage without applying excessive force. The slip-line was defined as a pinch force 10% above the actual measured slip force and the damage line was defined as a pinch force which was negatively related to the applied pull force (*Fpull*); damage-line = 5.75 – 0.4 Fpull.

As the purpose of the experiment was to investigate whether or not a participant can learn to stay within a predefined area of allowed pinch forces it is not important to know how the damage-line is defined. However, we wanted the damage-line to present a realistic damage-line. The damage-line was therefore chosen with these values for the following reasons; Pinch forces at which the human small intestine is perforated are approximately 10.3 +/- 2.9 N (Heijnsdijk *et al.* 2003). These perforation forces were determined without exerting a pull force, which meant that adding a pull force would result in lower perforation forces. We chose a start pinch force (zero pull force) of 5.75 N, which is well below the perforation forces for the small intestine. In our former study (Westebring-van der Putten *et al.* 2009b), where similar graspers were used, the minimum applied pinch forces at pull force levels of 5 N were around 3-3.5 N, Therefore, 5.75 N as a starting point for the damage-line is not impossible It also means that it is possible to have such a low pinch-force level at the end of the lift. The end-value of the damage-line was thus set at 3.75N just above the minimum measured values.

In condition V, the LED's (explained in section 4.4.2) informed the participant both of imminent slippage and of the applied pinch force exceeding a predefined level based on the hypothetical damage-line. In condition T, tactile feedback, as described in section 4.4.2, informed the participant of imminent slippage and maximum allowable pinch forces. In condition VT, both visual and tactile feedback was provided simultaneously.

The groups V, T and VT were told that after the learning sessions they had to perform a retention test where they had to lift the object without augmented feedback and still use as little pinch force as possible to prevent slippage. Group N served as a control group and received the same instructions but the only feedback they had was on the actual slippage of the object when the pinch force was too low and verbal feedback on excessive pinch forces. All the participants wore surgical gloves.

To define the dexterity starting level, each group lifted 8 times without feedback (2 targets 2 elasticity profiles) in what was known as the pre-test (Pre-L). After these initial lifts 10 learning sessions (L1 to L10) were performed, each involving 16 lifts with augmented feedback (except for group N, which lifted an object without augmented feedback) with a 1-minute rest between sessions to prevent fatigue. Participants had 10 minutes to rest after L10, followed by a retention test containing eight lifts with no augmented feedback (Post-L). Each eight lifts involved 4 target positions times 2 different stiffness profiles, randomly presented. The task in the learning sessions was exactly the same as in the pre- and retention test.

4.4.3.1. Results Exp1

The data derived from one participant from group T could not be used due to technical problems during the experiment. The results of Exp1 are listed in Table 4.4.1. The dexterity of the participants within the different groups did not significantly differ at the start of the experiment.

Comparison within groups Exp1

Groups V and T, did not learn from the learning sessions, as their variables in the last learning session (L10) were not significantly better than in the pre-test (see Table 4.4.1 and Table 4.4.2). As can be seen from Table 4.4.1 their median performance in the pre-test was already above a score of 50% safe lifts. Group VT as a whole did learn: after practicing they had significantly more safe lifts and less lifts where the pinch force crossed the damage-line. The group did not furthermore develop a dependency on the provided augmented feedback. However, the maximum applied force was not reduced over the course of the sessions. This means that the maximum pinch force was applied at different pull force levels, thus resulting in fewer damaged lifts. Group N as a whole did not learn to make more safe lifts. They did use less force after practicing but it was still too much to reduce the number of damaged lifts

Table 4.4.1. Results of Exp1

	Con.	***Safe lifts*** % Median(25-75pct)	***Damaged*** % Median(25-75pct)	***Slips*** % Median(25-75pct)	***Fmax*** **N** Mean(sd)	***SD*** **N** Mean(sd)
Pre-L	**N**	25 (25-81.3)	50 (6.25-71.9)	0 (0-32.3)	4.6(0.6)	1.0(0.3)
	T	62.5(40.6-71.9)	0 (0-31.3)	12.5 (0-21.9)	3.8(1.1)	0.9(0.5)
	V	62.5 (31.3-71.4)	14.3 (12.9-65.6)	0 (0-10.7)	4.6(1.3)	1.3(0.6)
	VT	31.3 (12.5-50)	62.5 (37.5-75)	0 (0-12.5)	4.1(0.8)	1.1(0.5)
L10	**N**	50 (44.5-70.3)	37.5 (16-51.6)	6.3 (0-10.9)	3.8(0.7)	0.7(0.2)
	T	80 (59.3- 100)	6.7 (0-12.5)	0 (0-5)	3.4(0.6)	0.8(0.2)
	V	68.8 (63.5-87.5)	31.3 (7.8-32.8)	0 (0-10.9)	3.8(0.5)	0.9(0.1)
	VT	78.1 (73.3-82.3)	9.4 (0-20)	6.5 (0-12.5)	3.8(0.4)	0.7(0.2)
Post-L	**N**	71.4 (53.1-84.4)	25 (3.6-41.5)	0 (0-13.8)	3.7(0.5)	0.6(0.2)
	T	62.5 (50 - 90.6)	0 (0-31.3)	0 (0-9.4)	3.6(0.5)	1.0(0.4)
	V	62.5 (28.1-75)	12.5 (0-31.3)	12.5 (0-25)	3.6(0.9)	1.1(0.3)
	VT	68.8 (57.1-75)	18.8 (0-28.6)	13.4 (0-25)	3.9(0.6)	0.7(0.2)

Pre-L: pre-test, L10: last learning session, Post-L: retention test, V: visual feedback, T: tactile feedback, VT: visual and tactile feedback, N: control group

Although the performance of most of the groups as a whole did not improve some individuals did learn, as can be seen from Table 4.4.3. In addition, there were participants who did not learn and scored, throughout all the sessions, fewer than 50% safe lifts. Some participants started with a competence level of above 80% in terms of safe lifts and were unable to improve. Table 4.4.3 shows that half of the participants who received augmented feedback became dependent while the other half did not. Figure 4.4.4 shows examples of the learning curves of an individual who did become dependent on the feedback signal and of one who did not.

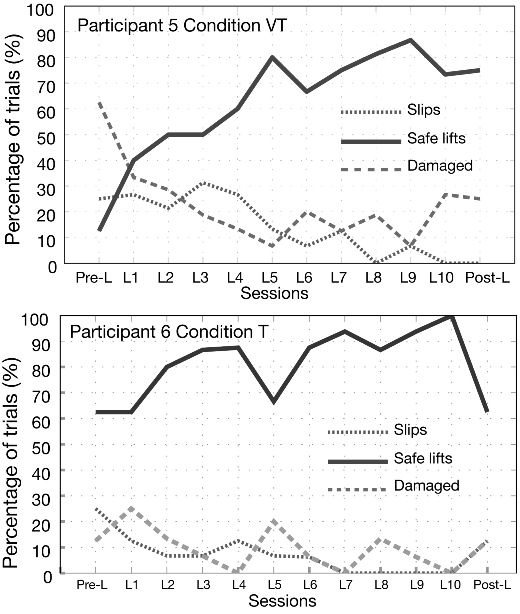


Figure 4.4.4. Learning curves of two individuals; one dependent and one not. Upper panel; a participant who did not become dependent and lower panel a participant who did become dependent of the feedback signal.

Comparison between groups Exp1

Comparisons made between the four groups after the learning sessions (L10) showed that no significant differences were found (see Figure 4.4.5 for the variable Safe Lifts). Additionally, there were no significant differences between the four groups in the retention test (Post-L).

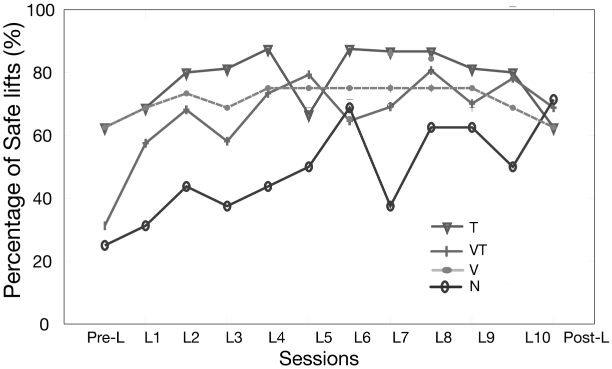


Figure 4.4.5. Median Learning curves for safe lifts for all the conditions in Experiment 1. The continuous lines are the median curves. T: Tactile feedback, VT: Visual and tactile feedback, V: Visual feedback, N not augmented, except from verbal feedback.

Table 4.4.2. Comparison within Groups of Exp1

Condition	***Variable***	***Pre-L, L10, Post-L***	***Post-Hoc Pre-L– L10***	***Post-Hoc Pre-L–Post-L***	***Post-Hoc L10-Post-L***
No (N)	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	$F_{20,2}$=8.33 p=0.005*	p =0.003*	p = 0.005*	p= 0.77
	SD	*NS*	*NS*	*NS*	*NS*
Tactile (T)	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	*NS*	*NS*	*NS*	*NS*
	SD	*NS*	*NS*	*NS*	*NS*
Visual (V)	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	*NS*	*NS*	*NS*	*NS*
	SD	*NS*	*NS*	*NS*	*NS*
Visual and Tactile (VT)	*Safe lifts*	$Chi^2_{17,2}$=10.71 p=0.005*	p=0.004*	p=0.006*	p=0.096
	Damaged	$Chi^2_{17,2}$=10.64 p=0.005*	p=0.003*	p=0.005*	p=0.037
	Fmax	NS	NS	NS	NS
	SD	NS	NS	NS	NS

** Significant. Pre-L: pre-test, L10: last learning session, Post-L: retention test, NS: not significant*

Table 4.4.3. Different Variance of Learning Profiles of Exp1

	Dep.	***Indep.***	***Imp.***	***Bad***	***Good***
V	3	4	3	1	3
T	3	4	5	1	1
VT	3	3	5	-	1
N	n.a.	n.a.	4	2	1

Number of participants Dep.: that became dependent on augmented feedback, Indep: that became independent on augmented feedback, Imp: improved significantly during learning. Bad: number of participants not obtaining 50% of safe lifts after learning and who did not perform better than before learning. Good: number of participants scoring over 80% of safe-lifts in the pre-test. V: visual feedback, T: tactile feedback, VT: visual and tactile feedback, N: control group

4.4.3.2. Discussion Exp1

As can be seen from Figure 4.4.5, groups who received augmented feedback tended to have an advantage over the group who only received verbal feedback (group N). This difference could be bigger if we had not given this group so much verbal feedback. It was the purpose of telling group N only once not to use too much force. However, the experimenter saw that the group was still using excessive force. To be sure that they understood their tasks we repeatedly gave them verbal feedback.

However, the performance of many participants did not improve, as they were already performing well at the start of the experiment. There were also some individuals who never succeeded in properly controlling their grasp force.

From this first experiment we can conclude that the task was too easy for most subjects. Presumably the subjects were able to completely focus on their respective grasp forces so that the kind of additional feedback they received became irrelevant. Because of the low number of participants no hard conclusions on dependency can be drawn. To determine whether augmented feedback is more beneficial when attention is drawn away from the grasping hand, a second experiment was conducted. In the first experiment slightly better results were obtained for augmented tactile feedback, which was why we only used augmented tactile feedback in the second experiment.

4.4.4. Experiment 2

Participants Exp2

Thirty-nine participants (right-handed surgeons and medical trained staff at the Catharina Hospital, the Netherlands) were assigned to two groups. Eleven participants where assigned to the control group for which no augmented feedback was provided (group N) and twenty-eight participants were assigned to group T where augmented tactile feedback was provided. All participants gave their informed consent.

The two groups were divided into subgroups according to laparoscopic experience level. Group T consisted of twelve participants with no experience, six had previously participated in Exp 1, four participants had virtual reality (VRT) and box-training experience, two participants had performed 20-150 real laparoscopic procedures in total and four participants had performed more than 100 procedures a year for more than four consecutive years. Group N contained four participants with no experience. Six participants also participated in Exp1 and one participant had only virtual reality training.

Analyses of variance (ANOVA) were conducted to compare the start level of dexterity of the different subgroups. The results showed that there were no significant differences between participants who only had virtual reality training and participants who had no training at all. These subgroups were therefore combined. A combination of VRT and box-training experience, and experience in performing 20 to 150 laparoscopic procedures resulted in equally skilled participants. These participants where consequently placed in one subgroup as well. Subjects who participated in Exp1 tended to be more skilled than participants with no experience at all. However, as the time between the two experiments varied from four and sixteen weeks and as the feedback modality that was used in Exp1 differed from participant to participant, it is hard to draw any conclusions about the transfer of learning from Exp1 to Exp2. An ANOVA showed that within group N there was no difference between the novices and the participants who also participated in Exp1. We thus combined them into one group N_{nov}. However, within group T the difference between the novices and those who participated in Exp1 was significant and so the beginners subgroup T_{beg} was created. Table 4 shows the composition of the groups and subgroups. To check if both subgroups of novices (N_{nov} and T_{nov}) had similar starting levels an ANOVA was conducted. This test showed no significant dexterity differences in starting levels between the two subgroups with novices.

Table 4.4.4. Compilation of the Subgroups of Exp 2.

Group	T				N
Experience level (sub-group)	Nov.	Beg.	Int.	Exp.	Nov
Number of p	12	6	6	4	11
Male	9	5	3	4	6
Female	3	1	3		5
Age	20-25	22-29	23-36	37-66	22-46
Data unused		1		1	

Level of experience; Nov: Novices with no experience or participants with only virtual reality training, Beg: Beginners, participants who participated in experiment 1 as well, Int: Intermediates, participants with virtual reality + box training experience and surgeons who had conducted 20-150 laparoscopic procedures, Exp: Experts, Surgeons who had conducted more than 100 procedures a year for more than 4 consecutive years N: no augmented feedback and T: tactile augmented feedback

Procedure Exp 2

The main task of Exp2 was the same as that of Exp1 but there was also an extra task for the left hand. While the right hand was holding the object at the target location (after completion of the lift), a button had to be pushed with the instrument that was being held with the left hand. The main purpose of this extra task was to distract attention from the grasping hand. Pushing a button was technically easy to implement and control, and fulfilled the goal. However, we could have used many other tasks as well. In real surgery a surgeon often has to perform additional tasks (e.g. cutting, palpating, removing tissue) along side lifting tissue with one hand, which will also distract attention from the hand performing the tissue lift.

The position of the button randomly varied between lifts to make the task more difficult and to avoid automatism. An audible sound signalled that the task had been completed and that the participant could therefore release the button and the object.

Participants either received augmented tactile feedback (T) as described in the procedure for Exp1 or no augmented feedback (N). Both groups were told to handle the object with extreme care and to use as little force as possible in order to prevent slippage. This was repeated between all the sessions. As the object was slightly modified (smaller contact area) the feedback actuators were set to provide feedback as follows: Damage-line = 5 – 0.1 Fpull and Slip-line = 10% above actual slip force

Exp1 showed that in general there was not much improvement in skills after 5 sessions. Therefore we reduced the number of sessions to five. The participants had to complete a pre-test (Pre-L) with no augmented feedback, five learning sessions (L1-L5) with augmented feedback (in group N there was no augmented feedback) and a retention test (Post-L) with no augmented feedback. Each session involved performing 10 lifts. Between sessions there was a two-minute break and there was a five-minute break between L5 and Post-L. Each session consisted of 2 target positions and 2 different stiffness profiles, which were randomly presented.

4.4.4.1. Results of Exp 2

The data obtained from two participants in group T could not be used due to technical problems during the experiment (see Table 4.4.4). The results of Exp2 can be found in Table 4.4.5 and figure 4.4.6. Figure 4.4.7 shows a typical plot of a pre-test and a retention-test of one individual who received augmented feedback. The pinch and pull forces are plotted against time and in the second series the pinch forces are plotted against the pull forces. As can be seen from the various sessions this participant evidently learns to control his/her pinching pressure. The initially high force used at the beginning of the lift is reduced and the spread of forces used is much smaller after learning. Such improvements are not observed in the plots of participants who did not receive augmented feedback.

Table 4.4.5. Results of Exp2

	Con.	***Safe*** **lifts %** Median (25-75pct)	***Damaged*** **%** Median (25-75 pct)	***Slips*** **%** Median (25-75pct)	***Fmax*** **N** Mean(sd)	***SD*** **N** Mean(sd)
Pre-L	N_{Nov}	0 (0 - 20)	70(60 - 87.5)	10 (2.5 - 20)	9.2 (3.6)	2.8 (1.0)
	T	20(0-50)	45(20 - 80)	10 (0 - 20)	8.0 (4.0)	2.5 (1.7)
	T_{Nov}	10(0 - 55)	40(20-80)	10(0 -15)	7.9 (3.4)	2.5 (1.7)
	T_{Beg}	40(32.8-72.5)	50(17.5-51.4)	0 (0 - 23.3)	6.2 (2.4)	1.9 (1.3)
	T_{Int}	10 (0 - 20)	85 (70 -90)	5 (0 - 20)	11.5 (4.6)	3.6 (1.2)
	T_{Exp}	50(50-65)	20(5 - 20)	10 (10 - 17.5)	4.3 (1.0)	1.4 (0.9)
L5	N_{Nov}	10(0 - 47.5)	60 (40 - 77.5)	10 (0 - 20)	6.8 (1.9)	1.5 (0.6)
	T	80(60 - 90)	10 (10 - 30)	0 (0-10)	4.4 (0.9)	0.9 (0.4)
	T_{Nov}	85 (80-90)	10 (0-10)	0(0 - 5)	4.1 (0.4)	0.7 (0.3)
	T_{Beg}	70(47.5-92.5)	10 (0 - 27.5)	10 (0 - 20)	4.5 (1.3)	0.6 (0.3)
	T_{Int}	60 (50-70)	35 (20- 50)	0 (0 - 10)	5.2 (0.6)	1.2 (0.5)
	T_{Exp}	60(52.5 - 75)	10(2.5 - 32.5)	10 (10 - 25)	3.6 (1.0)	1.2 (0.3)
Post-L	N_{Nov}	20(2.5 - 47.5)	60(42.5-89.2)	10(2.5 - 10)	6.4 (1.8)	1.7 (0.7)
	T	60(40 - 90)	25(0 - 60)	10 (0 - 10)	4.7 (1.4)	1.2 (0.5)
	T_{Nov}	55 (35-90)	35 (5-65)	0 (0 - 10)	4.7 (1.4)	1.3 (0.5)
	T_{Beg}	70 (52.5 - 90)	20 (0 - 32.5)	10 (7.5- 22.5)	4.6 (1.3)	1.0 (0.5)
	T_{Int}	40 (40 - 50)	50 (10 - 60)	5(0 -20)	5.3 (1.4)	1.1 (0.5)
	T_{Exp}	60 (60-75)	20 (5 - 27.5)	10 (2.5 - 10)	3.9 (1.3)	1.0 (0.7)

Pre-L: pre-test, L5: last learning session, Post-L: retention test. N: no augmented feedback and T: tactile augmented feedback. Nov: Novices, Beg: Beginners, Int: Intermediates, Exp: Experts.

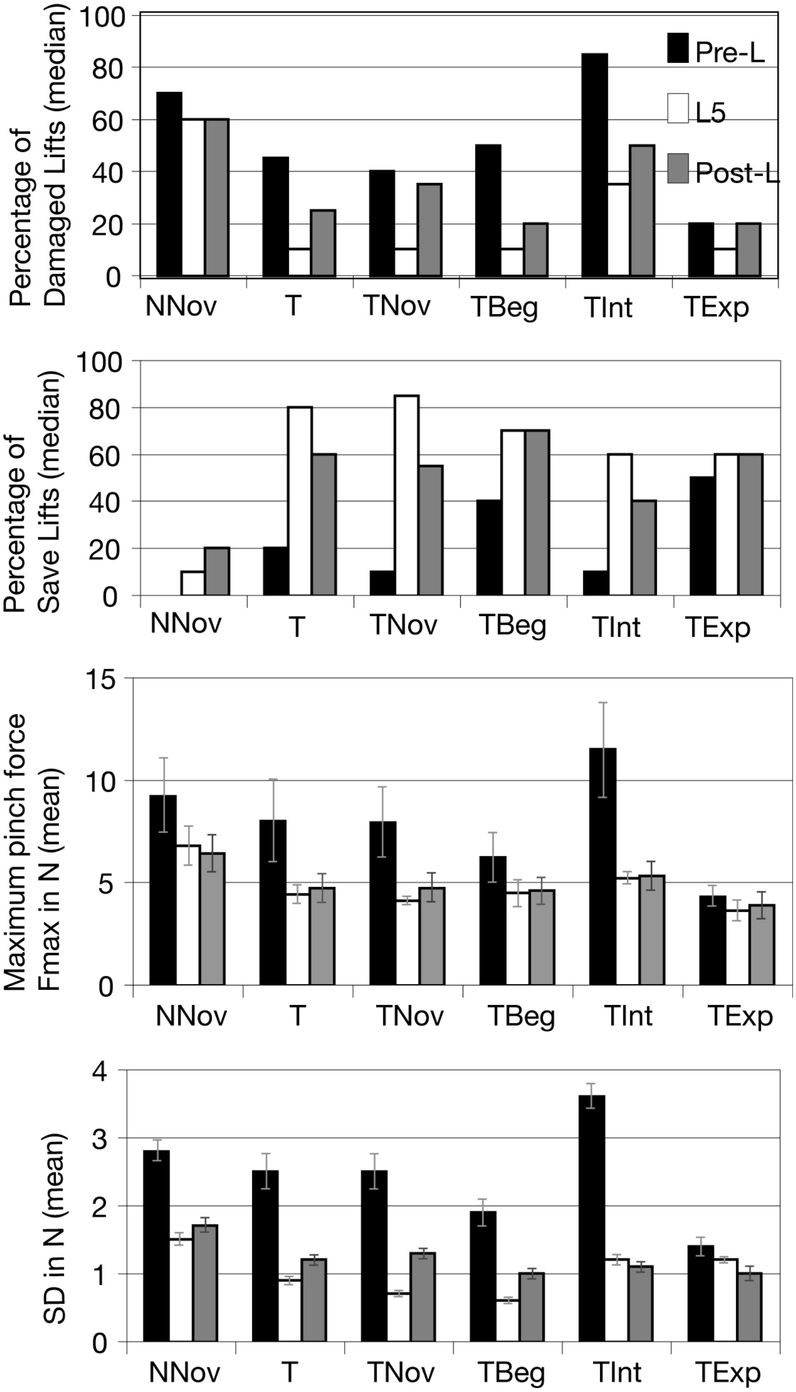


Figure 4.4.6. Data of table 4.4.5

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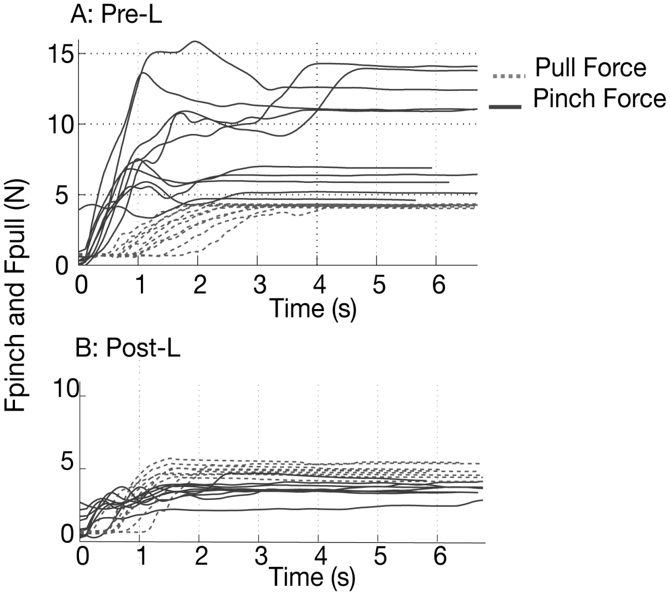

Figure 4.4.7. Pull and pinch force combinations during lifts before and after learning displayed by a participant of Group TNov. Upper panel Pre-L, Lower panel Post-L

Comparison within groups

Figure 4.4.8 shows the learning curves each subgroup for the variable *Fmax.* Figure 4.4.9 shows the typical learning curves of an individual drawn from each subgroup in relation to the variables *Safe, Slip* and *Damage*. For comparison the median of the whole group are drawn as well.

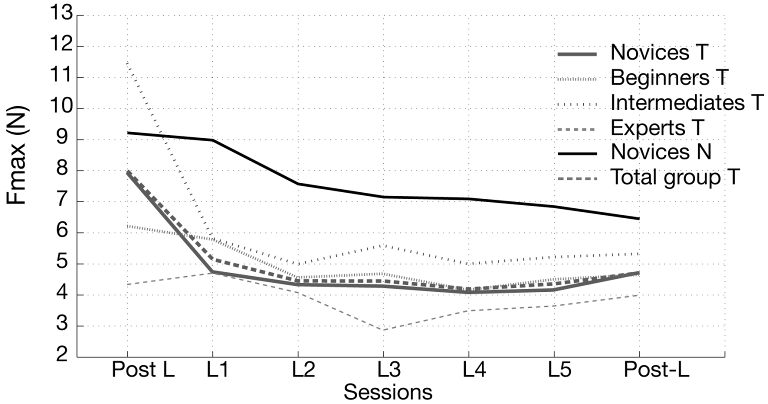

Figure 4.4.8. Mean of maximal pinch forces used by the different subgroups

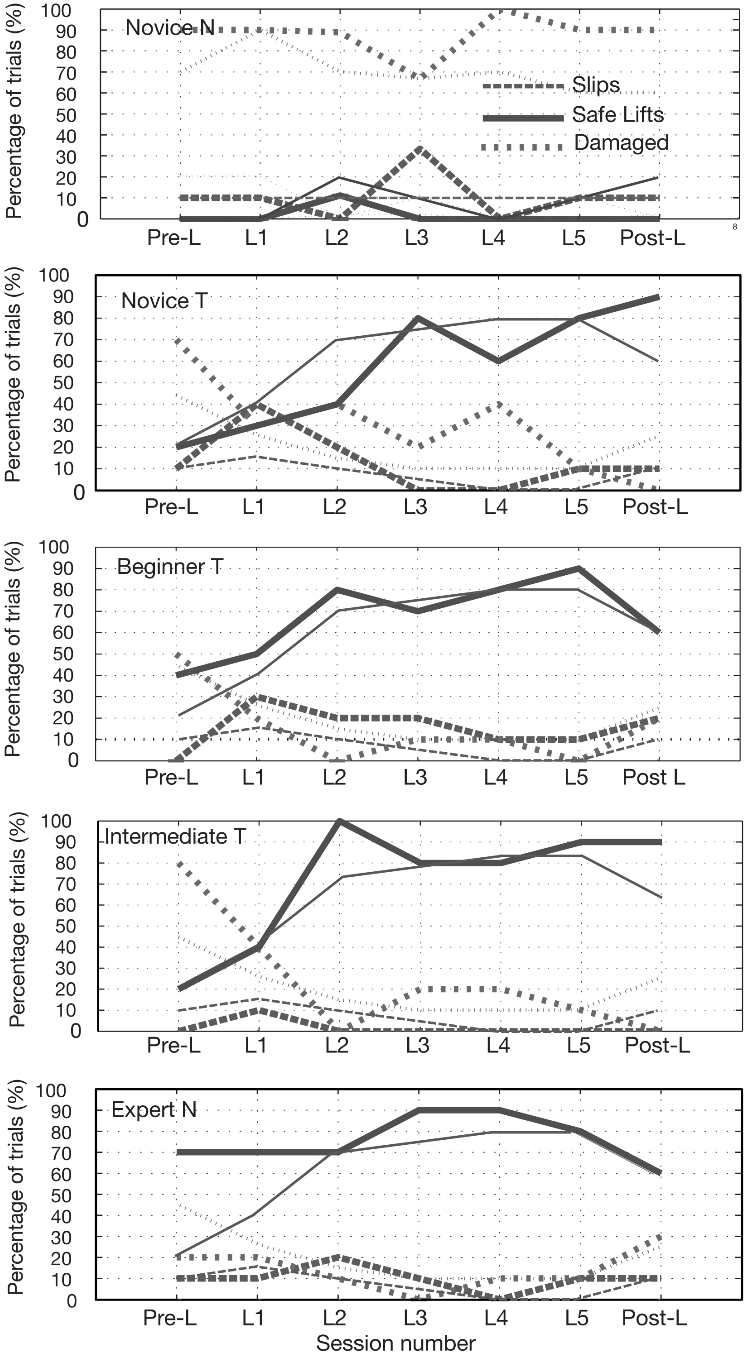

Figure 4.4.9. Thick lines: The individual learning curves of 5 individuals. Thin lines: Mean of the group. T: augmented tactile feedback, N no augmented feedback.

Table 4.4.6 shows that participants who did not receive augmented feedback (N_{nov}) did not produce more lifts within the safe-zone after learning. However, their performance became more stable over the course of time and they tended to use less force. If we look at the individuals concerned, there were six participants who did not improve and five participants who made improvements but did not exceed the 50% safe lift level (Table 4.4.7).

We analysed group T as a whole before we looked at the subgroups (Table 4.4.7). After learning, participants who received augmented feedback produced significantly more lifts within the safe-zone and applied significantly less force. As a group, these participants did not become dependent on the augmented feedback. However, after the augmented feedback was removed the participants experienced more slippage than during the last learning session but it was still significantly less than when they started (see Table 4.4.6). Basically, all participants improved during the learning process, three of them already performed well at the start (see Table 4.4.7).

Subgroup T_{Nov} improved after learning and had significantly more safe lifts and fewer damaged lifts. However, they became dependent on the augmented feedback (Table 4.4.7). Regarding the force used and the stability of their performance, they did not become dependent on the augmented feedback and they used significantly lower forces and had a more stable grasp after learning. At individual level, all participants improved during learning except for one who already performed well to start off with. Half of the participants became dependent on augmented tactile feedback.

As a group, subgroup T_{Beg} did not produce significantly more safe lifts or fewer damaged lifts after learning. There was a tendency to gain a more stable grasp and to use less force after learning. On an individual level, all except for the one who already performed well improved their skills during learning.

After learning, subgroup T_{Int} produced significantly more safe lifts and the grasp force of individuals became more stable. Since the percentage of damaged lifts was not significantly lower after learning there were significantly fewer slips when declaring the improvement in the number of safe lifts. The forces used after learning where significantly lower than before learning. No dependency on augmented tactile feedback developed. At individual level, all participants improved their skills and only one became dependent.

Subgroup T_{Exp} did not learn from practicing with augmented tactile feedback. If we look at the individual learning curves of the three experts there was one who already performed well while the other two improved their skills and became dependent on the signal. Figure 4.4.10 shows the results of one of them in the bottom panel.

Figure 4.4.10 shows the typical plots for the spread of the pinch forces used with a specific pull force for each subgroup. As can be seen, the spread of the forces used is smallest during L5, except for in the case of the participant from N_{Nov}. It can be seen that some of the participants became dependent on augmented feedback because the spread of forces in Post-L is larger than in L5.

Table 4.4.6. Comparison within Groups of Exp2

Condition	***Variable***	**Pre-L, L5 Post-L**	**Post-Hoc Pre-L – L5**	**Post-Hoc Pre-L–Post-L**	**Post-Hoc L5-Post-L**
N_{Nov}	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	*NS*	*NS*	*NS*	*NS*
	SD	$F_{(32,10)}$= 8.13 p=0.003*	p=0.001*	p=0.004*	p=0.64
T	*Safe lifts*	$Chi^2_{(77,2)}$=23.70 p<0.001*	p<0.001*	p<0.001*	p=0.02
	Damaged	$Chi^2_{(77,2)}$=13.01 p=0.001*	p<0.001*	p=0.001*	p=0.03
	Fmax	$F_{(77,2)}$ = 25.01 p<0.001*	p<0.001*	p<0.001*	p=0.5
	SD	$F_{(77,2)}$ = 22.41 p<0.001*	p<0.001*	p<0.001*	p=0.28
T_{Nov}	*Safe lifts*	$Chi^2_{(33,2)}$=15.06 p=0.0005*	p<0.001*	p=0.02	p=0.004*
	Damaged	$Chi^2_{(33,2)}$=9.46 p=0.009*	p<0.001*	p=0.19	p=0.012*
	Fmax	$F_{(33,2)}$=14.57 p=0.0001*	p<0.001*	p<0.001*	p=0.47
	SD	$F_{(33,2)}$=8.46 p=0.0019*	p<0.001*	p=0.011*	p=0.24
T_{Beg}	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	*NS*	*NS*	*NS*	*NS*
	SD	*NS*	*NS*	*NS*	*NS*
T_{Int}	*Safe lifts*	$Chi^2_{(15,2)}$=10.21 p=0.006*	p<0.001*	p=0.01*	p=0.22
	Damaged	NS	NS	NS	NS
	Fmax	$F_{(15,2)}$=12.79 p=0.0018*	p=0.001*	p=0.001*	p=0.94
	SD	$F_{(15,2)}$ =20.03 p=0.0003*	p<0.001*	p<0.001*	p=0.85
T_{Exp}	*Safe lifts*	*NS*	*NS*	*NS*	*NS*
	Damaged	*NS*	*NS*	*NS*	*NS*
	Fmax	*NS*	*NS*	*NS*	*NS*
	SD	*NS*	*NS*	*NS*	*NS*

** Significant. Pre-L: pre-test, L5: last learning session, Post-L: retention test, N: no augmented feedback and T: tactile augmented feedback Nov: Novices, Beg: Beginners, Int: Intermediates, Exp: Experts*

Comparison between groups Exp2

During the last learning session L5, the group that received augmented feedback performed significantly more safe lifts (80%) compared to the group that did not receive augmented feedback (10%) (p<0.001). In the retention test the group that received augmented feedback had a tendency to perform more safe lifts (50%) than the group that did not receive augmented feedback (20%) (p<0.05). During session L5, the number of damaged lifts was significantly smaller for participants who received augmented feedback (10%) when compared to the group that did not (60%) ($p<0.001$). In the retention tests group T_{Nov} tended to have fewer damaged trials (35%) than group N_{Nov} (60%) ($p=0.054$). After learning, the forces used became significantly lower for the participants who received augmented feedback (4.1N and 4.8N respectively) than for the group that did not (6.8N and 6.4N respectively) ($p<0.001$ and $p=0.011$ respectively). The group receiving augmented feedback maintained more constant force after learning than the participants who did not receive augmented feedback (*SD* 0.7 compared to 1.5 N) ($p=0.002$). However, during the retention test there were no differences between the two groups ($p=0.06$) on the variable *SD*, thus indicating dependency.

Table 4.4.7. Different Variance of Learning Profiles of Exp2

	Dep.	***Indep.***	***Imp.***	***Bad***	***Good***
N_{Nov}	na	na		6 (5)	-
T	10	16	23		3
T_{Nov}	6	6	11		1
T_{Beg}	2	3	4		1
T_{Int}	1	5	6		
T_{Exp}	1	2	2		1

Number of participants Dep.: that became dependent on augmented feedback, Indep: that became independent of augmented feedback, Imp: improved significantly during learning. Bad: number of participants who did not exceed 50% of safe lifts after learning, and who did no better than before learning. Good: number of participants scoring over 80% of safe-lifts in the pre-test. N: no augmented feedback and T: tactile augmented feedback Nov: Novices, Beg: Beginners, Int: Intermediates, Exp: Experts.

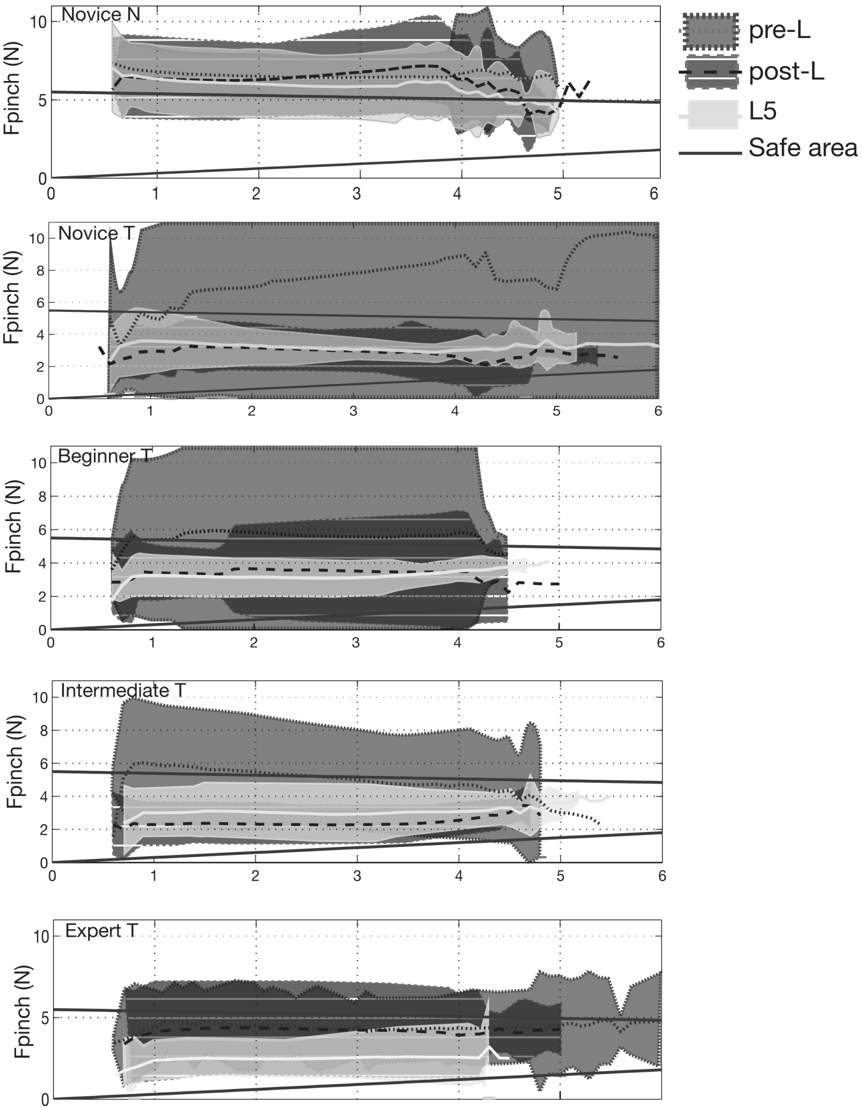

Figure 4.4.10. Range of lifts in safe area for sessions Pre-L, L5 and Post-L of 5 individuals. N: no augmented feedback and T: tactile augmented feedback

4.4.5. Discussion

The aim of these two experiments was to gather information on the influence of augmented feedback on force information on laparoscopic grasp control. Our first hypothesis asserted that in a two-handed task, augmented feedback is more beneficial than in a single-handed task as participants have to divide their attention. The results show that in Exp2 the augmented feedback aided performance while in Exp1 it did not. However, in Exp1 the control group did receive verbal feedback during the sessions, which is a type of augmented feedback as it provides information in the form of knowledge about results. In Exp2 the control group only got verbal encouragement to perform well at the beginning of each session. In reality when surgeons have to learn to control their grasp force there is no one to tell them whether they are pinching too hard as that is not currently measured. The only way to tell if the pinch force is too high or too low is by visually assessing matters. In most box-training exercises this, is difficult as the objects do not respond in the way that real tissue would respond. However, the properties of tissue are not exactly known and, therefore, the information that can be extracted from it has to be used with care. For example it can occur that when deformation is visible the tissue is already damaged. This means that augmented feedback aids performance even if attention has to be divided between two hands.

Our second hypothesis was that even experienced surgeons would use less force when they receive augmented feedback. The results show that individual experts benefited from the augmented feedback. As a group the experts already performed well at start. The group of surgeons with less experience than the experts (the intermediates) benefited enormously demonstrating significantly more safe lifts due to less slippage and lower maximal pinch forces. However, despite the fact that we did not intend to investigate this phenomenon we noticed, when analysing all the data, that both the experts and the intermediates had pinch/pull-force combination profiles that still deviate greatly from the profiles seen in the barehanded grasp control of adults, where pinch and pull forces are characterized by a virtually linear relationship when plotted against each other (Forssberg *et al.* 1991, Westebring-van der Putten *et al.* 2009b) . A considerable portion of the pinch force needed to complete the laparoscopic lift was already generated before the actual lift started (see Figure 4.4.7) thus indicating that pinch and pull forces were generated sequentially rather than in parallel. This same phenomenon is seen in children who are still developing their control of barehanded grasping (Forssberg *et al.* 1991). The results also showed a great spread of pinch forces generated with the same pull force (Figure 4.4.10). This spread decreased when practicing with augmented feedback but not as much as in adult barehanded grasping (Forssberg *et al.* 1991, Westebring-van der Putten *et al.* 2009b) . This could mean that it might take years of practice to achieve an ideal lift with a laparoscopic grasper.

Our third hypothesis was that participants would not become dependent on an applied pinch force augmented feedback signal. The results show that the majority of the participants did not become dependent on the feedback signal. However, approximately one third of the participants who received augmented tactile feedback did become dependent. This explains the large spread of the results. For the more experienced participants, this dependency is understandable as they have to unlearn a habit and this might take longer than 5 learning sessions and 10 lifts. For the less experienced who became dependent on the augmented feedback, it is possible that they might need longer learning periods to become independent. It seems that participants had a different capability to detect or interpret task-intrinsic feedback. The participants who became dependent of the augmented signal had difficulty detecting or interpreting the task-intrinsic feedback and relied on the augmented feedback. The participants who did not become dependent learned how to interpret the task-intrinsic feedback during the learning periods and used the augmented feedback as an enhancement during the learning periods. Another reason why some did become dependent on the augmented feedback might be because of the different strategies that were followed to stay in the safe zone. We asked the participants to describe their strategies. There were some who constantly tried to feel one of the feedback signals (representing either the slip-line or the damage-line) in order to remain on the edge of the safe zone. Others tried not to feel the augmented feedback signal, which resulted in the development of a better perception of the task-intrinsic feedback. Though, we did not analyse this thoroughly in this study, we do think it is an important concern that might explain why participants got dependent on the augmented feedback. In order to stimulate enhanced perception of the task-intrinsic feedback, it might be appropriate to adjust the augmented feedback to the level of expertise of the trainee. This could be achieved by moving the slip and damage-line to obtain a large safe area at the start of the leaning phase and to decrease it until the trainee is capable of generating the safe grasp needed to perform the task correctly.

4.4.5.1.1 Conclusion

It is clear that augmented tactile feedback for pinch force aids performance. Overall we saw that approximately one third of the participants who received augmented feedback became dependent on the signal. The results show that participants with all levels of experience benefited from the augmented feedback, and that even individual experts can benefit from augmented feedback.

Acknowledgment

The authors wish to thank Margriet Berben for her contribution. This work was supported in part by a grant received from the Catharina Hospital, Eindhoven, the Netherlands.

Chapter 5. Laparoscopic grasper with augmented tactile feedback

As in Chapter 4, it has been shown that augmented haptic feedback on grasp forces could aid the learning of laparoscopic grasp control. Therefore a new a grasper-handle design was developed. This new laparoscopic grasper handle with integrated augmented tactile feedback actuators is presented in the first part of this chapter. In the second part, two of these handles are used to see if people are able to learn grasp control with two hands at the same time.

Section 5.1 is published as:
"A Laparoscopic Grasper Handle with Integrated Augmented Tactile Feedback, Designed for Training Grasp Control. Lecture Notes in Computer Science; EuroHaptics 2010. A. M. L. Kappers e. a.. Berlin Heidelberg, Springer_Verlag. Part II: 243-250."
Section 5.2 is submitted as:
" The effect of augmented tactile feedback on grasp force control during a two handed laparoscopic grasping task"

5.1. A Laparoscopic Grasper Handle with Integrated Augmented Tactile Feedback, Designed for Training Grasp Control

During laparoscopic grasping, excessive grasp forces and tissue slippage may well lead to tissue damage. Because surgeons have difficulty gauging the force exerted on the grasped tissue, it is desirable to train them in applying the right degree of force in order to prevent tissue damage. Previously it was demonstrated that grasp force control can be learned when augmented tactile feedback is provided in a training task. The present paper discusses the design of a new laparoscopic grasper with augmented tactile feedback. Two grasper handles were developed and tested. Each of them contained augmented tactile feedback actuators.

5.1.1. Introduction

Laparoscopic surgery, a Minimally Invasive Surgery (MIS) technique performed in the belly alcove, is a very efficient operating technique. Laparoscopy is performed via small incisions with the help of long thin instruments. An endoscope (camera) is used to follow the surgeon's activities on a screen. When compared to open surgery the procedure has certain advantages and disadvantages. The advantages are mostly for the patient who experiences less trauma and is therefore in hospital for a shorter period and makes a speedier recovery. However, this technique brings with it difficulties for the surgeon because visually everything is indirect in much the same way that the tissue contact is indirect (Stassen *et al.* 2001). This can endanger the patient's health if, for instance, tissue is damaged (Dankelman *et al.* 2003).

In laparoscopic surgery, the surgeon's hands manipulate tissue indirectly using instruments. As a result, it is difficult for the surgeon to estimate just how much force needs to be applied to grasp tissue without exerting excessive force giving rise to slippage since haptic perception is distorted (Westebring-van der Putten *et al.* 2009b) by the interference caused by the instrument. Haptic perception provides feedback on the grasped tissue and is defined as a combination of tactile perception and kinesthetic perception. In an endeavour to find solutions to distorted haptic perception during MIS, a research project was initiated at Delft University of Technology in cooperation with the Catharina Hospital in Eindhoven. In our previous study we demonstrated that augmented tactile feedback can aid grasp control and shorten the laparoscopic grasping learning curve (Westebring - van der Putten *et al.* 2010b) when an object is being lifted. Surgeons can and in fact need to be taught and trained, before they practice actual surgery, to maintain a safe grasp faster and with greater accuracy. Ultimately this will improve patient safety and reduce training costs.

In the previous study, tactile-actuators were used to provide feedback on slippage and excessive pinch force. However, these actuators were not integrated into the grasper-handle itself, but where attached instead to the surgeon's hand and to the handle. This resulted in a bulky and less user-friendly system (handle A in Figure 5.1.1)(see (Westebring-van der Putten *et al.* 2009a) for details of the design). Moreover, from the ergonomic point of view, the grasper-handle needed to be improved. Although much research has been done in recent decades into haptic feedback in MIS, no specific research data could be found that provided evidence of augmented tactile feedback on grasp forces for the purposes of learning grasp control (for reviews see (Westebring-van der Putten *et al.* 2008b, Schostek *et al.* 2009, van der Meijden and Schijven 2009)). There is, however, one Patent that claims credit for inventing a minimally invasive surgical tool comprising a sensor that generates a signal in response to interaction with the tool and a haptic feedback system that generates a haptic effect in response to the signal (Ramstein *et al.* 2009). However, no research data could be found for this specific tool.

This paper describes in detail the design of an optimized grasper-handle, including the integration and miniaturization of actuators. The box-trainer set-up is explained as well, as this grasper handle is intended for use in training situations where grasp control can be learned. The main objective of the whole grasp-control-training device is to measure the effect of augmented tactile feedback during a grasping task with the aid of a laparoscopic handle both during and after having learnt to control the laparoscopic grasp.

5.1.2. Handle design and Ergonomics

The ergonomic characteristics of the new handle design, incorporating the feedback actuators of handle A, are based on the action guidelines for laparoscopic graspers (van Veelen *et al.* 2002). The final design is based on the handle designed by M.A. van Veelen (2002) (handle B) since, as was established during interviews with surgeons, its ergonomic shape was preferred to the shapes of other commercial graspers. The final prototype is shown in Figure 5.1.1, together with handle B and another commonly used handle (Storz, Tutlingen, Germany). The shape of the product is the result of an evaluation of alternative options for each part of the handle. The prototype was divided into three main sections: a back hinge, a front hinge and the body part. Different alternatives were designed for each part (a total of 10 alternatives), based on a Quality Function Deployment type of analysis (Chan and Wu 2002), in which the ergonomic attributes of the handle were identified and classified according to level of importance. User tests with foam models were performed in order to choose the most comfortable alternative design for each part. Figure 5.1.2 shows one of the 36 different foam handles used in the user tests.

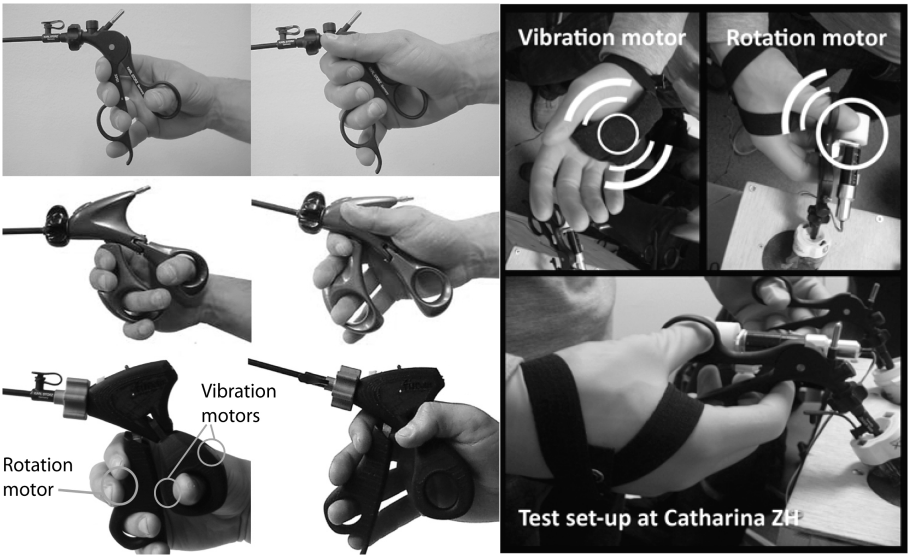

Figure 5.1.1. Left: Top panel: the commonly used handle (Storz), Middle panel: Handle B. Lower panel: final prototype. Right: actuators used in the first prototype (handle A) with tactile feedback.

The new handle can be used with both hands as it incorporates optimized versions of the actuators developed by E. Westebring. The actuators from the first prototype are shown in the centre of Figure 5.1.1 (see Section 5.1.2), and are thus in contact with the fingers and/or palm during use. As with handle B, our design incorporates elements such as the rotating back hinge, the large curves and the smooth surfaces, thereby preventing extreme bending of the wrist joint and minimizing the pressure points. However, the overall dimensions were adjusted to fit smaller hands, as handle B was too large for most users and the rotating knob was difficult to reach when precision gripping was required. A support was added for the little finger, as this feature is more comfortable than the original design in handle B. The main body of the handle is fabricated from Acrylonitrile Butadiene Styrene (ABS) created by means of Fused Deposition Modelling (FDM). In previous prototyping of handle B it was the Stereo Lithography (SL) technique that was used in combination with an epoxy resin. This resulted in a handle B prototype that was very fragile, causing parts of it break when dropped on the ground.

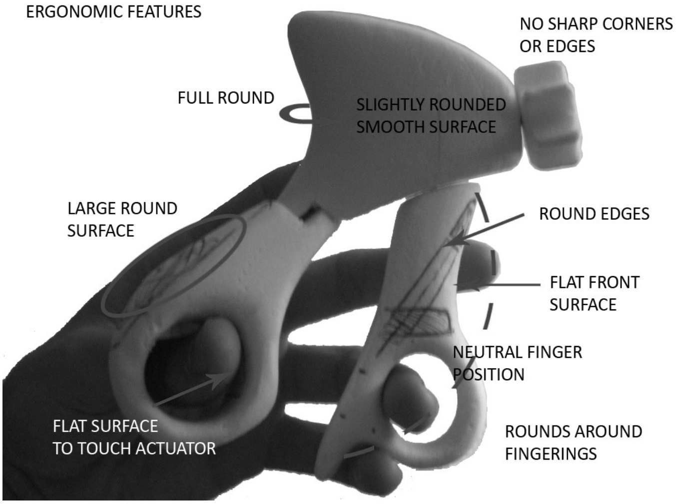

Figure 5.1.2. One of the foam models used in the user tests.

5.1.3. The Box-Trainer set-up

When manipulating tissue, surgeons exert a combination of pinching and pulling forces. Depending on the relative magnitude of the forces exerted, the tissue can slip, be damaged, or be grasped safely. Figure 5.1.3 shows the safe, damage and slip region as a function of the degree of pinch and pull force. When the pull force is high compared to the pinch force, the tissue slips out of the grasper, whereas when both the pull and the pinch forces are high, the tissue can be damaged. Even high pinch force without pull force can be detrimental. Every type of tissue grasped by an instrument has its own profile, as each tissue and grasper jaw has different properties (Heijnsdijk *et al.* 2004a). The boundaries of what is known as the safe area are called the slip-line and the damage-line (de Visser 2003, Westebring-van der Putten *et al.* 2009b).

In order to teach the surgeon how to control his grasp forces we developed a special box trainer. In the box-trainer there are 4 objects that simulate different tissue types and can be grasped by the surgeon/trainee. The objects are each equipped with two sensors so that the pull and pinch forces applied can be measured. The sensors were designed to measure forces applied between 0 and 15 N of the pinch force and between 0 and 7 N of the pull force. These forces where the applied range of forces measured in our former experiments under both non and augmented feedback conditions (Westebring - van der Putten *et al.* 2010b). The objects are attached to different springs, each with different spring constants and are built to virtually simulate the different types of tissues.

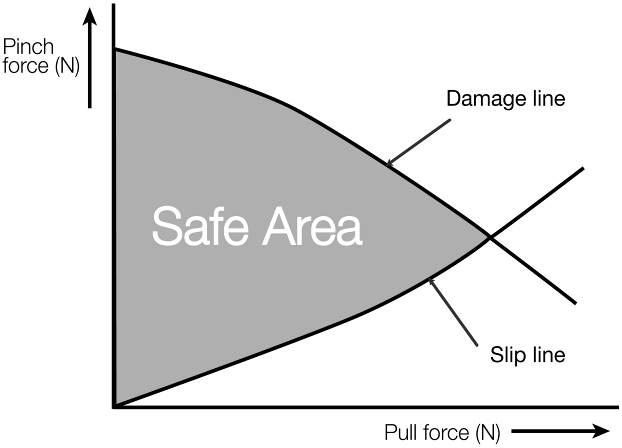

Figure 5.1.3. Safe area

Each of the grasper handles has 3 actuators to provide the user with augmented tactile feedback in relation to the grasp force; two vibrating patches, to display excessive force and a rotating cylinder to display slippage (as discussed in 5.1.2). A special situation arises when one of the actuators is not working optimally or is damaged. The controller measures the voltage across the actuators. If this is less than the optimal voltage then a red LED on top of the handle will be turned off. The sensors and actuators are discussed in more detail in the next section. The control process in brief is; the user grasps, with one of the two laparoscopic graspers, one of the objects. The sensors measure the pressure applied and the pull forces. Sensors send out data on the amount of pinch and pull force to a microprocessor. Data is read by the microprocessor and sent to a PC. The data is processed using our own software. Decisions are taken on the basis of the programmable slip and damage profiles of each object and the necessary data is transmitted back to the microprocessor for further action. The microprocessor sends independent signals to activate the actuators of the corresponding grasper handle. The user feels the feedback signals and is able to act accordingly

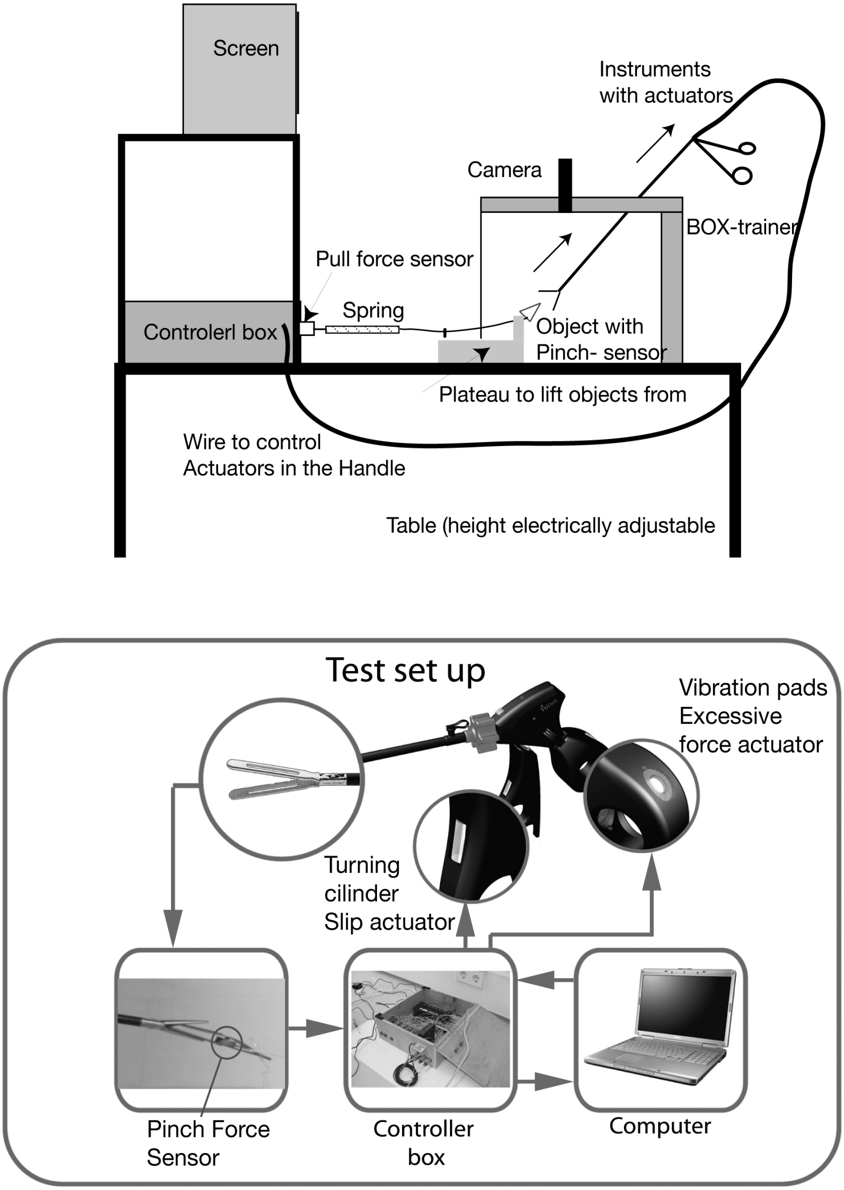

Figure 5.1.4. Test set up

Sensors:

Several different objects integrated with pinch and pull sensors were built and tested. The final objects to be grasped are made of a curved steel plate (10 x 80mm) forming a 15-degree wedge covered with 0.5 mm rubber. A miniature round force sensor measuring 9.8 x 4 mm (type KM10, ME-meßsysteme GmbH, Henningdorf, Germany) was placed underneath the steel plate. The sensor measures the pinch force applied to the surface of the object. The output signal of the sensor is fed into a custom-made amplifier. The responsiveness of the sensor to forces that were applied to the surface was determined with standardized weights. Figure 5.1.4 shows the test set-up.

Because different tissues may have different elasticity profiles, we attached each object to different springs with a wire in order to simulate the different tissue types. Each spring is attached to a pull sensor (type KD40S ME-meßsysteme GmbH, Henningdorf, Germany) to measure the pull force exerted on the object by the grasper. Slip is measured by comparing the applied pinch force with the object's actual slip-force. This slip-force was measured for each block beforehand and the resulting slip-lines were integrated into the software.

Actuators

Three miniature actuators are implanted in the grasper handle. One indicates whether tissue is slipping from the tip and the other two indicate if too much force is being applied. Figure 5.1.5 depicts the inside of the laparoscopic handle. In the front hinge, a rotating motor is integrated into the handle to provide feedback on slippage while two vibrating coin motors are located in the back hinge to provide feedback on excessive force. The two actuators that provide feedback on excessive force are positioned in such a way that both in the case of force and precision grip the user's hand touches one of them.

The actuators that provide feedback when excessive force is applied are 8mm vibrating coin motors operating at 3V. The coin motor choice was based on size and vibration strength. Due to the limited space in the back hinge, they had to be as small as possible. The vibration intensity should be great enough to be felt by a hand through a glove but also as low as possible to minimize vibration in the handle. The intensity that can be optimally felt with a minimum amount of vibration in the whole handle was determined by a process of trial and error. The motors were situated perpendicular to the skin and damping material was placed around the motor to prevent the whole handle from vibrating.

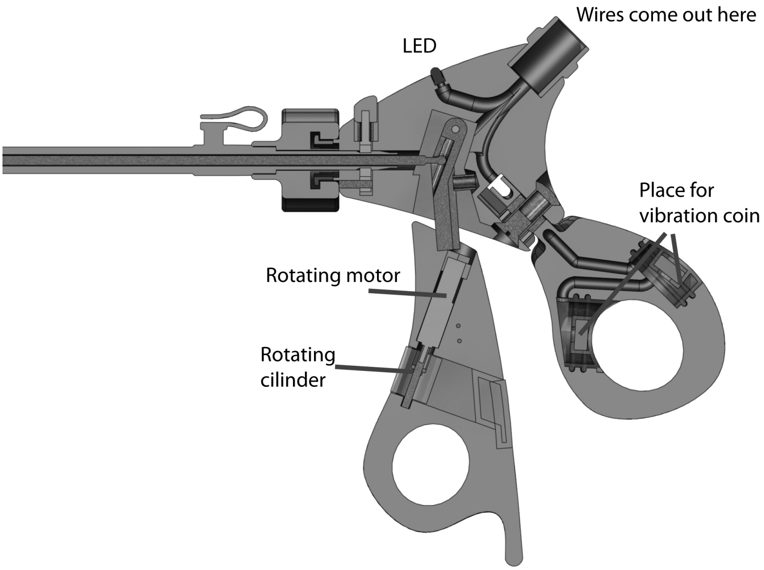

Figure 5.1.5. Miniaturized vibration motors are placed in the back hinge where the holes for the vibration caps are visible. The motor and turning cylinder is placed in the front hinge.

Since the product consists of a test device, it is likely that over the course of time the motor will fail. It is important to be able to then replace the actuator. Figure 5.1.5 shows the vibration motor located inside a silicon rubber holder that can be placed inside the available hole in the back hinge and fixed by means of ribs that fall into the same shape in the hole. In addition, the rubber cap has space inside for isolation material, which does not affect the motor's performance but it confines the vibrations mostly to the back hinge. The motor that rotates the cylinder when slippage occurs is a 6 mm round brushed precious metal 0.3 watt Maxon DC motor with a GP 6A gear-head. The motor plus gear-head have a nominal torque of 0,03 Nm, turn at a maximum speed of 84rpm and operate with a 4.5V power source.

The whole motor is located in the front hinge. The cylinder attached to the motor has a diameter of 15 mm and a length of 15 mm and is made out of PVC. The dimensions of the cylinder were based on research conducted by Murphy *et al.* (Murphy *et al.* 2004). As the sensitivity to the perception of slip at the fingertip very much depends on surface texture the surface of the cylinder should not be homogenous. Small features evoke more accurate perceptions than homogenously textured surfaces (Salada *et al.* 2004). The surface is therefore made rough by arbitrarily puncturing it with a hot needle. The research furthermore showed that the angle between the fingertip and the feedback did not seem to be relevant (Webster *et al.* 2005). Therefore, it was justifiable to place the cylinder in the front hinge so that it would tangentially touch the inner side of the user's second or third finger.

Data Acquisition

The analogue signals from the force sensors were captured at a rate of 200 Hz using an AD-converter (LabJack UE9) connected to a laptop via USB. Custom-made software, written in C++, was used to activate the actuators in the handle on the basis of the output of the force sensors via the digital output channels of the LabJack. Four digital LabJack outputs are used as input sources for the vibrating and slippage motors and two for the LEDs (i.e. for the two graspers). The digital output channels of the LabJack have a DC voltage of 3.3V, which is sufficient to drive the actuators and the LED. For each block, the slip-line and damage-line can be set according to the spring properties and the desired behaviour of the user. For example, by adjusting the damage and the slip-line the safe area can be enlarged for inexperienced surgeons and decreased when more skilled surgeons are practising. In this way, grasp control can be trained at each level of expertise. In order to be able to further analyse the performance of the user, the data of the force sensors is saved in a data file and stored on the PC.

5.1.4. Discussion and conclusions

The concept and analysis of an optimized laparoscopic grasper for the training of grasp control is addressed. The box trainer was equipped with sensors to measure pull and slippage forces, and miniature actuators that are integrated into the handle of the grasper provide augmented tactile feedback for the surgeon if the grasp forces are not in the safe area. Extensive user tests were carried out to demonstrate and to validate the proposed concept. It was shown that the grasper functions properly. We showed that when using handle A for one-handed grasping tasks(Westebring - van der Putten *et al.* 2010b), grasp control and the learning of it improved significantly with the aid of augmented tactile feedback (even when attention was distracted from the grasping hand). Therefore, the goal in our further research is to investigate whether grasp control performance improves when one has to learn a two-handed grasping task with the new handle presented in this article. As a two-handed grasping task is a realistic surgical task (it is used, for example, in bowel surgery when one performs bowel translocation) it is of interest to be able to deal with augmented feedback input from two hands at the same time. If a surgeon in training can learn to control his/her grasp forces with this device and does not become dependant on the augmented feedback this box trainer could be integrated into the curriculum for resident surgeons. The relevant research is in progress and data gathering will continue in the near future.

Acknowledgments

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5.2. The effect of augmented tactile feedback on grasp force control during a two-handed laparoscopic grasping task

In laparoscopy, the surgeon's intrinsic grasp-force feedback is reduced in comparison with open surgery. Previous research has shown that augmented feedback provided on grasp-force aids laparoscopic grasp control performance in one-handed tasks. This research is aimed at gaining more insight into the effect of augmented haptic feedback in two-handed tasks. The task was to lift objects with two hands, using minimal grasp-force. The learning effect and the dependency on the feedback provided were studied in two blocks. Each block contained a pre-, a learning- and a retention-session. The second block constituted a repetition of the first block repeated a week later. Thirty-four novice participants were divided into two groups; one group received tactile augmented feedback in the learning phase. The results showed that participants receiving augmented feedback applied lower forces than participants in the control group (4.92 N versus 6.51 N for the right hand) and did not become dependant on the signal. Except for reduced completion time there was no transfer of learning to the second week. This research shows that augmented tactile feedback can aid the learning of grasp control during two-handed tasks, although the effects are less than previously found for one-handed tasks

5.2.1. Introduction

In Laparoscopic surgery, it is possible for the surgeon to manipulate tissue indirectly with the use of instruments. Apart from the advantages of using MIS (reduced recovery time, reduced trauma and improved prognosis (Lee *et al.* 2009)) indirectly manipulating the tissue by using instruments reduces the quality of feedback information for the surgeon (visual, kinesthetic and tactile (Westebring-van der Putten *et al.* 2008b, Schostek *et al.* 2009)). The visual feedback is converted from a three-dimensional view to a two-dimensional monitored view. This reduces the hand-eye coordination and depth perception (Voorhorst. 1998, Wentink 2003). The kinesthetic feedback, which gives information about force, position and velocity through the muscles, tendons and joints, changes from being direct tissue contact feedback to being indirect contact gained through laparoscopic instruments. As well as the actual kinesthetic information, the surgeon receives feedback on friction forces from the trocar and the shaft together with data on the resistance of the abdominal wall and the scaling effects from the lever dimensions (Westebring-van der Putten *et al.*

2008b). The tactile feedback, defined as information about tissue properties gained from direct contact between the tactile receptors in the skin and the tissue, is not available when using laparoscopic instruments (Westebring-van der Putten *et al.* 2008b). This places higher demands on the surgeon's skills and greater experience is required if tissue damage is to be prevented (Cao *et al.* 2007). The tissue can easily be damaged by excessive force and slippage when the pinch and pull forces do not lie within certain boundaries (Cao *et al.* 2007, Westebring - van der Putten *et al.* 2010a).

As we have shown in previous research, tactile feedback alongside kinesthetic feedback is essential to the controlling of laparoscopic grasping forces (Westebring-van der Putten *et al.* 2009b, Westebring-Van Der Putten *et al.* 2009c). Only limited studies on the development of tactile feedback display systems are available in the medical field and most of them use visual feedback to provide tactile information; e.g. Schostek *et al.* (2010). On the other hand, in industries such as for example the video game industry and in perception studies, vibration feedback has proven to be an effective aspect of tactile feedback e.g. (Okamura 2009). However, such tactile feedback provides information about events like making and breaking contact, discerning surface texture, and using Braille but it teaches us nothing about actual grasping forces.

To improve safety in MIS operations, it is important to provide the surgeon with more feedback about applied grasp forces than the naturally available intrinsic feedback that the task provides. What is known as augmented feedback (Magill 2006) is supplementary to the task-intrinsic feedback. In previous research (Westebring - van der Putten *et al.* 2010b) the effect of augmented feedback on grasp force in laparoscopic grasp control was studied among novices and experts. The study showed that at all levels of experience, augmented tactile feedback on grasp force aids performance in grasp control (80% save lifts compared to 10%) for a one-handed laparoscopic grasping task, even when attention was drawn away from the grasping hand. However, in this experiment subjects only performed grasping movements with one hand while in real surgery both hands are often used to manipulate tissue. Furthermore, the augmented feedback that was provided in this study was provided for one hand while the other hand did not receive augmented feedback. It remains unclear whether the beneficial aspects of such feedback are also noticed when the grasping force of both hands needs to be controlled.

In order to complete a more familiar laparoscopic task, like translocating a colon, this current study made use of a two-handed grasping task. The aim is to determine whether pull and pinch forces are better controlled when augmented tactile feedback on slip and excessive forces is provided in the learning phase of a two-handed grasping task. The dependency on the signal was tested by performing a retention session, without augmented tactile feedback, directly after the learning phase. In order to test the transfer of learning to a later date, the experiment was performed again exactly a week later. In our former study (Westebring - van der Putten *et al.* 2010b) it was observed that with experienced participants the learning effect was affected by their routine knowledge, all participants in this study were therefore novices.

This research aims to gain more insight into the effect of augmented feedback in two-handed tasks. The following hypotheses were tested: firstly, the participants receiving augmented tactile feedback in the learning phase will be seen to control grasp forces better than participants not receiving augmented feedback in the learning phase. Secondly, if augmented feedback is no longer available their performance will also be better than that of the participants not receiving augmented feedback. Thirdly, the transfer of learning from the first to the second week will be evident from the improved performance seen exactly a week after the first performance.

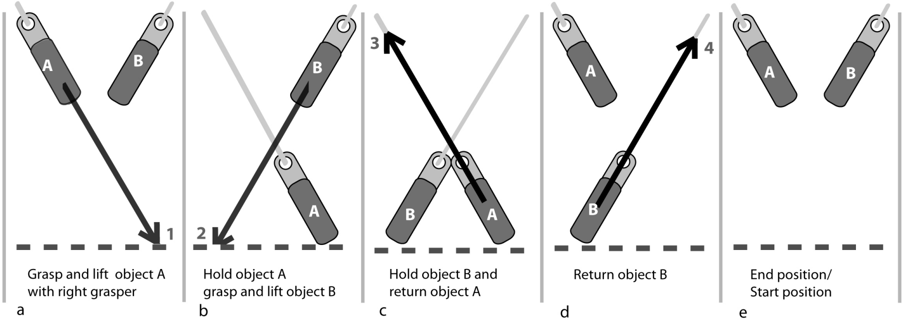
5.2.2. Method

Participants

Thirty-four participants (aged between 18 and 52 years) with no previous laparoscopic experience (18 male and 16 female) participated in this experiment. Four of the male participants were left-handed. The rest of the participants were right-handed. Balanced for gender, the participants were randomly divided into two groups. One group received augmented tactile feedback (the T-group) in the learning phase and the other group (the N-group) did not. All participants gave their informed consent.

Task

Using two laparoscopic instruments (in a box-trainer) the participants had to move two objects by exerting pull and pinch forces (see Figure 5.2.1). First they had to grasp with their right hand object A, which was positioned on the left side of the working area and pull it up to the right side towards the red line that could be seen on the screen. They had to halt and hold the object still there. While holding it, they had to grasp a second object B (positioned on the right) with their left tool and pull that towards the red line on the left. After that they had to return the objects to their original place, one by one, first object A, then object B.



a Grasp and lift object A with right grasper

b Hold object A grasp and lift object B

c Hold object B and return object A

d Return object B

e End position/ Start position

Figure 5.2.1. Schematic drawing of the specific order in which the objects should be grasped.

Experimental setup

The setup used in this experiment is explained briefly and can be seen in Figure 5.2.2 Two laparoscopic graspers (tips; type 33310 MH, Karl STORTZ, Tutlingen, Germany) with handles fitted with tactile feedback displays (Figure 5.2.3) were placed in a box-trainer. The force transmission ratio seen in Figure 5.2.3b (combination of frictional losses, force multiplication factors and hysteresis) of the grasper was determined by measuring pinch force at the tip when handle forces were varied (using a fixed jaw opening of 15 degrees). Participants had to follow their actions on a 2D TV-screen placed at eye level and at a distance of 100 cm. A Bullit-camera (type SecCam50, Nedis, 's Hertogenbosch, the Netherlands), which was placed in the top section of the box-trainer, delivered the visual data to the TV-screen.

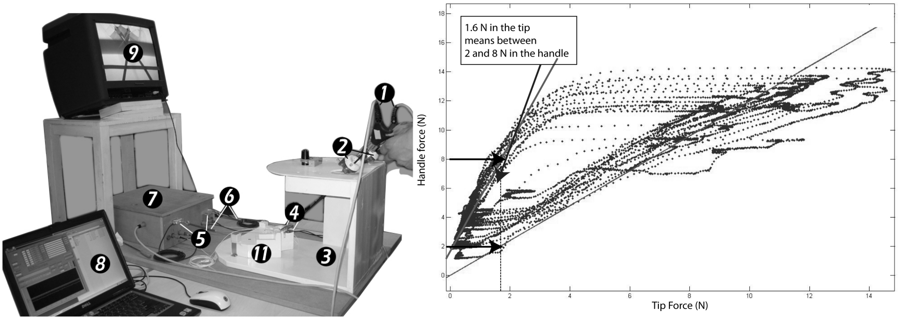


Figure 5.2.2. Left: Experimental setup; 1: Laparoscopic graspers; 2: Trocars; 3: Box-trainer; 4: Pinch force sensors in object; 5: Pull force sensors; 6: Springs; 7: Controller box; 8: Laptop with software program; 9: 2D screen; 10: Bullit-camera; 11: Holder for object. Right: Tip and handle forces of the grasper Tip and handle forces that were measured during several cycles of squeezing and releasing the handle (that had a fixed jaw opening of 15 degrees).

In order to simulate the grasping of elastic tissue the objects (made of aluminium, covered with 0.1mm thick rubber) that had to be grasped were connected to springs (pull force 5 Newton when spring is stretched up to the target area (170 mm.) and 0 Newton when the spring is at rest (100 mm.)). A pull-force sensor (type KD40S ME-meßsysteme GmbH, Henningdorf, Germany) and a pinch-force sensor (type KM10, ME-meßsysteme GmbH, Henningdorf, Germany) measured the forces exerted by the participants (see Figure 5.2.3). The pinch and pull sensors were calibrated by means of weights. Data was measured at 200Hz. A more extensive description of the box-trainer and grasper handles can be found in Westebring *et al.* (2009c). At the starting point the objects where placed in a holder that pre-tensioned the springs thus resulting in an offsetting of the pull force values as shown in Figure 5.2.4**.**

The output of the force sensors was used for 17 participants (the T-group) to provide augmented feedback via motors that were planted in the laparoscopic handles. These subjects received feedback in the learning phase when they executed forces beyond a pre-defined area. This area was defined as the combination of pull and pinch forces at which the applied forces did not exceed the set damage and slip lines. When the participants exerted too much pinch and pull force, the motors in the back hinge vibrated. When the object was about to slip, the cylinder in the front hinge turned. In order to ensure that participants did not apply peak pinch force (as observed in previous experiments) at the beginning of a lift (Westebring-van der Putten *et al.* 2009b), the damage-line was set at a lower offset and had less inclination than, according to the literature (de Visser 2003, Heijnsdijk *et al.* 2003), a typical damage-line would have had. The set area can be seen in Figure 5.2.4 in the Results section). The control group (the N-group) did not receive any augmented feedback.

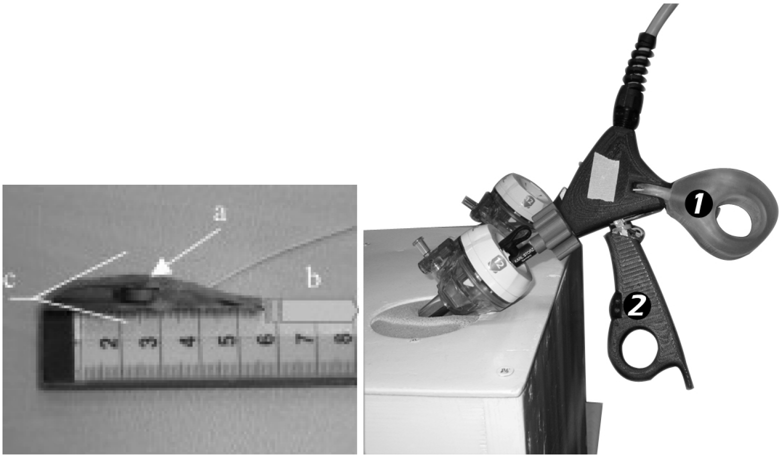


Figure 5.2.3. Left: Object that had to be grasped. a; the pinch force sensor, b; spring, c; grasper Right; Handle with augmented feedback displays. 1: vibrating patches to display excessive forces, 2: Rotating cylinder to display pending slippage.

General procedure

This experiment consisted of a pre-session and a retention session in which ten repetitions of the task were performed. In between those sessions the subjects carried out five learning sessions in which they did five repetitions. All participants started with the pre-session in which they did not receive augmented feedback. In the learning sessions the T-group received augmented tactile feedback on exerted forces. The N-group performed the same number of sessions without such feedback. In these sessions they had to learn how much force is needed to prevent slippage without exerting too much pinch force. These learning sessions were followed by the retention session, where the participants did not receive augmented feedback. After a week all participants repeated the same tasks under the same conditions. The sessions in the first week were called -A and the sessions in the second week were called -B. All participants were told to handle the objects with extreme care and to apply as much force as was needed to prevent slippage but no more. This was repeated at the beginning of each session.

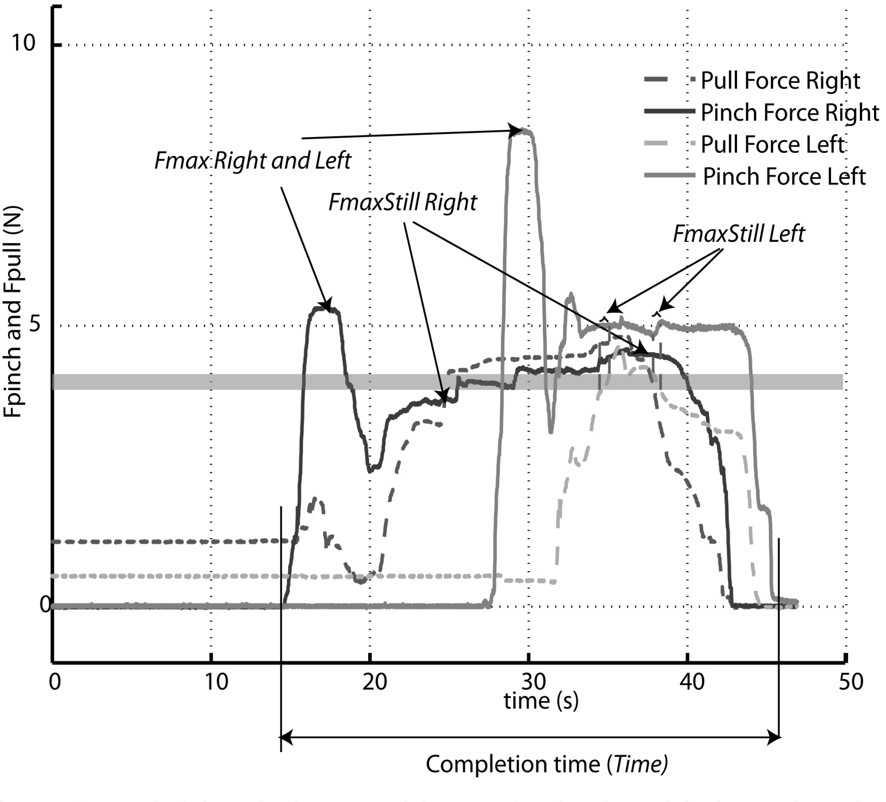


Figure 5.2.4. Typical data plot from a participant performing the task in the pre-A session. Variables Fmax, FmaxStill and Time are shown.

Data Analyses and statistics

In the experiment the following performance measures were analysed for each hand in the pre-session, in the learning sessions and in the retention-session. The percentage of lifts with slippage (*Slip*) was measured. For the lifts without slippage the maximum pinch force applied during the lift (*Fmax*) and the maximum pinch force applied during the lift phase where the object is held still (at a pull force level between 3.9 and 4.1 Newton) (*FmaxStill*) were measured (as shown in Figure 5.2.4). The completion time of the whole task was recorded (*Time*) in order to see if participants learned to do the task quicker. When the variable *Fmax* decreased the participant had learned to avoid peak forces when lifting. When the variable *FmaxStill* decreased the participant had learned to apply less force during the holding phase of the lift. Figure 3 shows a typical data plot from a participant performing the task in the pre-A session.

Comparisons Within Groups: For both groups, pre-session performance (*Slip, Fmax, FmaxStill* and *Time*) was compared with performance in the final learning sessions and with performance in the retention session. The first comparison was made to determine whether a training period with augmented feedback could lead to better performance. The second comparison was made to see if the performance level after training with augmented feedback can be maintained, or whether augmented feedback is a prerequisite for better performance. In addition, the sessions in the second week were analysed in the same way and the results were compared to those of the previous week in order to see if there was any transfer of learning to a later date.

Comparisons Between Groups: In order to establish whether the different groups started with a comparable level of dexterity, the performance of the groups with different feedback conditions in the first pre-sessions was compared. The second pre-session, the final two learning sessions and both retention sessions were also compared in order to ascertain under which conditions, performance was best after practice.

Data was analysed using analysis of variance (ANOVA) and a Bonferoni correction as multiple analyses of variance had to be carried out (therefore, the significance was set at $p<0.0125$). When ANOVA showed significant differences, post hoc Holm-Sidak analyses were conducted. The data of the variable *Slip* were not normally distributed so Krusskal Wallis ANOVA's and Wilkoxon rank sum tests were used. The MATLAB 2007b Statistical Toolbox was used to perform the statistical analyses.

5.2.3. Results

The results averaged across the participants can be found in Table 5.2.1. The data from four participants could not be used. Two of them, both belonging to the N-group, broke the back hinge of the handle by exerting too much pinch force. The data of two other participants was not collected properly due to technical problems. The dexterity of the remaining thirty participants did not significantly differ at the start of the experiment. Left-handed participants did not perform significantly differently from right-handed participants. They all applied significantly lower forces with their right hand ($p<0.001$).

Table 5.2.1. Results

	Group	*Fmax Right N Mean(sd)*	*Fmax Left N Mean(sd)*	*FmaxStill Right N Mean(sd)*	*FmaxStill Left N Mean(sd)*	*Slip Right % Median (25-75pct)*	*Slip Left % Median (25-75pct)*	*Time s Mean(sd)*
Pre-A	**T**	5.49 (1.20)	9.10 (1.77)	5.09 (1.10)	8.72 (1.65)	10 (0.0-25)	0 (0-0)	19.56 (5.97)
	N	6.03 (1.12)	9.84 (1.57)	5.32 (1.0)	9.35 (1.56)	10 (0-33.3)	0 (0-0)	17.43 (4.54)
L-A	**T**	4.94 (0.53)	7.56 (1.61)	4.46 (0.49)	6.48 (1.73)	16.7(2.8-26.7)	0 (0-10)	19.72 (7.43)
	N	6.41 (1.48)	9.82 (1.69)	5.53 (1.34)	9.07 (2.0)	6.7 (0-16.7)	0 (0-5)	13.56 (2.19)
Ret-A	**T**	4.92 (0.74)	8.03 (1.46)	4.47 (0.76)	7.13 (1.51)	10 (0-22.2)	0 (0-10.6)	14.78 (4.89)
	N	6.50 (1.50)	9.82 (2.02)	5.80 (1.43)	8.53 (2.30)	0 (0-7.5)	0 (0-10)	12.34 (4.54)
Pre-B	**T**	5.90 (0.92)	9.56 (1.44)	5.45 (1.03)	9.14 (1.46)	0 (0-0)	0 (0-0)	12.78 (4.14)
	N	5.90 (1.10)	10.46 (1.26)	5.35 (1.07)	10.0 (1.29)	10 (0 -20)	0 (0-0)	11.12 (2.23)
L-B	**T**	5.14 (0.94)	7.63 (1.46)	4.49 (0.62)	6.44 (1.44)	9.4(3.3-13.3)	0 (0-3.3)	14.63 (5.21)
	N	6.00 (1.18)	9.66 (1.57)	5.36 (1.0)	9.16 (1.63)	6.7 (0-13.3)	0 (0-0)	9.96 (1.77)
Ret-B	**T**	5.18 (0.89)	8.38 (1.43)	4.72 (0.77)	7.62 (1.58)	10 (0-10.0)	0 (0-0)	11.95 (3.91)
	N	5.95 (0.96)	9.30 (1.63)	5.43 (0.94)	8.64 (1.71)	0 (0-11.1)	0 (0-0)	10.10 (1.82)

Pre-A: First week's pre-session, L-A: last learning session of the first week, Ret-A: Retention session of the first week, Pre-B: Second week's pre-session, L-B: last learning session of the second week, Ret-B: Retention session of the second week, T: group with augmented tactile feedback, N: control group

Figure 5.2.5 displays the average group ranges of pinch-forces used at a certain pull force for the pre, the final learning and the retention sessions of the first week. As can be seen, both groups started at the same level and only the T-Group lowered the force factor over the whole trajectory of the lift after learning. The performance results of the second week did not differ significantly from the performance seen in the first week.

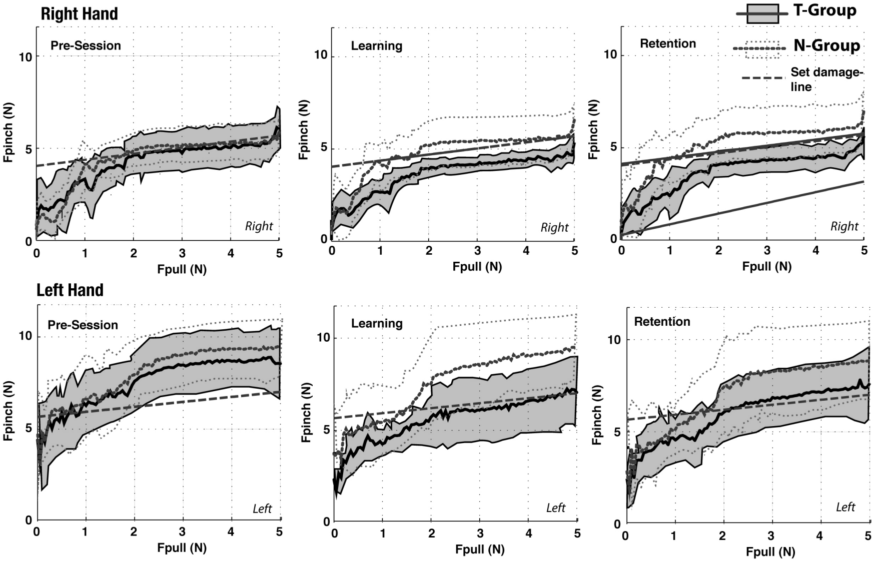


Figure 5.2.5. Mean force range during correctly performed lifts (the lifts with slip are omitted) during the pre, last learning and retention sessions of the first week for both the T-Group and the N-Group. Pull-force was plotted against pinch-force (mean +/- 1sd) for both the right and the left hand.

In Figure 5.2.6 the maximum pinch-forces (*Fmax* and *FmaxStill*) applied during the pre, learning and retention sessions are plotted for both groups. The solid lines are the values for the T-group and the dotted lines represent the values for the control group.

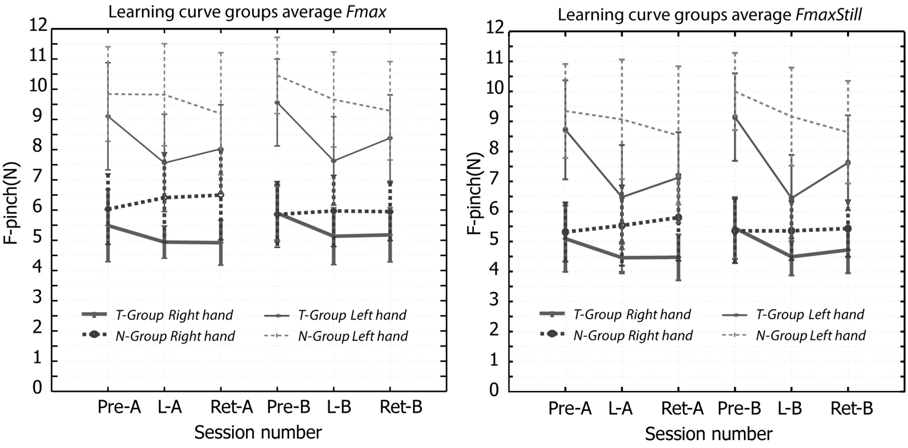


Figure 5.2.6. Learning curves for the group averages (sd) Left panel Fmax and Right panel FmaxStill.

Table 5.2.2. Statistical analysis of group data (Columns that contain only non-significant values are omitted.)

Variable	***Fmax***		***FmaxStill***		***Slips***	***Time***	
Group	**T**	**T**	**T**	**T**	**N**	**T**	**N**
	Right	Left	Right	Left	Left		
Between sessions (p)	F_{83-5} 3.78 0.0046	F_{83-5} 7.49 <0.001	F_{83-5} 4.51 0.001	F_{83-5} 15.5 <0.0001	Chi^2_{78-5} 15,13 0.01	F_{83-5} 14.24 <0.001	F_{59-5} 7.67 <0.001
Post-Hoc (p)							
Pre-A- L-A	ns	<0.0001	0.008	<0.0001	ns	ns	ns
Pre-A-Ret-A	0.016	0.0003	0.009	<0.0001	<0.0125	<0.0001	0.0007
Pre-A-Pre-B	*ns*	0.0006	ns	<0.0001	ns	<0.0001	<0.0001
Pre-A-L-B	ns	0.0005	ns	<0.0001	ns	<0.0001	<0.0001
Pre-A-Ret-B	<0.0001	0.05	ns	0.005	ns	<0.0001	<0.0001
L-A-L-B	ns	ns	ns	ns	ns	<0.0001	0.003
L-A-Ret-A	ns	ns	ns	ns	ns	0.0001	ns
L-A-Pre-B	0.0004	<0.0001	0.0002	<0.0001	ns	<0.0001	0.0125
L-A- Ret-B	ns	0.007	ns	0.0015	ns	<0.0001	0.006
Ret-A-Pre-B	0,0002	0.0003	0.0002	ns	ns	ns	ns
Ret-A-L-B	ns	ns	ns	ns	<0.0125	ns	ns
Ret-A-Ret-B	ns	ns	ns	ns	<0.0125	0.007	ns
Pre-B-L-B	0.007	<0.0001	0.0008	<0.0001	ns	ns	ns
Pre-B-Ret-B	0.007	0.011	0.006	0.0009	ns	ns	ns
L-B-Ret-B	ns	ns	ns	0.003	ns	ns	ns

Pre-A: First week's pre-session, L-A: last learning session of the first week, Ret-A: Retention session of the first week, Pre-B: Second week's pre-session, L-B: last learning session of the second week, Ret-B: Retention session of the second week, T: group with augmented tactile feedback, N: control group. Ns: non-significant. Omitted are columns Fmax: Group N Left and Right, FmaxStill group-N Left and Right and Slips: Group-T, Left and Right and group-N, Right.

Comparison within the T-group: Table 5.2.2 shows that for both hands the maximum pinch forces *Fmax* and *FmaxStill* were significantly reduced between the pre and retention sessions. The maximum forces *Fmax* and *FmaxStill* delivered in the L and Ret-sessions did not differ significantly from each other, with the exception of the Left hand that used slightly more force *FmaxStill* in Ret-B than in L-B, meaning there was almost no dependency on the augmented feedback signal. After a week with the left hand the T-group used more force *Fmax* and *FmaxStill* in Pre-B than in Pre-A. However, there was no significant difference in the applied forces *Fmax* and *FmaxStill* between both the learning and retention-sessions of the first and second weeks. For the T-group, the percentage of right and left-handed slips did not significantly change during the experiment. However, there was a change between the number of slips seen with the right and the left hands. At the start of the experiment there were significantly more right-handed slips than left-handed slips (p=0.0073). After L-A the percentage of right-handed slips no longer differed significantly from the left-handed slips. This meant that the T-group had learned to control *Slip* during the experiment. For the T-group the task completion time reduced significantly from session to session. In the second week the completion time was reduced when compared to the first week but after that it did not significantly reduce any further.

Comparison within the N-group: Table 5.2.2 shows that when both hands applied maximum forces *Fmax* and *FmaxStill* did not differ significantly between sessions. This means that the N-group did not learn to apply less force when learning. For the N-group, the percentage of right-handed slips did not significantly change during the experiment but the percentage of left-handed slips did differ during the experiment due to the significantly higher percentage of slips during Ret-A than during Pre-A and all B sessions. At the start of the experiment there were significantly more right-handed slips than left-handed slips (p=0.0059). After L-A, during Ret-A and Pre-B the percentage of right-handed slips did not differ from the percentage of left-handed slips. After L-B and during Ret-B there were significantly more right-handed slips than left-handed slips (p=0.006 and p=0.03 respectively). The task completion time reduced significantly from session to session. In the second week the completion time was not significantly different.

Comparison between groups

Table 5.2.3 shows that after the first learning sessions (L-A) and the retention session (Ret-A) the T-group executed significantly lower maximum forces *Fmax* and *FmaxStill* with both hands than did the N-group. The executed *Fmax* and *FmaxStill* during the second pre-session (pre-B) was the same for both groups, however the left hands showed a tendency to apply lower maximum forces. After the second learning sessions (L-B) and after the second retention session (Ret-B) the right hands of the T-group subjects applied or had a tendency to apply lower maximum forces *Fmax* and *FmaxStill* than those of the N-group. The left hand applied lower maximum forces after L-B, however, not during the Ret-B session. This means that the group that received feedback performed significantly better than the group that did not receive feedback. When feedback was removed the difference between the groups was only significant for the right hand during week 1.

There were no significant differences between the two groups for the percentage of right and left- handed slips. The T-group needed more time than the N-group to complete the task during sessions with augmented feedback. During both the pre and the two retention sessions, the task completion time did not differ between groups.

Table 5.2.3. Comparisons between groups

Variable	*Fmax*		*FmaxStill*		*Time*
Between groups	**Right T-N**	**Left T-N**	**Right T-N**	**Left T-N**	**T-N**
Pre-A	ns	ns	ns	ns	ns
L-A	<0.0001	<0.0001	0.003	<0.0001	0.013
Ret-A	<0.0001	0.049	0.0023	0.033	ns
Pre-B	ns	0.04	ns	0.05	ns
L-B	0.018	<0.0001	0.003	<0.0001	0.0026
Ret-B	0.015	ns	0.015	0.05	ns

Pre-A: First week's pre-session, L-A: last learning session of the first week, Ret-A: Retention session of the first week, Pre-B: Second week's pre-session, L-B: last learning session of the second week, Ret-B: Retention session of the second week, T: group with augmented tactile feedback, N: control group, ns: non-significant. Omitted is the variable Slip as it was non-significant.

5.2.4. Discussion

This experiment shows that augmented tactile feedback can aid the learning of two handed laparoscopic grasp control. After learning, less force is applied when object translocation is performed with both hands simultaneously. The amount of force executed during retention was significantly lower for the group that practiced with augmented tactile feedback than for the control group, although the force applied by some participants was still often beyond the set damage line (Figure 5.2.5). What might explain the latter point is the fact that for many participants the damage line was set at a too difficult level for them to accomplish the tasks during the short learning time (2 times 30 minutes) allowed for this experiment. Pilot tests performed with three participants did not reveal this; therefore, the settings in the experiments were not changed. Another explanation could be that the cause was the time delay between the measurement of the applied forces and the activation of the feedback motors. The delay in the setup was at least 100 ms (and maximally 115 ms depending on the computer occupancy gauged by measuring the input and output time of the relevant Labjack channels. The time the motors needed from starting to reaching full speed was not measured) which means that a participant feels the feedback signal at least 100 ms later than when he/she passes the set damage or slip-line, thus resulting in a delayed reaction. The human reaction time to tactile stimuli is about 200-270 ms (Murakami 2010) (Westebring-van der Putten *et al.* 2009a) and once the meaning of an augmented feedback signal has been thoroughly learned less demand is placed on limited cognitive resources. Gain changes in the sensitivity of spinal reflexes can contribute to reducing reaction times even further (the spinal reflex with haptic stimuli can be as short as 50 ms (Kandel 2000)) and in barehanded slips they are prevented within 60-80 ms (Johansson and Westling 1987a). Because of the significant delays (relative to human reaction time) in this experiment, the provision of feedback might have been less effective. Despite the limitations in the current study the beneficial effects of augmented feedback were still clearly present. If we consider that a bowel is damaged when the pinch force exceeds 10N (Heijnsdijk *et al.* 2003, Wagner and Howe 2007) and if we use this magnitude as a criteria to evaluate the performance of participants, the percentages of safe lifts would be 80% for the T-group and 60% for the control group, thus showing a 20% better performance for the latter.

In general, participants did not become dependent on the augmented feedback signal. However, not all individual participants showed independence, especially regarding the left hand (50% of the participants) Previous research (Westebring - van der Putten *et al.* 2010b) has shown that novices became more dependent on augmented feedback than participants with a higher level of experience (50% of the novices, 33% of the beginners, 16.5% of the intermediates and 25% of the experts). This suggest that the more experience a participant has beforehand, the better he/she can use the provided augmented feedback to guide his/her grasp forces and control these forces even in the absence of the augmented feedback signal. This suggests that for efficient learning without the development of dependency, augmented feedback should probably not be given in every practice trial. This strategy has also been proved to be beneficial in research in other areas of motion control (Magill 2006).

The participants in both the control group and the group that received augmented feedback performed significantly worse with the left hand than with the right hand. An explanation for this can be found in the movement order of the task. The task always started with a right-handed lift, thus possibly drawing attention to the right hand. When the left-handed lift started, an object still had to be held with the right hand. This could possibly have distracted the subjects from controlling left-handed forces at the same time. This might also explain why left-handed participants did not perform better with their left hand than right-handed participants

During this experiment’s learning sessions, participants who received augmented feedback needed more time to perform the task compared to the control group. This corresponds with the results of Wagner *et al.* (2007) to the effect that for novices the time needed to perform a task is lengthened by obtaining force feedback. They also found that the time required to perform a surgical task for an expert receiving force feedback was shortened. It would be interesting to test experienced participants on this dual task, in order to establish whether their performance time could also be shortened by tactile augmented feedback.

Our third hypothesis concerning the transfer of learning from the first to the second week did not stand; we did not see visibly improved performance exactly a week after the first trial. This means that either the practice sessions in the first week were too short or the period between the two phases was too long. In order to see how much training is needed to attain the plateau of the learning curve more tests are required.

In this experiment the object properties were kept constant, this means that no conclusions can be drawn on whether the learned grasp control can be transferred to other materials like real bowel tissue. Transfer of learning was, however, shown in our former (one handed) experiment (Westebring - van der Putten *et al.* 2010b), where we used two different randomly presented object property characteristics.

In this experiment we showed that augmented tactile feedback on grasping forces can aid the learning of grasp control in MIS. Augmented feedback might also possibly be beneficial to other disciplines as well as manual MIS. In comparison with the reduced feedback provided during MIS, no natural feedback is available at all in tele-operated Robot assisted Minimal Invasive Surgery (RMIS). This lack of feedback is a drawback for the surgeon, which is why providing him with sufficient feedback, constitutes a technical challenge.. Extensive research is being done into the development of kinesthetic feedback systems, also sometimes known as force feedback systems, as reviewed by Okamura (2009). These systems measure the pull forces (not the pinch forces) and the torque applied by the instrument and they display the measured forces of the hand of the surgeon without the friction and resistance influence created by the instrument. Previous studies by Wagner *et al.* (2007, 2007) with force feedback systems have shown that force feedback has proven to be effective in reducing potential tissue damage (Wagner *et al.* 2007) and that amplified force feedback results in improved accuracy in a mock blunt dissection task (Wagner and Howe 2007). In this later study, the feedback provided information on the pulling and pushing forces. Supplying force feedback in virtual reality simulators for laparoscopic surgery (Panait *et al.* 2009) has shown that in more advanced tasks the force feedback provided results in superior precision and less time being required to complete the task. Apart from providing information about torque and force, research [11] has shown that force feedback systems that provide information about compression, angular displacement and grasping force in combination with visual feedback lead to better tissue characterization than just having visual feedback or force feedback in isolation (Tholey *et al.* 2005). All these studies show that providing force feedback improves performance. However, it is the complexity and cost of the force feedback systems required that prevents them from being adopted in general practice. The augmented feedback used in the current study is relatively easy to implement and could be used to improve performance in these other fields.

From this experiment we can conclude that augmented tactile feedback can aid the learning of grasp control during a two-handed task though it is more difficult than a one-handed task.

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Chapter 6.

Conclusions, discussion and recommendations

This chapter recapitulates and discusses the conclusions and findings emerging from the research presented in this thesis. The guidelines derived for training devices containing augmented haptic feedback are presented. Recommendations for future research are made.

6.1. Recapitulation

The purpose of this thesis was to answer the question:

"Can augmented feedback on haptic information enhance the surgeon's control of laparoscopic grasp force?"

The research described in this thesis shows that augmented haptic feedback does improve the surgeon's ability to control laparoscopic grasp forces. In order to perform a safe operation, it is the task of the surgeon to grasp the tissue in a way that will not damage it or allow it to slip. As was shown in Chapter 1, the amount of force that can be safely applied depends on the tissue characteristics and the type of instrument. Just how much force a surgeon does apply to the tissue depends on the instrument used, on the task in hand (is the tissue removed or not), the additional tasks (to stop bleeding elsewhere), experience, skill and the emotional state of the surgeon. As was presented in Chapter 2, surgeons need haptic feedback since that is reduced when traditional MIS instruments are used and it is absent in RMIS as well.

In order to control the force applied to the tissue in the best way, tactile feedback is needed as shown in the experiments described in Chapter 3 where grasp control was compared between tool and barehanded grasping. It was shown that this factor plays an even more important role in grasp control than kinesthetic feedback. The question that arose was whether humans can learn to control their grasp, without this tactile and with distorted kinaesthetic feedback, with the help of augmented feedback on this missing / distorted information.

Several augmented feedback modalities where studied in Chapter 4 and it was augmented tactile feedback that scored best to provide information on the missing tactile and distorted kinaesthetic information. This led to the design of a laparoscopic training device with grasping tools that contain augmented tactile feedback on imminent tissue slippage and excessive forces. The testing of the device showed that laparoscopic grasp control can be learned with the help of augmented tactile feedback during a certain training period, even in a two-handed task.

The ideal situation would be that resident surgeons learn laparoscopic grasp control without becoming dependent on the augmented feedback provided. As a result, they will be able to perform surgery without newly designed instruments that provide augmented feedback all the time. Furthermore, the additional costs required developing instruments that are allowed in surgery, and changes of instrument due to electrical component failure can be prevented. Chapter 4 and 5 show that it is indeed possible to learn a better laparoscopic grasp control without augmented feedback once practiced with.

6.2. Learning to control laparoscopic grasp forces

In Chapter 2 the learning of barehanded grasp control was explained. If the force profiles produced during the learning of barehanded grasp control are compared to the force profiles occurring during the learning of laparoscopic grasp control, it can be seen that they are not totally different. Chapters 3, 4 and 5 show that, during laparoscopic lifts, the pinch and pull force does not increase in parallel but in sequence as in the barehanded grasping of young children, meaning that laparoscopic grasp control is not as good as an adult's barehanded grasp control. This results in the need for large margins to prevent slippage in laparoscopic grasping.

It is not clear whether a person can make laparoscopic grasp control rise to the same level as barehanded grasp control, as we still see sequential force generation during laparoscopic lifts performed by experts (Chapter 4). This can be explained by the fact that even the experts are not at the end of the learning curve if, compared to the learning curve required for barehanded grasp control, this curve extends to at least 8 years of daily grasp practice (Forssberg *et al.* 1991). An additional explanation is that cutaneous mechanoreceptors in the skin are not in contact with the object and cannot therefore, provide sufficient information to control grasp forces in a more efficient way, as in barehanded grasp control. This result in more slippage than would emerge from barehanded lifts. This later explanation is supported by the fact that the force profiles seen in laparoscopic grasping are similar to the force profiles seen in barehanded grasping with impaired cutaneous receptors and in children where the cutaneous sensory system is not yet fully developed (Johansson and Westling 1984, Forssberg *et al.* 1995). This results in bigger safety margins and much more object slippage.

In Chapters 2 and 5 it was found that augmented tactile feedback can bring the force profiles from barehanded and laparoscopic lifts closer together and can especially reduce performance variability. The turning cylinder that indicates slippage accounts for brief bursts of action potential elicited in the dynamically sensitive units of the tactile afferents of the fingers and can trigger a change in force balance, resulting in an increased safety margin for the prevention of further slips. This change includes a rapid reflex response (latency 60-80 msec. (Johansson and Westling 1987b, Johansson and Westling 1987a, Johansson *et al.* 1992)) together with the updating of a sensorimotor memory that maintains the new force balance. The vibrating patches that indicate excessive force account for a decrease in the safety margin. In this way the augmented tactile feedback enhances laparoscopic grasp control.

In this thesis no experiments were performed in which barehanded tasks were compared to tasks done wearing surgical gloves. Nonetheless, research showed that wearing surgical gloves does influence touch sensitivity but it does not influence two-point touch discrimination[7] (Thompson and Lambert 1995, Tiefenthaler *et al.* 2006). Additionally, the experiments reported in Chapter 4 showed that wearing surgical gloves provides a good perception of the tactile displays used.

Various training programs can be created to teach laparoscopic grasp control. In order to achieve a training program that actually teaches what is desired it is crucial to know what is learned with the current system and what should be changed if such learning goals are to be achieved.

In this thesis it was shown that trainees could learn laparoscopic grasp control in a two-handed translocation task involving two objects with the same mechanical properties. However, in a two-handed task it was difficult to achieve the pre-set level of expertise probably due to the too short practice sessions (max. duration of 25 task repetitions) with sharply set slip and damage-lines. The results of the experiments described in Chapters 4 and 5 show that there is a transfer of learning from a situation with augmented tactile feedback to a situation without augmented feedback. For a one-handed task it was demonstrated that it was possible to learn grasp control with two different material properties at the same time. The aim of the training device would be to train a trainee to control laparoscopic grasp forces in all surgical situations.

To achieve the goal of training grasp control, several training programs must first be investigated. In addition to the aspects presented in this thesis it would be necessary to investigate the following matters: transfer of learning to other tissue types, transfer of learning to other instrument types with different force transmission ratios, transfer to other tasks and the effect of training length. The former facets can be investigated with the current set up.

6.2.1. Learning to use laparoscopic graspers with different properties.

In practice, surgeons use different tools. Therefore, they need to learn to coop with all of them. When humans learn to control a tool they develop an input-output map for that specific tool, in other words, they learn how their actions relate to the movements of the tool. For a laparoscopic grasper this means that surgeons develop a specific input-output map for the behaviour of that specific grasper, which is dependent on its force transmission ratio. In the research presented in this thesis participants developed these maps for the laparoscopic grasper used in the specific experiment. The training device developed in this project is a good training device as it allows the learner to transfer what has been learnt to other situations as can be seen in Chapter 4. In other words, participants adapt the input-output map of the new situation.

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[7] Two-point threshold; the distance between two separate tactile stimuli that can be distinguished as two different points. The threshold differs according to the skin area.

Research on the plasticity[8] of input-output maps showed that despite extensive practice (>9 years) in one situation humans and monkeys are able to quickly adjust their motor output to compensate for the new conditions (Yamamoto *et al.* 2006). The experiments presented in this thesis did not test whether the developed map could be adjusted to the use of different graspers or how much practice is needed in the new situation to establish a new or adjusted map. Nevertheless, research into tool usage suggests that such remapping is possible after a relatively brief period of practice with the new tool. For example, Yamamoto *et al.* (2006) showed that after learning to handle a tool (400 initial trials) long-term retention was seen after 30-60 trials of practising with another tool-response condition.

Humans can retain an adjusted input-output map during a practice gap of more than a year (Yamamoto *et al.* 2006) suggesting plasticity of the initial map. Such long-term retention can only be achieved if initial practice is sufficient. Research showed that the number of practice trials required to lead to long-term retention lies in the region of 400 to 500 practice trials (Yin and Kitazawa 2001, Yamamoto *et al.* 2006). This might explain why our retention findings presented in Chapter 5 were so limited when participants had to repeat the trials a week after the first practice period. The participants had practiced the task 25 times, which was evidently enough for short-term retention but not for long-term retention.

The above information shows that remapping is possible in a relatively short period of time once the initial map has been established, thus suggesting that the developed device could be used as a calibration unit in addition of a training device. The advantage could be that a surgeon would be able to train grasp control using a tool with a certain force transmission ratio so that after that he or she only needs a short session of training with the tool that he or she is going to use during actual surgery. For example, before actual surgery starts a surgeon can practice the specific situation on the calibration device with the patient's tissue information and tool specifications programmed. As a result remapping establish before and not during actual surgery.

6.2.2. Frequency of providing augmented tactile feedback

Several studies in other fields suggest that when augmented feedback is not provided at all times during learning, the likelihood of becoming dependent is much smaller than when augmented feedback is provided all the time (Winstein *et al.* 1994, Magill 2006). In the research presented in this thesis, augmented feedback was

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[8] Plasticity: in the context of adjusting input-output mental maps plasticity means that the map will be adjusted when we expose humans to an altered input-output relationship. An error correction process results in a reshaping of the human's behaviour, thus resulting in an adjusted map. Once established, the new or adapted map can be retained: Yamamoto, K., Hoffman, D.S. & Strick, P.L., 2006. Rapid and long-lasting plasticity of input-output mapping. Journal of Neurophysiollogy, 96, 2797-2801.

provided during all the practice repetitions, however, this resulted in dependency in maximally 50% of the novice learners (only 10% in the intermediate to experienced learners) (Section 4.5). It is therefore worth optimizing the frequency of augmented feedback in order to reduce the chance of becoming dependent on the signal.

There are several ways to lower the frequency rate while still taking into account the fact that, in order to learn, each motor skill has its own optimal relative frequency for providing augmented feedback. Promising techniques will be briefly described below. Further extensive description and examples can be found in Magill's book (Magill 2006)

The *fading technique* is one way of bringing down the frequency. With this technique augmented feedback will be systematically reduced; for example, in the first twenty-two trials of every practice session augmented feedback is provided, then eight trials are done without, after which the frequency is systematically reduced from twenty-two to two trials. Sessions can be repeated till the task is learned.

Another technique is the *performance-based bandwidth criteria* in which the bandwidth needed to provide augmented feedback can be adjusted to individual performance. A bandwidth criteria was used in the experiments described in this thesis by setting the damage and slip lines, and creating a fixed bandwidth. However, the bandwidth was not performance based and thus the same for each participant. Therefore, some experienced a 100% frequency, as their starting skill level was not high enough. Intermediate and experienced participants were more skilled at the start and therefore experienced a frequency reduction in the feedback provided. In these more experienced participants less dependency was seen. The bandwidth technique allows for individualization of the systematic reduction of the frequency of augmented feedback during training.

An alternative technique that can be used to reduce frequency is the *Self-selected Frequency Technique* where the individual is provided with augmented feedback only when he or she asks for it (Janelle *et al.* 1995). In this way, individuals can use augmented feedback to engage in their own problem-solving strategies as they learn the skill and are able to test the validity of their own progress assessment.

6.3. Design guidelines

6.3.1. Guidelines for improving the laparoscopic grasp control training device

A surgeon can only learn laparoscopic grasp forces when the training device teaches safe grasping in several situations in a manageable training setting. In order to achieve that, the current device needs some improvements.

Position of sensors. If the sensors that measure the exerted forces were located in the tip of the grasper instead of in the object, it is possible to grasp different objects without having to modify the whole device. It would also be possible to practice with real tissue. In addition, this would allow freedom of movement so that different movements can be practised. Placing the sensors in the tip would amount to a major improvement and would probably increase the possibility of transferring learning to surgery.

Improving the mechanical properties of the instrument. As well as the force transmission ratio (which is not bad for the instrument that was presented in this thesis) hysteresis is an important mechanical property influencing the available task-intrinsic feedback needed to control grasp forces. Furthermore, a large hysteresis makes the augmented feedback signal inaccurate, as forces in the tip have to rely on forces in the handle being increased or decreased by the user. The force sensor in the tip does not have this problem, therefore, it can detect excessive grasp force when the user increases his grasp force. Once the user senses the displayed augmented feedback signal he or she decreases the grasp force. Due to hysteresis the force in the tip can suddenly drop below the slip level thus causing slippage when the user changes his or her grasp force too quickly. Reducing the hysteresis of the instrument will make the augmented feedback signal more reliable. However, augmented feedback might help to teach people how to cope with the hysteresis as well and it can be used for Feedforward[9] control.

Real-time feedback. The augmented feedback signal should be preferentially a real-time signal. The current delay (minimally 100 ms) in sensing the applied force and starting the actuators is relatively big so that when performing fast a trainee perceives the feedback when the applied forces are far above or far below the set safe area. Even when the feedback actuators display information straight away after crossing the boundaries one needs to take the human reaction time into account.

The safe area setting. The safe area must be set according to the properties of the tissue grasped. It would be preferable if the device had a number of pre-set safe areas of different tissue types in its memory so that the trainee could choose which tissue he/she wants to practice with.

Software The interface of the computer program underlying the hardware should be user friendly. The user cannot currently operate the system by himself/herself. When the training device is located in a hospital skills lab the trainee should be able to operate the device without help. Furthermore, the individual scores should be accessible so that the trainee and the teacher can assess progress over the course of time.

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[9] Feedforward control: control based on prediction Rosenbaum, D.A., 2010. Human motor control, second ed. London: Elsevier.

6.3.2. General design guidelines for grasping-tools incorporating augmented haptic feedback in order to control grasp forces.

The knowledge of natural haptic perception and the way to present augmented haptic information feedback to the user in order to overcome the problems arising from indirect manipulation, can be used in other areas as well. For example, areas where direct tissue contact is impossible such as: virtual reality, robotics, the (chemical/nuclear) industry where human hands cannot touch material or the fruit industry where fruit has to be harvested by tools. It is also possible to use augmented tactile feedback on grasp forces during actual tool use instead of only during training.

From the fundamentals of natural haptics, the cross-model effects[10] and the results of the experiments conducted in conjunction with this thesis, design guidelines can be derived for tools, together with the augmented haptic feedback required to enhance grasp control. These guidelines are only for the augmented haptic feedback angle, other aspects such as: tip design, ergonomics must be taken into account as well but are not discussed here.

- Mechanoreceptors that adapt fast cannot be used to transmit a continuous signal such as a constant or slowly changing grip force (Chapter 2). Fast adapting mechanoreceptors can be used to transmit sudden changes.
- Haptic input must take into account sensitivity to stimuli across various skin locations (for example, the two-point threshold diminishes from palm to fingertips, spatial resolution is about 0,9 mm on the fingertip in the absence of any lateral skin movement (Wall and Brewster 2006) to 2.5 mm on the index finger (Boff *et al.* 1986)).
- Stimuli must be at least 5.5 ms apart to ensure that receptors perceive individual cutaneous signals. (Boff *et al.* 1986)
- To activate an individual's pressure sensors, the force exerted must be greater than 0.06 to 0.2 N/cm^{2} (Boff *et al.* 1986).
- To perceive vibration from a single probe 28 decibels must be exceeded (relative to a microsecond peak) for 0.4 to 3 Hz frequencies.
- To feel a textured surface relative motion between the surface and the skin must be maintained.
- Thresholds for step indentations at the fingertip are in the region of 10 μm (Wall and Brewster 2006).
- The force transmission ratio of the tool itself must be as low as possible (see Chapter 3) However, it does not need to be 1:1 as larger forces at the

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[10] Cross-model effect: During multi sensory task such as grasping strong links between brain activity of vision and haptics exist. Therefore, dynamic tactile cues and the reverse could support reoriented visual attention {Gray}.

handle lead to small accurate forces at the tip. A force transmission ratio greater than 1:3 causes fatigue in the hand muscles as constantly applying 9N to the handle is enough to fatigue the muscles (de Visser *et al.* 2002).

- The Augmented tactile feedback signal provided must be real-time (Chapter 5).

6.4. Recommendations for future research

Before using the laparoscopic grasp control training device presented in this thesis, in practice, certain elements need to be investigated in addition to implementing the guidelines already given.

The transfer of learning to surgery should be studied. In other words, the transfer of learning to other (not practiced) combinations of tissue type and instruments. The optimal training length should furthermore be investigated.

The possibility to use the device as a grasp control calibration unit before actual surgery starts should be investigated too. In this way a direct transfer of the device used in practice to actual surgery can be established. A prerequisite is that the training device contains information about the patient's tissue properties and that the same instrument type is used during surgery as during this calibration.

The mechanical properties of soft tissue should be studied, as this information is necessary for establishing the safe area in the training device. Knowledge about the mechanical properties of healthy and sick tissue is essential if correct grasp control is to be mastered.

The best frequency for displaying the augmented tactile feedback signal during the training period should be investigated.

6.5. General Conclusion

The research presented in this thesis showed that using augmented haptic feedback during learning could enhance laparoscopic grasp control. When properly implemented for the training of resident surgeons the future could look like this:

> *Judith's daughter Marian finished her study in medicine in 2020 and started as a resident in the Catharina Hospital with a view to becoming a surgeon. When she asked her mother about her scars, Judith told her the story of her laparoscopic surgery that had turned into open surgery due to bowel puncturing. Marian told her mother that nowadays, this would not happen anymore as medical students learn to control laparoscopic grasp force with the help of augmented haptic feedback.*

In the skills lab in which Marian practised her skills the box-trainers are equipped with laparoscopic graspers that provide augmented tactile feedback on grasp forces. The feedback is provided in such a way that natural responses are evoked and grasp control can be learned during all the procedures practised. The program Marian has to practice is especially tuned to her needs which means that it is not provided continually but at intervals to make sure that Marian can easily implement her learned laparoscopic grasp control in surgery where augmented feedback is not available. Marian and the other resident surgeons are not allowed to perform surgery before they show that they can manipulate different tissue types without damaging them. The smart box-trainers help them train to a sufficient level to perform safe surgery.

When Judith went with her daughter to a so-called 'open day' at the hospital and saw the sophisticated equipment her daughter trained with she was happy. No more people would have to suffer like she did.

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Summary

A Sense of Touch in Laparoscopy

Using Augmented Haptic Feedback to Improve Grasp Control

Laparoscopy is Minimally Invasive Surgery (MIS) that is conducted in the belly alcove and which enables instruments, which enter the body through small incisions, to manipulate tissue. The possible complications arising during laparoscopic surgery are partly caused by improper grasp control on the part of the surgeons using the graspers. This is mainly caused by a reduction in the perception of haptic information (combination of tactile and kinaesthetic information) from the grasped tissue as a result of indirect grasping. The experiments presented in this thesis focus on the improvement of laparoscopic grasp control and the related learning aspects, to see if the former might be improved by means of augmented feedback received on haptic information.

The aim of this thesis is to answer the following main research question:

> ***"Can augmented feedback on haptic information enhance the surgeon's control of laparoscopic grasp force?"***

To understand natural haptics and perception, the parts of the human motion control system involved in grasping are discussed in Chapter 2. The discussion includes barehanded human grasp control and a description is given of the sensory systems involved.

A literature review describes the current situation surrounding haptics in MIS, the factors that influence the amount of grasp force applied to the tissue and precisely what sensory information is at present available during the use of laparoscopic graspers. Questionnaire results show the importance of this topic from a surgeon's point of view. Surgeons need haptic feedback as that is reduced when traditional MIS instruments are used and it is completely absent in Robotic assisted Minimally Invasive Surgery (RMIS).

At the start of this PhD project it was not clear which factors control the application of laparoscopic grasp force to tissue. Experiments, presented in Chapter 3, were done in which tasks that were carried out barehanded were compared to tasks that were carried out laparoscopically via instruments with various force transmission ratios. These experiments provided insight into how accurately a human can sense forces and tactile information through a laparoscopic instrument during tissue-grasping tasks. The results of experiments show that in order to successfully control the force applied to the tissue, tactile feedback is essential. The question is whether humans can learn to control their grasp without such tactile feedback but with the help of augmented feedback that compensates for the missing haptic information.

The principals of human grasp control discussed in the opening chapters show that both haptics and vision are important in the controlling of hand forces. These principals are the same as those required for the safe control of instruments in MIS. However, the instruments cause a disturbance in visual and kinaesthetic feedback and they cannot provide tactile information at all.

The numbers of consequential and inconsequential errors that are being made due to insufficient grasp force control indicate that there is a need to enhance the currently available combination of visual and haptic feedback. The matter of whether augmented feedback can help performance in laparoscopic grasping is tested and discussed in chapter 4. Several augmented feedback modalities are considered (visual, tactile, illusionary and combinations thereof). Experiments, show that having augmented tactile feedback on grasp forces is a good way to help in laparoscopic grasp control. Surgeons at all levels of experience benefit to control their grasp forces with the aid of augmented haptic feedback. With the help of augmented feedback they learn more quickly to control their laparoscopic grasp force and apply reduced overall grasp forces.

In addition to receiving augmented haptic feedback all the time during tool usage the question raised if it is possible to train the surgeons to cope with the distorted intrinsic feedback provided by the current graspers by means of only training with augmented feedback. This is supported by the fact that it is known that augmented feedback during the learning process can aid performance in several tasks other than grasping.

The advantage of learning to cope with distorted intrinsic feedback is that there is no need for the development of new and expensive instruments in the operating room as the normal instruments can still be used.

The results of experiments presented in Chapter 4 show that the majority of surgeons do not become dependent on the augmented signal. This implies that when the augmented feedback is removed they continue to perform with the same improved force control and thus learned to deal with the intrinsic feedback available. Furthermore, experiments showed that performance was still enhanced when the participant’s attention was distracted by introducing an additional aiming-task (with the second hand), while the task whereby controlling grasp forces was needed continued with the other hand.

To optimise the augmented haptic feedback signal used in the experiments presented in Chapter 4, a design for a new grasper handle was developed. This new laparoscopic grasper handle with integrated augmented tactile feedback actuators is presented in Chapter 5. To see if people are able to learn grasp control with two hands simultaneously, two of these new handles were used in experiments. The results show that learning with two hands simultaneously is indeed possible and that people do not get confused as a result.

From the research done during this PhD project it can be concluded that augmented tactile feedback on grasp forces can aid laparoscopic grasp control even if it is only provided during a training period. Furthermore, the research conducted resulted in the development of a working prototype of a laparoscopic grasper containing augmented tactile feedback on grasp forces together with guidelines for training devices containing augmented haptic feedback.

Samenvatting

Tastzin bij laparoscopie

Verbeterde knijpkracht controle door gebruik van toegevoegde haptische feedback

Laparoscopie is Minimale Invasieve Chirurgie (MIC) uitgevoerd in de buikholte waarbij weefsels worden gemanipuleerd via instrumenten die worden ingebracht via kleine incisies. De mogelijke complicaties die laparoscopische procedures met zich meebrengen worden gedeeltelijk veroorzaakt door een gebrek aan knijpkracht controle van de chirurg die de instrumenten hanteert. Dit wordt hoofdzakelijk veroorzaakt door de gereduceerde haptische informatie (tactiele en kinesthetische informatie) die wordt waargenomen via het indirect vasthouden van weefsel. De experimenten die in dit proefschrift worden gepresenteerd zijn gericht op het verbeteren van de laparoscopische knijpkracht controle en het aanleren hiervan. Er zijn aanwijzingen dat toevoegen van feedback over haptische weefsel informatie de laparoscopische knijpkracht controle kan verbeteren. Het doel van dit proefschrift is de volgende hoofdonderzoeksvraag te beantwoorden:

‘Kan toegevoegde feedback over haptische informatie de laparoscopische knijpkracht controle van de chirurg verbeteren?’

Om de natuurlijke[11] haptiek en waarneming te kunnen begrijpen worden delen van het menselijke bewegingscontrolesysteem die hierop betrekking hebben, besproken in Hoofdstuk 2. De controle van de menselijke knijpkracht met de blote handen wordt besproken en de zintuigen die daarbij betrokken zijn worden beschreven.

Een literatuurstudie beschrijft de huidige situatie omtrent haptiek in de MIC, de factoren die de hoeveelheid kracht die wordt uitgeoefend op het weefsel beïnvloeden en de zintuiglijke informatie die beschikbaar is tijdens het gebruik van de laparoscopische grijpinstrumenten. Enquête resultaten laten zien hoe belangrijk dit onderwerp is vanuit het standpunt van de chirurg. Chirurgen hebben haptische feedback nodig omdat deze gereduceerd is bij traditionele MIC instrumenten en zelfs afwezig is in Robot geassisteerde Minimaal Invasieve Chirurgie (RMIC).

In het begin van dit promotieproject was het niet duidelijk welke factoren er precies een rol speelden bij het doseren van de laparoscopische knijpkracht op het weefsel. Experimenten, gepresenteerd in Hoofdstuk 3, waarbij taken uitgevoerd met de blote handen werden vergeleken met laparoscopisch uitgevoerde taken, waarbij gebruik

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[11] Natuurlijke in deze context betekent dat de haptische informatie verkregen van het aangeraakte object niet waargenomen wordt via een instrument maar direct door de menselijke hand.

werd gemaakt van instrumenten met verschillende kracht overbrengingskarakteristieken, gaven inzicht in hoeverre men in staat is krachten en tactiele informatie waar te nemen via de instrumenten tijdens weefsel-pak taken. De resultaten van experimenten laten zien dat voor een succesvolle dosering van de knijpkrachten tactiele feedback essentieel is. De vraag is of mensen kunnen leren hun knijpkracht te doseren zonder deze tactiele feedback maar met de hulp van toegevoegde feedback die de missende haptische informatie zou moeten compenseren.

De principes van menselijke knijpkracht controle, besproken in de eerste hoofdstukken, laten zien dat haptiek en visuele informatie een belangrijke rol spelen in de controle van hand krachten. Deze principes zijn hetzelfde voor het controleren van instrumenten tijdens MIC. Echter, de instrumenten zorgen er voor dat visuele en kinesthetische feedback verstoord worden en dat tactiele informatie helemaal niet wordt doorgegeven.

Het aantal fouten, met en zonder consequenties, die gemaakt worden door inadequate laparoscopische knijpkracht dosering laat zien dat de huidige combinatie van haptische en visuele feedback verbeterd moet worden. Of toegevoegde feedback de prestatie kan verbeteren wordt in dit promotie onderzoek getest en besproken. Verschillende feedback modaliteiten (visueel, tactiel, Illusies en combinaties van deze) worden bekeken in Hoofdstuk 4. Experimenten laten zien dat toegevoegde tactiele feedback over knijpkrachten een goede manier is om het doseren van laparoscopische knijpkrachten te ondersteunen. Chirurgen met alle expertise niveaus profiteren van het oefenen van knijpkracht controle met toegevoegde haptische feedback. Als gevolg van trainen met toegevoegde feedback leren de chirurgen sneller hun laparoscopische knijpkracht te controleren en de door hun uitgeoefende krachten zijn lager.

Naast het continu toevoegen van feedback tijdens instrument gebruik rees de vraag of het mogelijk is de chirurg te trainen om beter met de beschikbare verstoorde feedback van de huidige instrumenten om te gaan. Dit zou kunnen door alleen te oefenen met behulp van toegevoegde feedback. Dit wordt gesteund door het feit dat het bekend is dat toegevoegde feedback tijdens het leerproces, in andere taken dan vastpakken, de prestatie kan verbeteren. Het voordeel van het leren omgaan met de beschikbare verstoorde feedback is dat er geen nieuwe en dure instrumenten ontwikkelt hoeven worden om in de operatiekamer te gebruiken omdat de huidige instrumenten gewoon gebruikt kunnen worden.

De resultaten van de experimenten uit Hoofdstuk 4 laten zien dat de meerderheid van de chirurgen niet afhankelijk wordt van het gegeven signaal. Dit impliceert dat wanneer het toegevoegde feedback signaal wordt weggehaald, de chirurg de taak nog steeds met gereduceerde krachten zou kunnen uitvoeren net zoals met feedback. Experimenten laten verder zien dat het uitvoeringsniveau nog steeds verhoogd is wanneer de aandacht van de deelnemer werd afgeleid door het toevoegen van een richt-taak voor de tweede hand. Deze richt-taak werd toegevoegd terwijl de taak waarbij controle van de laparoscopische knijpkracht met de andere hand nodig was gewoon doorliep.

Om het toegevoegde haptische feedback signaal dat gebruikt werd in de experimenten van Hoofdstuk 4 te optimaliseren is een nieuw handvat ontworpen. Dit nieuwe handvat met tactiele actuatoren wordt gepresenteerd in hoofdstuk 5. Om te zien of mensen in staat zijn om met twee handen tegelijkertijd te leren hoe ze hun laparoscopische knijpkracht moeten controleren werden twee van deze handvatten gebruikt in de experimenten die gepresenteerd worden in Hoofdstuk 5. De resultaten laten zien dat dit daadwerkelijk kan en mensen niet in de war raken van de feedback op beide handen tegelijk.

Geconcludeerd kan worden dat toegevoegde haptische feedback helpt om de laparoscopische knijpkracht te controleren, zelfs als dit alleen tijdens de training wordt toegepast. Verder heeft het onderzoek uitgevoerd tijdens dit promotieproject, geresulteerd in zowel een werkend prototype van een laparoscopisch grijp instrument met toegevoegde tactiele feedback over knijpkracht ontwikkeling, als richtlijnen voor trainingstoestellen die toegevoegde haptische feedback bevatten.

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Noor

Curriculum Vitae

Eleonora van der Putten was born in Leiderdorp, the Netherlands, on 26th of May 1974. She married Fokke Westebring in 2005 and they got three children together; Merel (2005), Madelief (2007) and Floris (2010)

She finished her secondary education (VWO) in 1992 after which she started studying Industrial Design Engineering at Delft University of Technology. In July 1997 she graduated on the subject of "Biomechanically adjusted sport-climbing shoes" and the design thereof.

While working as a human factor engineer at several companies (e.g. IBM, Philips Design) and finishing a semi-professional career in sport climbing, she started studying Human Movement Sciences on a part-time basis at the Vrije University in Amsterdam in September 2004. She graduated in June 2006 with her thesis entitled 'Oxygenation in the m. erector spinae during low-level contractions'.

During her work, her studies and her initial research in the field of Human Movement science, Eleonora was inspired to go further and she was fortunate to start her PhD research project in September 2006. This research project was conducted in cooperation with the Catharina Hospital in Eindhoven. During her PhD project she was invited to present her work on various conferences and to lecture ergonomics at the faculty of product development at the Artesis Hogeschool in Antwerp, Belgium.

Being inspired not only by human movements but also by the movements of animals, she started a part-time training in animal chiropractics, which she finished in 2010.

Eleonora is keen to continue contributing to research in the area of movement science and is in the process of applying for grants.

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Patents

Flower support with stem protector: 06716676,9-1261-NL2006050043
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