# Haptic feedback for laparoscopic surgery instruments
Ph.D. Thesis

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# Abstract

The present thesis focuses on the use of haptic feedback technologies to provide information to surgeons during laparoscopic or minimal access surgery (MAS) with the aim of assisting them in improving their gestures.

Better overall outcomes for patients have led MAS to become standard for many surgical interventions. However, loss of visual depth perception, difficult hand-eye coordination and distorted haptic sensation seriously complicate this task for the surgeon. We explore the potential of haptic cues for intuitively assisting surgeons during MAS gestures. Evaluated forms of feedback mainly focus on haptic (tactile and kinaesthetic) cues, but including comparisons to visual and multi-modal combined haptic and visual cues.

Experiments on surgical tool navigation show encouraging results for the benefit of haptic cues in improving surgical gestures, with clear superiority of soft guidance virtual fixtures over other forms of feedback. However, promising results for the use of vibrotactile feedback are also obtained. These results are confirmed in preliminary experiments on tool navigation in preliminary experiments on tool navigation during a laparoscopic cutting training task. Parallel work on feeding back interaction forces highlighted significant differences in the usability and design requirements for tactile cues when compared to instrument navigation applications. This led us to design and perform preliminary testing on tactile cues appropriate force information in the case of intra-corporeal suture knot tying.

Chapter I presents laparoscopic surgery, with its advantages, drawbacks and associated challenges. A general state of the art on solutions for overcoming surgeon limitations in action and learning is provided in this chapter. This leads to a more detailed state of the art on methods for compensating and overcoming perceptual limitations in laparoscopy is presented in chapter II. Chapters III and IV respectively present the current state of our work on surgical tool navigation and feedback of surgical tool-tip interaction forces. States of the art more specific to these sub-problems are provided, experiments are detailed and general conclusions on the feasibility and

added benefit of haptic feedback for these tasks are drawn. Chapter V goes over the conclusions drawn from our exploratory work presented in chapters III and IV in the light of a more general state of the art on information communication through tactile cues in order to draw up a list of recommendations for the design of tactile feedback systems with applications in MAS.

## Acknowledgements

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Chapter 1

# Introduction

Contents

## 1.1 Laparoscopy - History, benefits, drawbacks and challenges

Surgical procedures have gradually evolved from a surgeon-centred approach, where a larger surgical incision meant better access to the operating site but also demonstrated higher surgical proficiency on the part of the practitioner, to a more patient-centred approach, where the aim has become a maximum reduction of patient discomfort, post-operative treatment and complications. Since the advent of Minimal Access Surgery (MAS)[1] at the beginning of the 1900's with the first diagnostic laparoscopies and thoracoscopies [123], the aim has been to make surgical procedures less and less traumatic to the patient, starting with a gradual reduction of the size of surgical incisions.

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[1] Also widely referred to as minimally invasive surgery although, as has been remarked by Cushieri in the editorial for Surg. Endosc. (1992) 6:214, this is both semantically incorrect and fails to convey the main aspect of the procedures - namely the significantly reduced access trauma. Hence in the present manuscript, we will refer to these procedures with the terms MAS and laparoscopic surgery used in an interchangeable manner.

In this context, laparoscopy became widespread in the 1950's, first as a purely diagnostic procedure, then as a surgical procedure. Since the performance of the first laparoscopic cholecystectomy[2] at the end of the 1980's [224], MAS has become standard in many surgical interventions ( [89], [253], [256]).

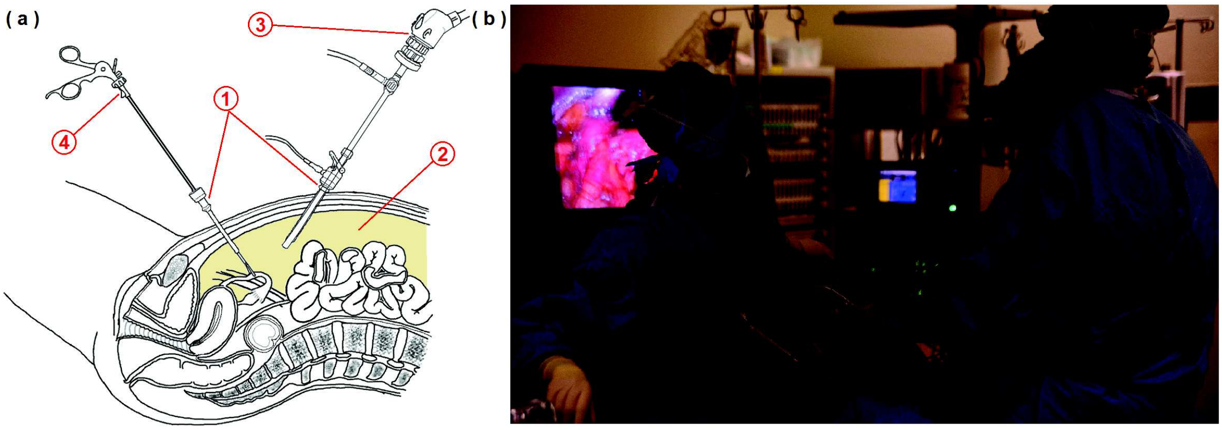

Figure 1.1: *(a) Schematic view of a laparoscopic surgery*[3]*; (b) Close-up of a surgeon manipulating laparoscopic instruments*[4]

During a laparoscopic procedure, two or more thin elongated instruments (part no.4 in fig. 1.1) and an endoscopic camera (also referred to as laparoscope - part no.3 in fig. 1.1) are inserted through ports placed in the abdomen of the patient (also referred to as trocars - part no.1 in fig. 1.1). In order to ensure a sufficient workspace, the abdomen of the patient is insufflated with $CO_2$ (part no.2 in fig. 1.1) in order to lift the abdominal wall away from the organs, resulting in what is referred to as a pneumoperitoneum.

The practitioner watches the movement of his or her instruments on one or several external screens which display the image acquired by the endoscopic camera, allowing him to operate. The main advantage of this technique is the drastic reduction of the size of the incisions required to perform the surgery (see fig. 1.2 and table 1.1 for the example of cholecystectomy). Current standard laparoscopic instruments and cameras usually require inner trocar diameters ranging from 5mm to 12mm, thus usually leaving the patient with between 3 and 5 scars of these dimensions. While we choose to limit the discussion in this thesis to laparoscopy, it should be noted that the insights gained here may in some cases easily transfer to other similar minimal access procedures such as thoracoscopy (chest surgery) or arthroscopy (minimal access joint surgeries). The main reason for our focus on laparoscopic surgery among all endoscopic procedures is the growing demand for these procedures, making it one of the largest medical segments with about 7.5 million surgeries performed annually worldwide, and a projected global market for laparoscopic devices of approx. USD 8.5 billion by 2018[5].

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[2] Cholecystectomy : gallbladder removal surgery

[3] Adapted and redrawn from www.melakafertility.com

[4] Photo credits: Thomas Howard 2015

[5] "Laparoscopic Devices: A Global Strategic Business Report" announced by Global Industry Analysts, Inc.

[6] Photo credits : (Left) Steven Davidson, MD, DDS; Nasir Aziz, MD, MA, PGY-1; Rashid M. Rashid, MD, PhD, PGY-2; Amor Khachemoune, MD, CWS - as published in Medscape J Med. 2009; 11(1):18; (Right) www.abdopain.com

Figure 1.2: *(Left) Residual scar after an open cholecystectomy; (Right) Scars two days after a laparoscopic cholecystectomy. See table 1.1 for detailed comparative information.* [6]

### Benefits of minimal access surgery

Overall, these smaller incisions are easier to close and faster to heal, producing a better cosmetic result [74], reduced post-operative hospital stays and convalescence [27] and incidentally reduced operating costs [91]. They also show evidence of lower rates of post-operative complications [168]. It is however important to note that the stated benefits are highly dependent on the type of procedure performed and the method of evaluation. In [63], the author points out the complexity of assessing the actual cost to benefit ratio of MAS when compared to open surgery. Ethical problems and practical limitations do not necessarily permit proper randomized comparative trials, e.g. in [195], the authors note that patients undergoing laparoscopic appendectomy generally had a lower severity of illness than those assigned to open appendectomy, putting the validity of comparison between the open and laparoscopic procedures into question. Cuschieri et al. [63] note that patient outcomes are also inconsistently analysed across studies, focussing either on short term metrics (morbidity[8], mortality[9], blood loss etc.) or on long-term metrics such as hospital stay, convalescence, return to normal activity, return to surgery. The article raises an interesting discussion on the need to standardize these metrics and making them more relevant to actual patient well being (e.g. using metrics such as Quality-of-Life-Adjusted-Years[10] or survival rates). Also, the author notes that cost analyses should always be put into the context of overall case load.

Finally, it is imperative to keep in mind that each patient is unique and therefore benefit of a given procedure will greatly vary from one patient to another depending on the specificities of their case.
Given this, the author lists the following as the main core strengths and benefits of MAS:

- Reduced operative trauma (subdivided into surgical trauma - necessary to the procedure

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[7] Based on information from Covidien®as published in [61](retrieved 12/2015)

[8] Morbidity refers an incidence of ill health in a population.

[9] Mortality refers to the incidence of death or the number of deaths in a population.

[10] The quality-adjusted life year (QALY) is a measure of disease burden, including both the quality and the quantity of life lived used to assess the value of a medical intervention. Each year in perfect health is assigned the value of 1.0 down to a value of 0.0 for being dead, with years not lived in full health receiving an intermediary score.

| | **Open procedure** | **Traditional laparoscopic procedure** | **Single-incision laparoscopic procedure (SILS)** |
|---|---|---|---|
| No. of incisions | 1 large incision (see fig. 1.2 left) | 3 - 4 small incisions (see fig. 1.2 right) | 1 incision |
| Incision size(s) | approx. 15 cm | 5 - 20 mm per incision | 20 mm |
| No. of visible scars | 1 large scar | 3 - 4 small scars | none or 1 small scar |
| Hospital stay | 3 - 7 days | 1 - 3 days | 1 - 3 days |
| Post-operative pain | Moderate | Mild or minimal | Mild or minimal |
| Recovery time | Return to work in up to 6 weeks | Return to work in under 10 days | Return to work in under 10 days |

Table 1.1: *Comparative table with indicative values for scar sizes and healing times relating to conventional open, conventional laparoscopic and single-incision laparoscopic cholecystectomy procedures* [7]

(e.g. ablation), and access trauma)

- Reduced incidence of major wound complications and reduced adhesive complications
  This assertion is e.g. confirmed by [168] and [195] but disputed by [49], [74], [265] and [190].
- Shorter hospital stay
  This assertion is e.g. confirmed by [74], [91], [168], [265] and [195] but disputed by [49] and [88].
- Reduced duration of short-term disability (convalescence)
  This assertion is e.g. confirmed by [265] and [190] but disputed by [49] and [88].

The following further benefits of MAS also appear in literature on the subject:

- Better cosmesis ( [74], [190]),
- Lower overall cost [91], although this is disputed by e.g. [74] and [187],
- Better diagnosis ( [190], [28]).

### Drawbacks of minimal access surgery

As stated previously, the current approach in surgery is largely patient-centred, meaning that drawbacks incurred in terms of surgeon comfort are judged as acceptable if the overall outcome for the patient is better. However, evidence suggests that the incurred limitations lead to a sub-optimal performance on the surgeon's part, resulting in sub-optimal patient outcomes. This also only adds to the complexity of properly evaluating the medical benefit obtained from laparoscopic surgery procedures, in that a certain amount of the negative points found for laparoscopic surgery can likely be traced back to sub-optimal performances on the part of surgeons and could be lessened should the ergonomics of the task be improved.

Bishoff et al. [36] perform a study of laparoscopic bowel surgery, concluding that bowel perforations and abrasions occur in a small percentage of patients, however are most often not recognized during the operation and can easily lead to devastating consequences for the patient. They conclude that it is highly important to recognize and treat these bowel injuries immediately upon occurrence during surgery. Deziel et al. [73] perform a large scale study of complications of laparoscopic cholecystectomy by surveying 4292 hospitals, concluding the procedure is associated with a significant rate of bile duct injury. Furthermore, although the observed mortality rate was low, 18 out of 33 observed post-operative deaths resulted from operative injury. In order to better understand the mechanisms of error in endoscopic surgery, Joice et al. [140] perform an in-depth analysis of errors. **They conclude that a majority of errors observed could be associated with the motor control of instruments, which lead to the highest requirements for corrective action.** The instruments associated with the highest error rate were graspers and electrosurgical hooks, with significant use of either too much or too little force, indicating either a poor design of laparoscopic graspers with regard to the task at hand, inadequate perception of applied forces, poor surgeon judgement or a combination of all three. Position and orientation of hooks prior to application of current also represented a significant portion of errors. Consequences of these errors are also observable on a larger scale: Lam et al. [160] analyse the impact of the introduction of laparoscopic gynaecological procedures, concluding a rise in the variety and incidence of complications, as well as a significant amount of intra-operative injury.

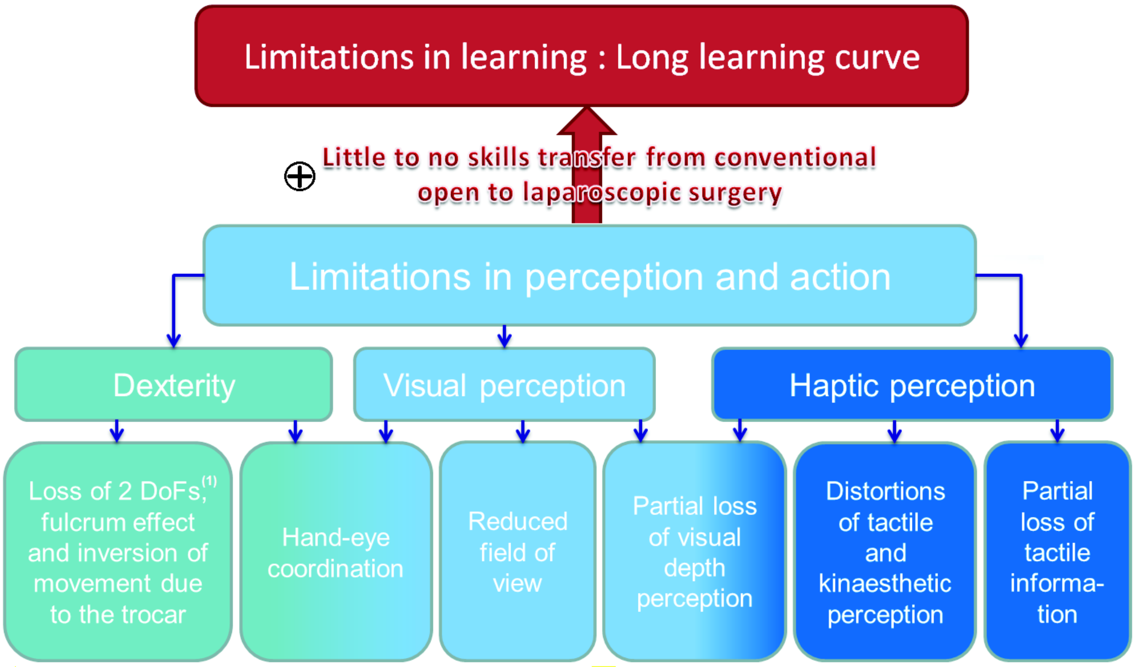

Figure 1.3: *Classification of limitations of MAS in terms of surgeon perception and action, which impact both the execution of laparoscopic surgeries and learning of laparoscopic techniques by preventing skills transfer between open and laparoscopic surgery*
*In fig. (1): (mechanical) Degrees of Freedom*

As mentioned above, laparoscopic techniques are highly inconvenient for the surgeon [64]. In addition to the prolonged operating times [91] when compared to open surgery, the surgeon is faced with a series of limitations in perception and action due to the specific kinematics and ergonomics of laparoscopic surgery. These limitations affect both learning and execution of these surgeries and can be generally categorized as either perceptual (loss or disturbance in the natural perception of the operating theatre) or relating to performance (lack of mobilities, degraded ergonomics, reduced performance due to perceptual issues) [303] - see fig. 1.3.

It is important to remember that the classification provided in fig. 1.3 serves to clarify problem sources, not to show them as perfectly distinct problems. While they have a certain number of distinct components, issues overlap between learning and execution of surgery, and within the dexterity and perceptual limitations respectively, whereby the dexterity limitations are somewhat related to the perceptual proprioceptive limitations and so on.

## 1.2 Lack of skills transfer from open surgery and the long learning curve in laparoscopic surgery

The issues affecting learning of laparoscopy are two-fold: on the one hand, the complexity in executing laparoscopic tasks (which will be dealt with in the following sections) hampers learning, and on the other, there appears to be little to no possible transfer of skills between conventional open and laparoscopic surgery, forcing surgeons to re-learn procedures from scratch ( [82]).

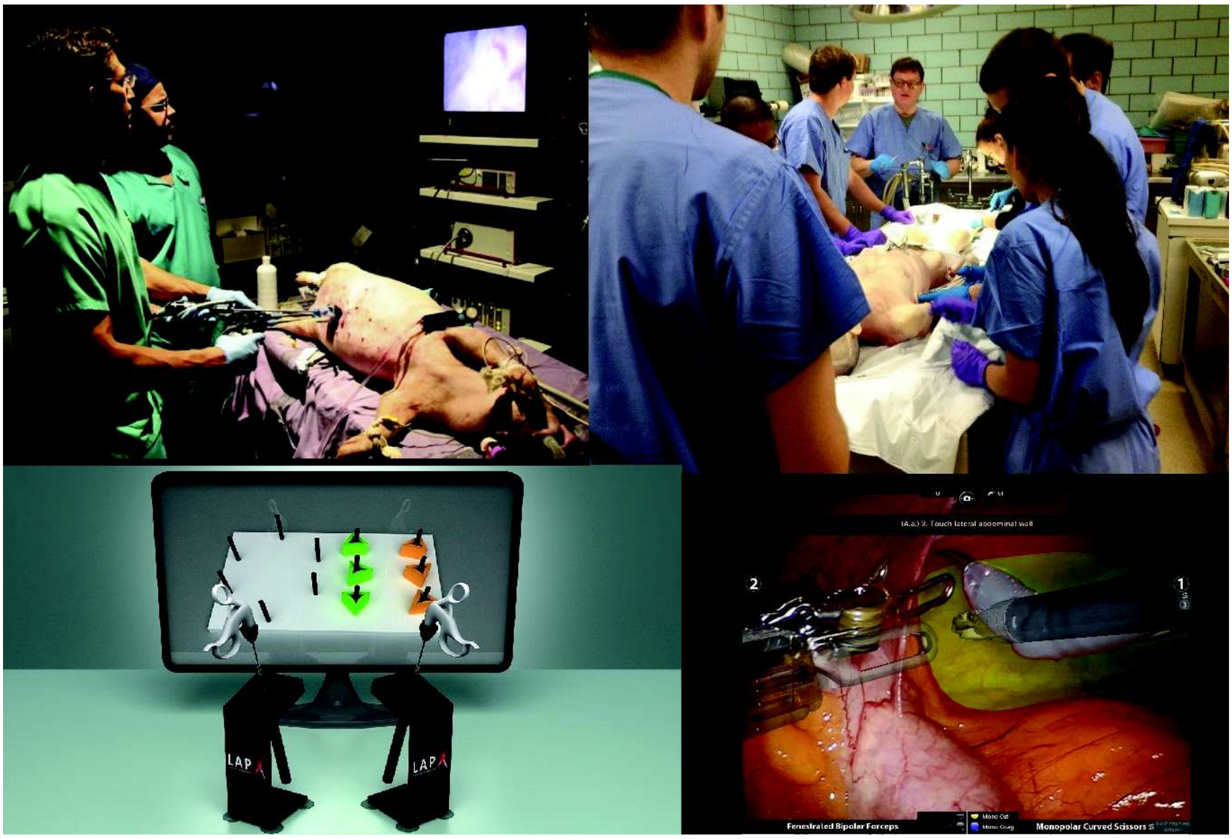

Figure 1.4: *Training options for laparoscopy : (top left) Conventional training on animal (porcine) model offers a reasonable compromise between realism, cost and accessibility when compared to training on cadavers (top right), prompting the development of virtual reality (bottom left) and augmented reality systems (bottom right) aiming to provide readily accessible, flexible and realistic training at minimal cost (shown here: LAPX VR System and Mimic Tech Maestro 3D Augmented Reality System for Intuitive Surgical's DaVinci console respectively)* [11]

In their analysis of the learning curve for robotic surgery using the DaVinci, Kaul et al. [147] hypothesize that the combination of changed haptic perception via laparoscopic instruments and changed vision via endoscopes could be a significant reason for the steep learning curve in laparoscopy. Finally, surgeons practising laparoscopy cannot train solely for laparoscopic procedures. As some procedures are still performed in open surgery and there may be cases where laparoscopies must be converted to open surgeries in an emergency, surgeons are expected to learn both open and laparoscopic approaches.

Training in laparoscopy basically requires learning or re-learning fundamental motor skills specific to minimal access surgery, most notably through the standardised exercise programs regrouped under the name *Fundamentals of Laparoscopic Surgery* (FLS) [84]. Current laparoscopic surgery training is also based on training on animals and cadavers (see fig. 1.4 top left and right respectively) which provide realistic settings, however this leads to high costs and limited access to training. To overcome this challenge, much work has focussed on designing laparoscopic surgery simulators, be it virtual reality (VR) simulation [92], augmented reality (AR) simulation ( [39], [59]) or VR simulation with haptic feedback ( [17], [58], [280], [247], [313]). Examples of such VR and AR systems are shown in fig. 1.4 bottom left and right respectively. Overall, the respective benefits of AR, VR and conventional training methods on surgeon skills are still unclear ( [227], [50], [111]), and the benefit of haptic feedback for AR and VR applications still remains disputed. However, alternate approaches for improving laparoscopy training based on systematic analysis of benefits from various exercises ( [215]), exercise intensities ( [245], [115], [56]) and training routines ( [114]) have shown to significantly reduces the number of technical errors arising during surgeries.

## 1.3 Limited dexterity in MAS

The limitations in dexterity experienced by laparoscopic surgeons stem both from particularities in the operating room ergonomics, workspace limitations inherent to endoscopic surgeries and particularities in the tools used.

### Operating room ergonomics

Supe et al. [262] present an overview of ergonomics theory applied to laparoscopic interventions. They highlight major axes that could improve laparoscopic performance in terms of comfort and dexterity, such as instrument design, trocar placement, monitor placement and operating table placement. Other attempts at improving the ergonomics of laparoscopy have focussed on optimizing port placement with regards to the obtainable workspace [148]. Fig. 1.5 provides an overview of recommendations on and impacts of these various factors with regards to access to the surgical site and freedom of movement in the operating room.

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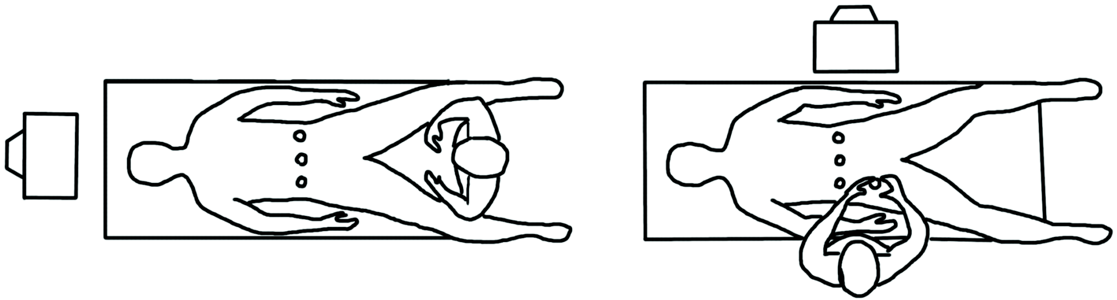
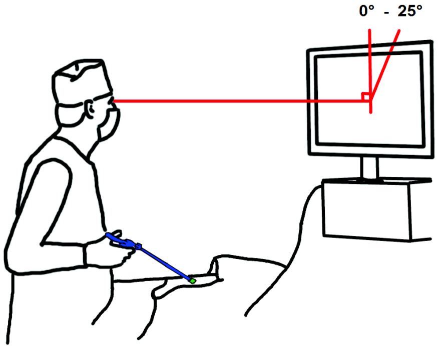
[11] Photo credits : (top left and right) https://www.ttuhsc.edu/; (bottom left) http://www.medical-x.com; (bottom right) http://www.mimicsimulation.com

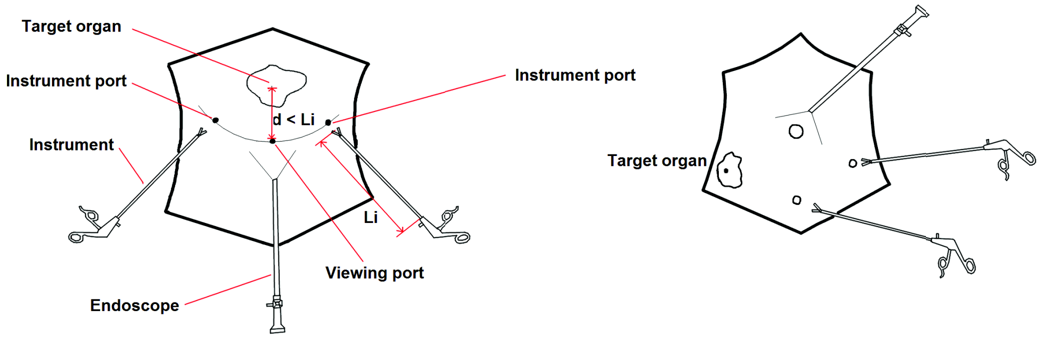


Preferred European operating table positioning

Preferred American operating table positioning



Optimal screen placement and surgeon posture



Triangulation

Sectorization

Figure 1.5: *Ergonomics considerations relating to the issue of limited dexterity. Top row: Possible surgeon placement with regards to the operating table, preferred European placement on the left, preferred American placement on the right. No clear consensus exists on which is more efficient for a given intervention, leaving the choice up to surgeon preference. Centre image: Optimal monitor placement directly in front of the surgeon at eye height or slightly lowered with an angle <25° to the eye's horizontal plane ensures minimal neck strain. The operating table should be raised so as to ensure instruments are maintained at elbow height. Bottom row: Depending on operating room configuration, surgical scenario and surgeon preference, two trocar arrangements are possible with respect to a target organ to ensure best access to the workspace, triangulation on the left and sectorisation on the right. Instrument manipulation angles should ideally be maintained between 45 degrees and 60 degrees.* [12]

### The workspace and degrees of freedom remain inherently limited

However, even with an optimal choice of operating room arrangement and trocar placement, there is an inherent limitation of the available workspace due to the fact that the entire surgery is carried out within the patient's inflated abdomen. Added to this comes the fact that even when

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[12] Drawn based on the review by Supe et al. [262]

optimally placed, there is no way around the fact that trocars act as mechanical constraints for the instruments, removing two of their available degrees of freedom. Also, using an excessive number of trocars would both complicate the procedure and partly defeat the purpose of laparoscopic surgery through the sheer number of incisions required. These factors, along with the limited field of view offered by the endoscope, interact to seriously hamper instrument movements around the target organs, in particular for surgeries requiring larger workspaces (e.g. liver and bowel surgery).

Several solutions to this aspect have been researched and brought to the market, at first in the form of pre-bent instruments allowing better access to the surgical site (see fig. 1.6 (a)). These devices however are not very adaptable and require special flexible trocar tubes, limiting their capacity for being deployed in different surgical scenarios. Miernik et al. [192] perform a comparative evaluation of pre-bent and conventional laparoscopic instruments in the particular case of SILS[13]. They conclude that although pre-bent instruments can compensate partially for the loss of triangulation in SILS, performances remain better using conventional laparoscopic access and instruments.

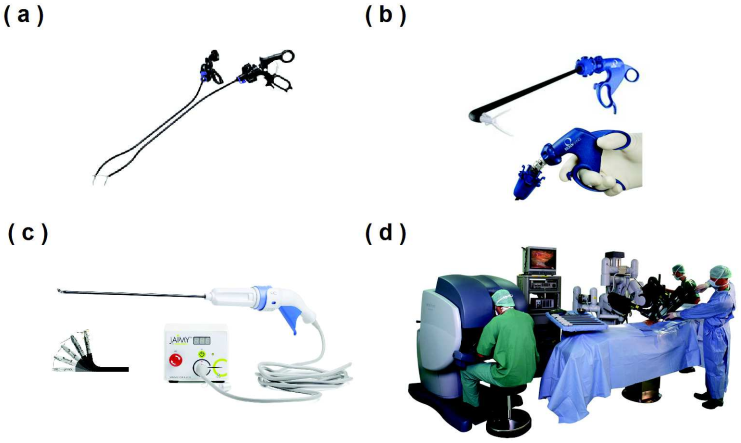

Figure 1.6: *(a) Pre-bent (Olympus HiQ LS Curved phi 5mm instrument), (b) articulated (Novare Surgical RealHand HD instrument), motorized (Endocontrol Jaimy) and robotic (Intuitive Surgical DaVinci S) laparoscopic surgery instruments*

A step further was taken with the development of basic articulating instruments, which could be inserted into the abdomen straight, and deflect inside according to the surgeons needs (see fig. 1.6 (b)). Although this type of instrument does to some extent restore a 6-degrees-of-freedom movement for the instrument tip, designing them to remain easily manipulated and capable of both accuracy and sufficient force transmission has proven to be a challenge. In this domain, Oleynikov et al. [202] present a prototype of a laparoscopic grasper whose tip can move relative to the shaft of the instrument thanks to a ball-joint controlled via a spherical control embedded in the handle. Trejo et al. [276] assess the prototype compared to conventional graspers and note a significant increase in comfort of use by surgeons. Similarly, Gossot et al. [107] present an endoscopic instrument with a deflectable and rotatable tip controlled at the instrument handle. Another similar approach, where the deflection of the handle with respect to the shaft is mirrored by the deflection of the tip with respect to the shaft is shown in [166]. Yet another prototype

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[13] Single-Incision Laparoscopic Surgery: laparoscopic procedure whereby both instruments and the endoscope all pass through a single trocar, usually at the level of the umbilicus, resulting in a single, sometimes invisible scar.

by Melzer et al. [189] features a deflectable and rotatable instrument tip. A parallel approach to articulating the tip relative to the shaft was to articulate the handle relative to the shaft in order to increase the comfortable workspace by providing improved ergonomics, as is the case in [129]. [127] perform an in-depth evaluation of various combinations of articulations in laparoscopic instruments, and re-use this idea in [122], where the authors present a dexterous motorized instrument with articulating handle.

A natural development based articulated instruments came in the form of motorized instruments (see fig. 1.6 (c)), which can restore intra-corporeal freedom of movement without complicating their use for the surgeon ( [320], [218]). Despite challenges in terms of cost and sterilizability, such motorized instruments as the Jaimy®needle-holder (Fig. 1.6 (c)) have successfully been brought to the market. Finally, another radical solution to improving access to the target organs comes in the form of Robot-assisted Minimally Access Surgery (RMAS) with such systems as the teleoperated DaVinci©robot by Intuitive Surgical ®(see fig. 1.6 (d)). This system features motorized instrument tips with full 6 degrees of freedom that are intuitively manipulated from a teleoperation console, however they usually also come at the cost of a much smaller overall workspace associated with bulky systems that are impractical to rearrange, limiting its application to surgeries requiring a large workspace. To overcome this, intermediary modular systems with larger workspaces (see fig. 1.7) are currently under research in various institutions.

Figure 1.7: *Examples of modular, large workspace RMAS solutions currently undergoing development: (a) the modular teleoperated robot arm system developed at DLR; (b) the Achille co-manipulator robot arm developed at ISIR.*

Of course, all of these developments are always faced with the challenge of evaluating performances and performance gains through instrument design changes.

To this end, Herman et al. [127] present a method for evaluating the ergonomics and increase in performance obtained from extra mobilities in laparoscopic tools, their kinematic configurations and the ways they are controlled. Hanly et al. [116] present an evaluation method for assessing the benefits of RMAS[14], and perform a review of robotic abdominal surgery using the DaVinci® system, concluding that the greatest benefit from the added precision and dexterity of robotic surgery over conventional laparoscopic procedures is obtained in cases where complex reconstruction is required.

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[14] RMAS : Robotically assisted minimal access surgery

#### Instrument length and fulcrum effect at the trocar complicate movement

Manasnayakorn et al. [181] have shown that the length of laparoscopic instruments can in certain cases act as a detrimental factor on intervention speed and accuracy. In combination with this issue, the fact that the instruments are inserted through trocars that act as fulcrum points, introducing a variable lever effect presents a major difficulty for surgeons in execution of movements ( [198]). Beyond the added difficulty for movement and manipulation, this variable lever has been shown to introduce highly non-intuitive haptic perceptions of applied forces, sometimes masking them and sometimes amplifying them ( [219]), an issue we will further discuss in chapter II.

## 1.4 Perceptual issues in MAS

Beyond the motor and learning limitations of laparoscopic surgery, we focus on the degraded perception the surgeon has to deal with. Lamata et al. [161] and Xin et al. [314] provide good reviews of these perceptual challenges induced by the laparoscopic surgery setting. They conclude that contrary to tasks in everyday settings, where degradations of information from one perceptual modality may be compensated thanks to the redundancy between senses, in laparoscopy both visual and haptic information is degraded, leading to an overall worse perceptual experience.

### 1.4.1 Degraded visual perception

The degradation of visual perception in laparoscopy when compared to open surgery is three-fold: first of all, the available field of view is reduced, secondly, the use of the laparoscope leads to a partial loss of depth perception, and finally, natural hand-eye coordination is severely disturbed. All in all, these factors seriously complicate hand-eye coordination for the already fine dexterous surgical task and seriously increase visual cognitive load.

#### Reduced and constrained field of view

The laparoscope is inserted into the abdominal cavity via a trocar, similarly to the surgical instruments. Its movements and the possible field of view are therefore also mechanically constrained, leading to a limitation of the possible views of the operating site for the surgeon. A few studies have addressed this problem and aimed at developing articulating, automated ( [83], [197]) or wide-angle [153] laparoscopes for a more suitable field of view. For further information, [269] provide an interesting study on important design factors for endoscopic video systems.

#### Partial loss of depth perception

In open surgery, surgeons have direct visual access to the operating site, allowing them to use perceptual methods from everyday life to obtain depth information. According to Shah et al. [248], the screens on which the laparoscope image is displayed filter out most of the available depth cues, making depth perception extremely difficult. Depth perception is however not entirely eliminated, and trained surgeons are capable of evaluating the respective positions of objects based on the size of their instruments on the screen. 3D endoscope systems that restore depth perception are currently available, although they have not significantly entered clinical practice due to conflicting evidence as to their usefulness (Studies such as [185] and [118] conclude they do not significantly improve quality of surgical gestures, while others such as [293] and [278] conclude that they lead to significant gains in terms of speed and accuracy).

#### Severely disturbed natural hand-eye coordination

Finally, the monitor displaying the laparoscopic image taken from a point of view which is not the surgeon's is also removed from the patient, leading to severe impairment of natural hand-eye coordination during surgery. Hanna et al. [117] find that performance can be significantly improved by placing the monitor forward with respect to the surgeon and at hand level rather than at eye level as is currently mostly the case in the OR. As stated previously, the trocar acts to invert instrument tip movements with respect to the hand, and that with a varying amplification of movements due to the fulcrum effect [302]. The display of this movement captured by the endoscope on the monitor further amplifies this effect by further removing the magnitude of the presented movement from that interpreted by the body's kinaesthetic feedback.

Risucci et al. [232] analysed the impact of good visual perception on performance of laparoscopic tasks. They noted a significant margin for improvement in surgeons at all levels of training which they relate to degraded visual perception, and note a strong correlation between surgeons natural visual perception skills and quality of execution of laparoscopic tasks.

### 1.4.2 Degraded haptic perception

There is strong consensus on the fact that haptic perception is seriously affected during laparoscopic surgery, as tissues are no longer directly manipulated, with a few studies having aimed at quantifying this degradation.

#### Discrimination of harness, shape and texture

Some studies ( [34], [219]) have evaluated hardness, shape and texture discrimination in laparoscopic settings, consistently concluding that performance is reduced when compared to bare-handed contact, with the exception of texture identification, where the laparoscopic tools sometimes seem to act to amplify texture sensation.

Ottermo et al. [206] compare palpation tasks (discrimination of hardness and size) between open surgery and laparoscopic surgery, concluding that performance is degraded in laparoscopic surgery using conventional instruments. They then compare palpation performance to that using a laparoscopic instrument with sensor array at the tip allowing for visual presentation of the tactile information. This however neither degrades nor improves performance when compared to conventional laparoscopic tools in a significant manner. For novices, they note that the sensor array does indeed help in discriminating hardness, but not shape. Also, experienced surgeons use significantly more force when palpating, which is thought to be a result of their experience with tissue strength, and in a few cases they use excess force, resulting in damage to the tissue.

**Perception of forces**

Others have looked into perception of forces ( [252], [219], [198]), concluding that several interfering factors (play, backlash and friction in mechanical transmission, trocar friction, fulcrum effect, resistance of the abdominal wall) can reach the same order of magnitude as the tool-tip interaction forces, thereby seriously disturbing haptic perception of applied forces. The trocar introduces important disturbing forces [279], mainly through friction within the trocar valves (necessary to maintain the pneumoperitoneum), but also through the interaction of the trocar with the abdominal wall which reacts in a non-linear elastic fashion with varying stiffness depending on the location of the trocar and its current angle to the abdominal wall.

The magnitude of these disturbing forces does not completely overshadow haptic perception, however it makes fine control of interaction forces using feedback from the sense of touch almost impossible.

This degraded perception of force becomes problematic in two manners: It is directly a problem as laparoscopic grasping instruments often damage tissue ( [183], [184], [281]) during manipulation. And it is more indirectly a problem in that it forces surgeons to operate suboptimally, with many surgeons relying almost solely on visual cues to estimate applied forces while their sense of touch remains ignored. Therefore, although haptic sensation is not entirely lost in laparoscopy, it is clear that it is modified to an extent that requires significant re-learning of sensori-motor associations on the part of the surgeon if it is to be used as an efficient source of information.

## 1.5 Concluding remarks on the limitations of laparoscopic surgery

Regardless of the discussion on benefits and drawbacks of laparoscopic surgery and their objective evaluation, these surgical procedures are growing standard in the operating room. Therefore, in the interest of better cost-effectiveness, even better patient outcomes and greater surgeon comfort, there is great interest in addressing the drawbacks of MAS and limiting their potential negative impacts.

As we have seen, MAS is accompanied by a broad spectrum of limitations for the surgeon. The issues of dexterity and learning have been extensively studied by others, whereas work on addressing the limitations in perception remains mainly limited to improving visual perception or providing visual feedback of missing information. We therefore choose to focus on the perceptual issues in laparoscopic surgery, and aim to examine alternate methods and perceptual channels for addressing these issues. The following chapter will present an overview of existing work on this topic and introduce this thesis' research axes in detail.

Chapter 2

# Overcoming perceptual limitations in laparoscopic surgery

Contents

## 2.1 Previous works on overcoming perceptual limitations in LS

Considering the relatively large body of work dealing with limitations in dexterity for laparoscopic surgery, in the present work, we aim to offer and evaluate solutions to the issues arising from limited perception in laparoscopy, i.e. there is insufficient information available to the surgeon, and/or the information available is of too poor quality to allow good task execution. The rationale behind this being that perceptual capabilities need to follow motor capabilities if good performances are to be achieved overall. Since open surgery was the previous standard for surgeon comfort and performance, a satisfactory objective in restoring perception would be to recreate the perceptual environment of open surgery. Ultimately, it would however be interesting to create a perceptual environment that improves on that of open surgery, so as to bring surgeon capability ever closer to its potential maximum.

We previously discussed how perceptual issues in laparoscopy can be broadly categorized as pertaining either to vision or to touch, thus on the one hand work has been done on making visual perception through the endoscope system as good as or better than natural vision. This is of particular interest as it is widely recognized that the degradation in haptic perception leads surgeons to rely almost exclusively on visual information during laparoscopic surgery. On the other hand, having identified this imbalance between the use of vision and haptics in laparoscopic surgery, a certain amount of work has been directed towards making the sense of touch reliable again for surgeons [102]. This also remains a major issue in the development of RMAS[1], where contrary to laparoscopic surgery, haptic perception is completely lost due to the decoupling inherent to teleoperation [70]. In the following, we provide a short overview of work on both these axes.

### 2.1.1 The issue of degraded visual perception

The degradation of visual perception in laparoscopy when compared to open surgery is threefold: First of all, the available field of view is reduced and constrained, secondly, the use of the laparoscope leads to a partial loss of depth perception, and finally, natural hand-eye coordination is severely disturbed. Risucci et al. [232] analyse the impact of good visual perception on performance of laparoscopic tasks. They note a significant margin for improvement in surgeons at all levels of training which they relate to degraded visual perception, and note a strong correlation between surgeons natural visual perception skills and quality (speed and accuracy) of execution of laparoscopic tasks.

#### Constrained field and point of view for the laparoscope

The laparoscope is inserted into the abdominal cavity via a trocar, similarly to the surgical instruments. Its movements and the possible field of view are therefore also mechanically constrained, leading to a limitation of the possible views of the operating site for the surgeon. A few studies have addressed this problem and aimed at developing articulating, automated ( [83], [197]) or wide-angle [153] laparoscopes for a more suitable field of view. For further information, [269] provide an interesting study on important design factors for endoscopic video systems.

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[1] Robot-assisted Minimally Access Surgery

### Partial loss of depth perception

When considering limitations to visual perception in MAS[2], partial loss of depth perception is often considered as the main component. Shah et al. [248] show that the screens on which the laparoscope image is displayed filter out most of the available depth cues. Some visual depth cues however remain, such as instrument overlap and the size of the instruments on screen but these are highly dependent on the endoscope and instrument positions and thus neither reliable nor easy to use.

Products attempting to compensate for these drawbacks, such as 3D endoscope systems, are already widely used in operating rooms (see fig. 2.1). These systems generally receive good acceptance on the part of surgical teams, however they are themselves subject to limitations:

Figure 2.1: *Laparoscopic surgical team using a 3D endoscope and screen system, observing the stereoscopic image thanks to 3D glasses*

First of all, the stereoscopic 3D image reconstructed by the 3D screen and glasses provides a level of depth perception which is still far from natural depth perception [309].

Second, a significant body of work deals with the evaluation of medical benefit from such systems which are significantly more expensive than conventional endoscope systems. However, to our knowledge, there has been no consistent demonstration of significant improvement in performance from the use of such systems. For example, studies such as [185] and [118] conclude they do not significantly improve quality of surgical gestures, while others such as [293] and [278] conclude that they lead to significant gains in terms of speed and accuracy.

To try and go beyond the limits of 3D screen and glasses systems, some products aim at a more immersive display of the stereoscopic endoscope image so as to benefit from the eye's natural stereoscopy.

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[2] Minimal Access Surgery

Figure 2.2: *Left: Sony Professional HMS-3000MT 3D Head-Mounted Displays (HMD) for laparoscopic surgery being used experimentally at Greifswald University Hospital in Germany* [3]*; Right: DaVinci S console with immersive 3D binocular vision* [4]

Probably the most widespread of these systems comes in the field of RMAS with the DaVinci console (see fig. 2.2), where the surgeon is seated at a dedicated console comprising a headrest with binocular display of the endoscopic image. For conventional laparoscopy, certain attempts have been made at creating head-mounted systems to provide a similar level of visual comfort to surgeons [33] (see also fig. 2.2). These however remain in the early experimental stage, and face potential problems of acceptance, most notably for reasons of safety and cost. First of all, should a surgeon using such a system need to convert to open surgery in an emergency, the removal of the head-mounted display may pose problems. A second drawback for these systems is their significant cost, a DaVinci system currently selling for around 2.5 million €and equipping a surgical team with head-mounted systems carries a significantly higher cost than equipping them with simple 3D glasses.

Finally and most importantly, both the DaVinci console and head-mounted displays suffer from a limitation inherent to immersive displays in that they severely reduce or completely remove the surgeon's situational awareness [322]. As previously discussed for 3D screen systems, the medical benefit from immersive vision systems has not yet been proven either, which is that much more of a problem in the face of the added safety issues arising from lack of situational awareness and communication within the surgical team.

Alternate approaches for restoring functional depth cues without necessarily requiring costly hardware have focussed on using structured light and/or forms of augmented reality in the endoscopic image (see fig. 2.3). Reiter et al. [230], Collins et al. [60] and Ackerman et al. [3] demonstrate the feasibility of such systems using either conventional or custom-built hardware without evaluating impacts on navigation performance.

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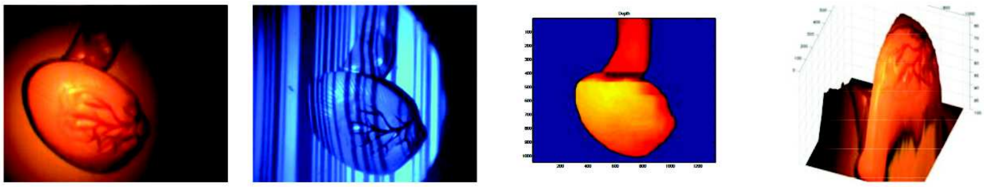
[3] Photo credits : Sony Professional via http://www.healthcare-in-europe.com/

[4] Photo credits : Intuitive Surgical Inc.



Color Image Blue Image Depth Image 3D Reconstruction

Figure 2.3: *Structured light : Experimental results of a Surgical Structured Light for 3D Minimally Invasive Surgical Imaging* [5]

### Misalignment between surgeon and endoscope PoVs

A third issue affecting visual perception in laparoscopy is the difference in point of view between the surgeon observing the screen and the endoscope recording the surgical scene projected onto the screen. This misalignment increases visual cognitive load and impairs hand-eye coordination. The monitor displaying the laparoscopic image is also removed from the patient, leading to severe impairment of natural hand-eye coordination during surgery. Hanna et al. [117] find that performance can be significantly improved by placing the monitor forward with respect to the surgeon and at hand level rather than at eye level as is currently mostly the case in the operating room.

In chapter I, we also mentioned operating room ergonomics recommendations with regards to screen, trocar and endoscope placement which also aim to compensate for this drawback, although it should be noted that this optimal set-up is rarely achieved in hospitals for various reasons - such as lack of knowledge, conflicting priorities and the resulting clash with the reality of surgical workflows in hospitals. Also, even if such measures are successfully implemented, they can only reduce the extent of the discomfort caused by the misalignment and never completely solve the problem.

The previously mentioned immersive systems such as the DaVinci console or Head-Mounted Displays (see fig. 2.2) on the other hand are ideal tools to correct this misalignment, but suffer drawbacks of cost, acceptability and safety with regards to emergencies and the disruption of surgeon situational awareness.

## 2.1.2 The issue of degraded haptic perception

As previously mentioned, the mechanics and ergonomic aspects of laparoscopic surgery lead to severe distortions in the perceptions of applied forces, contacted textures and tissue hardness. This has been shown to be a major issue, leading both novice and expert surgeons to apply excess forces to sutures and tissue during manipulation, and preventing proper palpation and related diagnosis.

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[5] From Reiter et al. "Surgical Structured Light for 3D Minimally Invasive Surgical Imaging" [230]

In [303], the author offers an in-depth analysis of haptic perception in laparoscopic surgery, its limitations, degradations when compared to open surgery and the consequences thereof. Some studies ( [34], [219]) have evaluated hardness, shape and texture discrimination in laparoscopic settings, consistently concluding that performance is reduced when compared to barehanded contact, with the exception of texture identification, where the laparoscopic tools sometimes seem to act to amplify texture sensation. Ottermo et al. [206] compare palpation tasks (discrimination of hardness and size) between open surgery and laparoscopic surgery, concluding that performance is degraded in laparoscopic surgery using conventional instruments. This result is consistent with Greenwald et al.'s findings that palpation is significantly more efficient and accurate with bare fingers than with laparoscopic tools [109]. Others have looked into perception of forces ( [252], [219], [198]), concluding that several interfering factors (play, backlash and friction in mechanical transmission, trocar friction, fulcrum effect, resistance of the abdominal wall) can reach the same order of magnitude as the tool-tip interaction forces, thereby seriously disturbing haptic perception of applied forces.

Also, experienced surgeons use significantly more force when palpating, which is thought to be a result of their experience with tissue strength, and in a few cases use excess force, resulting in damage to the tissue. This degraded perception of force becomes problematic in two manners: It is directly a problem as laparoscopic grasping instruments often damage tissue ( [183], [184], [281]) during manipulation. And it is more indirectly a problem in that it forces surgeons to operate suboptimally, with many surgeons relying almost solely on visual cues to estimate applied forces while their sense of touch remains ignored.

#### 2.1.2.1 Restoring sensations of texture and hardness

Palpation is a critical component of surgery, as differences in hardness and texture between tissues can be used to assess whether the tissue is healthy or pathological (e.g. tumours are usually significantly harder than surrounding tissues, allowing their localisation through palpation even when embedded within tissue and hidden from view). Palpation can also serve the purpose of securing gestures, allowing the surgeon to detect veins and arteries or similar sensitive structures precisely and thus to avoid them.

##### Solutions for palpation in conventional and robot-assisted laparoscopy

As with many issues relating to haptics in Minimal Access Surgery, the bulk of work performed with regards to restoring adequate haptic perception focuses on robot-assisted laparoscopy, mainly teleoperated. Studies looking into conventional kinaesthetic feedback in tele-manipulated RMAS settings (Reliable and Enhanced Stiffness Perception in Soft-tissue Telemanipulation - De Gersem 2005, Feller 2004 - The effect of force feedback on remote palpation), conclude on the one hand that telemanipulation systems with force feedback can allow for discrimination of smaller stiffness differences during palpation, and on the other that spatial accuracy in detecting hard inclusions in tissue is usually identical to that of direct palpation but at the cost of prolonged task execution times in teleoperated settings. Gwilliam et al. also note a reduction in peak forces and task errors during palpation when force feedback is provided [113].

The standard approach for restoring adequate and reliable palpation in laparoscopy and RMAS consists in the use of tactile sensors (e.g. [207]) mounted on the instrument tip combined with a form of display which can be either visual, auditory or tactile.

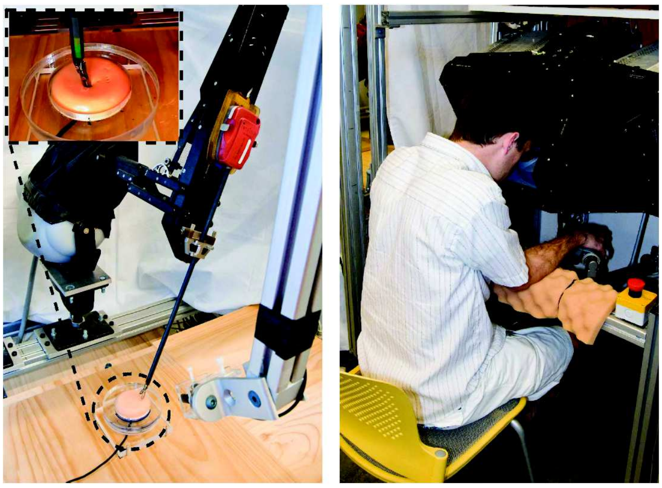
(a) Patient-side Manipulator (b) Master Manipulator

Figure 2.4: *Experimental teleoperation palpation set-up using visual substitutive force feedback as well as conventional force feedback. On the left is the patient-side (slave) manipulator fitted with force sensors, and on the right is the master manipulator with visual and conventional force feedback capability.*[6]

### Visual feedback of palpation information

On-screen visual feedback of tactile information seems a natural avenue for substitutive feedback as screens are necessarily present in the operating room and visual feedback is a powerful way of conveying spatial and intensity information. Gwilliam et al. [113] evaluate visual force feedback in teleoperated palpation tasks (see fig. 2.4), concluding that coupled haptic and visual force feedback minimizes forces applied to the tissue while minimizing subject task error, but only in novice subjects. Schostek et al. on the other hand [244] present visual pressure distribution patterns obtained by a tactile sensor mounted in a laparoscopic grasper jaw for palpation applications, concluding significant improvements in accuracy, speed and confidence.

### Audio feedback of palpation information

Audio feedback has been explored relatively little in palpation applications per se, although some work suggests that it may yield improvements in these tasks. L'Orsa et al. [174] evaluate audio notification cues warning of excess force application when contacting a thin membrane. The cues successfully reduced mean applied forces and thereby prevented unintentional punctures of the membrane. Crossan et al. [62] present a concept of using audio feedback to alert in case of too high palpation forces in simulated veterinary procedures but do not provide an evaluation of resulting performances.

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[6] From Gwilliam et al. [113]

### Tactile feedback of palpation information

Schoonmaker et al. [243] present an experiment at evaluating phantom tissue probing using a laparoscopic grasper providing vibrotactile feedback to inform the user about the applied tool-tip interaction forces. All three evaluated forms of tactile feedback improve overall performance, resulting in lower probing depth error and lower maximum applied forces. Zhou et al. [324] also present the use of a vibrotactile feedback for palpation assistance in MAS, with more accurate and confident palpation performed at lower peak forces when the feedback was provided.

## Restoring sensations of interaction forces

Grasping and manipulating (by pushing, pulling, cutting) in the presence of degraded or distorted haptic perception can become problematic, as insufficient grasping force leads to tissue or suture slippage and excess grasping force can lead to ischemia or injury and suture breakages. Adequate restitution of the perception of grasping forces has thus been the scope of a certain number of studies both in conventional and robot-assisted laparoscopic surgery.

### Conventional distal interaction force feedback for robot-assisted laparoscopy

Most work on presenting force feedback in robot-assisted laparoscopy has been aimed at teleoperated robotic surgery systems, where perception of forces is normally completely lost due to the decoupling between master and slave. Several experimental platforms with force feedback capabilities, e.g. [179], [235], have been developed. These platforms are composed of a master manipulator (see fig. 2.4 right) which imposes displacements on a slave-side manipulator (i.e. the patient-side robot - see fig. 2.4 left). This slave-side manipulator in turn is equipped with force sensors allowing for reproduction of the interaction forces encountered on the slave side at the master manipulator. Extensive work on the evaluation of performance gains obtained through such feedback has also been performed (e.g. Wagner et al. ( [295], [294]), Tavakoli et al. ( [267])). Most notably, Weber et al. [297] perform a meta-analysis of 21 studies comparing surgical task performance with and without force feedback. They conclude that force feedback has a moderate effect on task accuracy, a strong beneficial effect on the control of average and peak forces and no effect on task completion times. They also note that the magnitude of beneficial effects from force feedback tended to be reduced when visual depth information was available.

### Audio feedback of interaction forces

Kitagawa et al. [151] evaluate the use of audio feedback of interaction force magnitudes in RMAS, concluding that in order to be effective, such feedback must not be continuous. However, discrete audio feedback of interaction forces was useful in assisting surgeon control of forces in an RMAS setting.

On a related note, MacMahan et al. [188] and Bark et al. [26] evaluate audio feedback of tool contact vibrations in robot-assisted laparoscopy, concluding a positive impact of such feedback on user confidence without improving or impeding task performance.

#### Visual feedback of interaction forces

In the previously mentioned work by Kitagawa et al. [151], visual force feedback was also evaluated for RMAS, concluding that in terms of accuracy and precision in control of forces, performances were thereby brought back to the level of or even improved over direct manipulation. Reiley et al. [229] evaluated the contribution of visual force feedback on suturing performance using an RMAS system, concluding that for novices in RMAS, visual force feedback led to lower mean and peak applied forces as well as reductions in suture breakages. Akinbiyi et al. [9] present a force and tissue oxygenation sensor for DaVinci instruments with visual feedback, also leading to lower peak and mean forces during manipulation.

Tavakoli et al. [267] also explore visual force feedback in telemanipulated suturing, concluding a beneficial effect of visual force feedback on applied forces at the cost of a trade-off with task completion time.

#### Vibrotactile feedback of interaction forces

Westebring [303] presents extensive work on feeding back grasping force information though vibrotactile feedback. The author concludes that feeding back information on grasp force and tissue slippage either visually or through tactile feedback both improved performance, with tactile feedback leading to faster reaction times in case of tissue slippage for subjects of all previous expertise levels.

Overall, these works show potential for feedback through various sensory modalities to compensate for degradations in perception and improve surgeon performances in RMAS. However, haptics seem to have received comparatively little attention for applications in conventional laparoscopy, motivating our proposed work detailed in the following.

## 2.2 Proposed work - Haptics for augmenting perception in laparoscopic surgery

In the present work, we propose to evaluate various forms of haptic feedback to compensate for poor perception in laparoscopic surgery. We propose to identify the key components of information whose degradation between open surgery and laparoscopy are limiting factors in terms of performance so that we may restore this information to the surgeon and thus achieve an improved gesture at minimum cost and complexity.

## 2.3 Surgical procedures that may benefit from added feedback

In order to narrow down the scope of this study to key surgical procedures that would most benefit from added feedback in terms of gesture improvement, we discussed the issue with surgeons and related the obtained conclusions to our bibliographical work on the matter.

Three axes of work appeared as potential candidates:

- Surgical tool navigation, in particular during resection tasks.
- Control of interaction forces during suturing (i.e. needle insertion and knot tying forces).
- Palpation, in particular with respect to the identification of tumours below organ surfaces and the differentiation of tumours from benign lesions.

### 2.3.1 Palpation

On this last issue of palpation, tumours and fibroses appear identical when inspected visually, however when they are palpated, it is easy to distinguish the relatively soft and harmless fibroses from tumours which are generally quite hard. Palpation tasks could therefore benefit from the use of sensorized instruments equipped with tactile displays for presenting tissue stiffness, and this benefit would likely increase in cases where the tumours are hidden beneath the organ surface, where visual inspection yields no result but palpation shows a change in surface texture and stiffness. As explained previously, augmented palpation using tactile sensing and feedback in various forms has been extensively studied for laparoscopic ( [316], [244], [207], [205]) as well as RMAS ( [273], [102], [177], [169], [150], [113], [71]) applications. We therefore chose to not tackle the issue in the scope of this thesis for two reasons: Moreover, the technical issue of the necessary tactile sensing and feedback elements does not seem reasonable to tackle in the given time-frame, as to our knowledge, there are still no off-the-shelf sensing and feedback solutions, forcing development of the system from the ground up. Lastly, the issue of augmented palpation borders on recreating a natural sense of touch through a sensorized instrument equipped with a form of tactile display. While the separation with our choice of using tactile cues to feed back only specific task-dependent missing information to the surgeon is not entirely clear-cut and greatly depends on the technical implementation, we believe this issue still strays too far from the core problem presented here.

### 2.3.2 Laparoscopic instrument navigation

Interest in haptic feedback for surgical navigation is more limited in the scientific community, despite works such as [119] investigating feedback for improving surgical navigation performance during resection, and [38], [40] and [41] exploring possibilities for the use of haptic feedback in surgical navigation. This lower apparent interest is however not justified by the lack of clinical importance of the issue. Rather it is the scope and complexity of the issue that seem to be limiting factors here. There is extensive work to be found on the use of haptic feedback for guidance in tasks involving rigid structures, where target trajectories are easily defined. However, in surgery, there is an ongoing challenge in defining resection trajectories and forbidden regions as organs are non-rigid structures whose position within the patient may vary between pre-operative diagnosis and the operating room, and which are subject to physiological movement. Therefore, quite some work has focussed on the challenge of registering between various pre-operative and per-operative imaging systems and the current position of organs within the patient (e.g. [40], [41]) and on the compensation of physiological motion for various tasks (e.g. [240]). Attempts at feeding back navigation information based on this registration and motion compensation have often focussed on the use of augmented reality and visual displays (e.g. [292]).

Intra-corporal navigation of a surgical instrument is only considered as secure if there is real-time visual control over the instrument in order to ensure that no anatomical structures lie in its trajectory. It is therefore unreasonable to think of haptic feedback for navigation as an option for completely replacing visual feedback on the instrument position. When the surgeon can see his instrument on screen, one could believe that added feedback for navigation loses its potential use. However, while the surgeon keeps an eye on his instruments at all times, it is harder for him to precisely navigate with respect to a pre-operative surgical plan, anatomical reference points that may become occluded or leave the field of view due to zooming in with the endoscope. This orientation task becomes all the more difficult when anatomical motions and organ deformations come into play. If real-time tracking of anatomical references defined by the surgeon intra- or pre-operatively can be implemented, added feedback to assist precise navigation towards targets or away from forbidden regions could become extremely helpful.

### 2.3.3 Control of interaction forces during suturing and tissue manipulation

Concerning suturing, it is very hard to correctly evaluate force applied to suture wires in laparoscopy as:

- The suture wire is only very rarely pulled along the trocar axis in order to tighten the knot, leading to the previously discussed problems for haptic perception due to the fulcrum effect.
- In certain situations, one end of the suture wire is not held by the surgeon, but by the assistant, making correct estimation of the traction force applied by the assistant impossible for the surgeon.

Wire diameters and materials widely vary, as well as the forces to be applied for a correct suture knot depending on the organs (e.g. when suturing on the spleen, knots are not even tightened as any pulling on the fragile tissue would immediately tear it). Finally, visual feedback only provides limited information and does not compensate for the lack of force information since the wire does not visibly deform when pulled. Experienced surgeons may use indirect information obtained by the deformation of the tissue being sutured to estimate forces, however this is limited and unreliable due to the variabilities previously mentioned. It is important to note that bad suturing can have potentially fatal consequences for the patient. In the current state of affairs, complication rates for laparoscopic surgeries are somewhere in the 1/1000's ( [214]), which may seem small, but when compared with complication rates for more standardized and well mastered processes such as anaesthesia for example where complication rates are in the 1/100.000's ( [8]), the margin for improvement by standardization becomes obvious.

Extensive work has been performed on suturing in RMAS, as the complete lack of haptic feedback exacerbates the already existing problem of excessive applied forces present in laparoscopic surgery (e.g. [32], [145], [152], [151], [242], [267]). It is interesting to note that positive effects of feeding back force information have been observed for RMAS tasks other than suture knot tightening, such as e.g. dissection ( [295], [294]), needle insertion ( [199], [212], [208]) or catheterization [178]. Force control tasks can therefore be generalized beyond suturing, with beginners potentially benefiting from added feedback on forces applied to organs in order to avoid punctures during manipulation, and even experienced surgeons being able to use the added information in order to for example avoid accidental cutting of hidden blood vessels.

### 2.3.4 Choice of methods for feeding back information to the surgeon

Now that the candidates for most relevant information have been defined, it is necessary to look into how to provide the information to the surgeon. Feedback can make use of one or several of the following modalities: Visual, Audio, Tactile*, Kinaesthetic*, Proprioceptive*. The perceptual modalities marked with (*) are often grouped under the term ‘haptic’ perception.

Feeding back the lost information can either occur through the natural sensory modality through which the information would be acquired if this were possible (e.g. using stereoscopic cameras and 3D monitors to restore visual depth perception in a camera image), or through what is referred to as sensory substitution, where the information is transmitted via another perceptual channel (e.g. audio or visual feedback of interaction forces).

Instrument position information is a naturally largely visual and marginally haptic percept, and visual perception has been shown to dominate perception when both visual and haptic information are available [126]. Distal interaction forces on the other hand are a largely haptic and marginally visual percept, although visual force cues are present to a limited extent in laparoscopic surgery [314].

It would therefore seem reasonable to feed back position information visually using methods such as magnification, augmented reality, visual guides, and on-screen proximity or deviation cues. Similarly, it would seem reasonable to attempt to use haptics (either kinaesthetic force feedback and magnification in teleoperated RMAS or tactile feedback) to convey information on interaction forces. However, on the one hand there is reason to believe that visual cognitive load is already very high in laparoscopy. Multiple resource theory [307] suggests that further adding visual information may result in drops in performance, not because of lacking information, but because of the excessive mental effort required to adequately process and make use of it. As previously explained, tactile perception remains largely unused in laparoscopy, and may thus present a good alternative for presenting information without overloading the visual modality. On the other hand, approaches such as kinaesthetic force feedback magnification are more or less limited to teleoperated RMAS and therefore require alternate approaches when dealing with conventional laparoscopy or co-manipulated RMAS.

In the present work, we therefore propose an alternative approach to those initially described: Considering that surgeons are only using their sense of touch very little in laparoscopic surgery, haptics appear as an interesting modality for communicating information to the surgeon without excessively disturbing perception or increasing cognitive load. Furthermore, it seems that for given tasks, surgeons only perform sub-optimally in MAS as they are lacking very specific information components at any given time. These can e.g. be the magnitude of applied force in cutting and suturing tasks, precise information on the instrument tip position in navigation and positioning tasks, and information on local tissue stiffness in palpation tasks. Restoring those information components without bothering with restoring full perception of the surgical site appears to be a good compromise between improving performance in laparoscopy and system complexity.

## 2.4 Objectives of this work

The objectives of this thesis are to evaluate the respective contributions of added information via various forms of haptic feedback to the performance of different conventional laparoscopic surgery gestures. We aim to clarify the benefits that could be obtained by incorporating haptic feedback as an augmented reality feature in per-operative[7] laparoscopic procedures. Specifically, we aim to focus on the feedback of tool-tip position and interaction force information to the surgeon as they seem the most relevant to the surgeon and the least addressed in the literature. A first objective is to assess the respective improvements, if they exist, and discuss the cost/benefit ratio for tactile and kinaesthetic feedback systems respectively. Should improvements be observed, secondary objectives are:

- Assess to what extent and how these improvements may be optimized
- Determine the added value of presenting information via haptics versus e.g. vision
- Determine whether haptic feedback is preferable by itself or in a multi-modal context

Developed systems will have to be compatible with the surgical work-flow and should comply with surgeons' perception and decision making approaches in the per-operative context as well as design constraints for medical equipment.

## 2.5 Outline of this thesis

In order to provide insight into whether feedback in the form of haptic cues may benefit surgeons in terms of gesture quality, especially with regards to instrument guidance and control of interaction forces, this thesis is structured as follows:

Chapter III presents our work on the first identified axis for improving MAS gestures thanks to haptic feedback : surgical tool navigation. A brief state of the art on technology for measuring the position of laparoscopic instruments in 3D space is given, followed by a state of the art on surgical navigation and the use of haptic cues for navigation in non-surgical and surgical contexts. Four series of experiments aiming at evaluating the effect of haptic on navigation speed and accuracy both in free space and during a laparoscopic cutting task are presented and discussed.

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[7] per-operative, i.e. during the surgical procedure, as opposed to pre- or post-operative

Chapter IV presents our work on the second identified axis for improving MAS gestures thanks to haptic feedback : control of tool-tip interaction forces. In order to feed information on tool-tip interaction forces back to the surgeon, it is first necessary to measure these forces adequately. A first section therefore deals with a state of the art in measuring both grasping forces and the sum of tool-tip interaction forces. A second section then presents a state of the art of force feedback for MAS, followed by three series of experiments aiming at evaluating the impact of haptic feedback on the control of forces in suture knot tying tasks.

Having assessed the potential of vibrotactile feedback in assisting both in navigation tasks and force control tasks, chapter V presents an extensive state of the art on vibrotactile feedback used to draw up recommendations for the design of cues and vibrotactile feedback systems for applications to laparoscopic surgery.

Finally, chapter VI sums up the general conclusions of this work as well future prospects for research on the subject and applications.

## 2.6 Contributions and publications

The main contributions of the present work lie in testing the impact of tactile feedback on task performance for applications in conventional laparoscopic surgery, as to our knowledge tactile feedback has only been explored for applications to open surgery or robot-assisted laparoscopic surgery with the exception of force feedback applications. However, even in the works on tactile force feedback for laparoscopic surgery mainly remain at the stage of development of laparoscopic tools allowing this functionality without evaluation of the impact on performance (with the exception of Westebring's work on feeding back grasping force information [303]). This evaluation of the impact on task performance is done comparatively to other conventional options for information feedback (visual, kinaesthetic) .

The work presented in this thesis was published in the following:

- Howard, T., & Szewczyk, J. (2014). Visuo-haptic feedback for 1-D Guidance in laparoscopic surgery. In 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (pp. 58-65). IEEE.
- Howard, T. & Szewczyk, J. (2014). Haptic and visuo-haptic feedback for guiding laparoscopic surgery gestures. 3rd Surgetica Conference. Chambery, France.
- Howard, T. & Szewczyk, J. (2015). Haptic and visuo-haptic feedback for guiding laparoscopic surgery gestures, in CARS 2015, Barcelona, June 24-27, 2015.
- Howard, T., & Szewczyk, J. (2016). Assisting Control of Forces in Laparoscopy Using Tactile and Visual Sensory Substitution. In New Trends in Medical and Service Robots (pp. 151-164). Springer International Publishing.
- Howard, T., & Szewczyk, J. (2016). Exploring the potential of haptic feedback for assisting navigation of laparoscopic surgical instruments. Frontiers in Robotics and AI, 3, 37.

## Chapter 3

# Haptic feedback for assisting surgical tool navigation

Part of the work presented in this chapter was published in the following:

- Howard, T., & Szewczyk, J. (2014). Visuo-haptic feedback for 1-D Guidance in laparoscopic surgery. In 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (pp. 58-65). IEEE.
- Howard, T. & Szewczyk, J. (2014). Haptic and visuo-haptic feedback for guiding laparoscopic surgery gestures. 3rd Surgetica Conference. Chambery, France.
- Howard, T. & Szewczyk, J. (2015). Haptic and visuo-haptic feedback for guiding laparoscopic surgery gestures, in CARS 2015, Barcelona, June 24-27, 2015.
- Howard, T., & Szewczyk, J. (2016). Exploring the potential of haptic feedback for assisting navigation of laparoscopic surgical instruments. Frontiers in Robotics and AI, 3, 37.

## Contents

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The work presented in this chapter focuses on easing navigation tasks in laparoscopic surgery using haptic feedback. As navigation assistance requires both tracking of the instrument and knowledge of surgical target positions, we begin by briefly presenting various methods for tracking the position of surgical instruments, tracking surgical targets and per-operative registration between both.

## 3.1 Tool tip and surgical target position measurement

In order to assist the surgeon in accurately moving his instrument along given trajectories within the body, it is first necessary to accurately track the position of the instruments and of the surgical targets in space. The correct choice of tracking systems highly depends on the application's workspace, accuracy and cost requirements, which explains the diversity of available tracking systems. In our present work, we used commercially available optical and electromagnetic tracking systems as these largely fulfilled our requirements towards instrument tracking performance. Definition, registration and tracking of surgical targets is a very broad topic worthy of in-depth analysis and having given rise to a very large and diverse body of study and technical solutions. For practical reasons, we have not tackled this issue in the present work, where we focus solely on the issue of feeding back navigation information under the assumption that surgical targets are known. However, in order to back our hypothesis according to which it is possible to adequately define, register and track both surgical instruments and targets in real time, we present a short overview and discussion on the issues and technical solutions pertaining to these tasks in the present section.

### 3.1.1 Mechanical tracking

Mechanical tracking in general relies on the knowledge of the static relationship or kinematic linkage between a reference and a target or instrument. Such systems can allow for very high tracking and registration accuracy, but the presence of a mechanical linkage or reference structure usually introduces constraints due to bulkiness and clutter and limited workspaces.

Figure 3.1: *Left : Surgeons use a stereotactic frame to locate surgical targets during neurosurgery.*[1]*; Middle : FARO Gage 3D coordinate measurement arm, a hand-operated metrology tool that can find applications in precise registration of rigid targets* [2]*; Right : Stryker MAKO co-manipulated orthopaedic surgery robot - knowledge of the kinematic linkage of the robot can allow for tracking of the tool-tip position in space* [3]*.*

Mechanical tracking is usually employed for tracking rigid surgical targets through stereotaxy (see fig. 3.1 left) or coordinate measurement machines (see fig. 3.1 centre). Tele-manipulated or co-manipulated robots (such as the MAKO arm shown in fig. 3.1 right) can be fitted with rotary encoders on their axes, similarly to coordinate measurement machines, allowing for accurate tracking of the end-effector tool during surgery. This is particularly advantageous in that the robot actuation can then allow for active gesture guidance.

### 3.1.2 Optical trackers

Optical tacking systems are already widespread in clinical applications, both for instrument tracking and locating rigid surgical targets, as in orthopaedic surgery, where they are used to register the position of bones with respect to RMAS systems. They have the advantage of relatively high accuracy over large workspaces, allowing them to be adapted to a variety of surgical requirements.

On the downside, optical tracking systems require that line of sight be maintained between the tracking device and the instrument being tracked, which in the case of laparoscopic surgery poses some constraints in terms of marker placements, as they usually cannot be tracked within the body. Optical tracking of laparoscopic instruments hence requires fixation of a sufficient number of markers at the level of the instrument handle so as to reliably track the instrument in any configuration or grasp - raising potential issues of clutter and confusion between tracked instruments when several are used in close proximity. Finally, fitting instruments with tracking markers can make these less handy for surgeons.

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[1] Photo credits : http://ogles.sourceforge.net/Ogles/ogles-doc/

[2] Photo credits : www.faro.com

[3] Photo credits : www.stryker.com

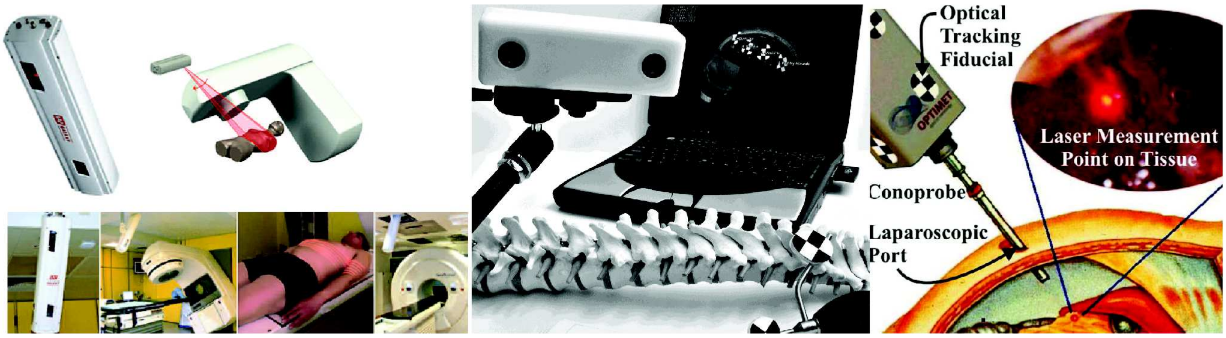

Figure 3.2: *Left : Lap Laser Galaxy patient topography laser system* [4]*; Claron MicronTracker videometric tracking system* [5]*; Surgical target tracking through surface imaging prototype from Vanderbilt University* [6]*;*

### Videometric tracking systems

Videometric tracking systems identify patterns of markers apposed on the object to be tracked in video images obtained by one or more previously calibrated cameras. Examples of such systems are the VISLAN with AR toolkit [146] and the commercially available Claron tracker (Claron Technology Inc., Toronto, Ontario,Canada). These systems usually have the advantage of a very large workspace and decent possible frame rates as they mainly depend on the camera technology and image processing algorithms used. However they are also less robust to interference and usually require large patterned markers to function adequately, which can limit their applications.

### Surface imaging

Surface imaging technologies have received some attention, mainly in academic circles, with regards to tracking organs ( [209], [194], [162]). The general concept lies in the use of cameras allowing for depth estimation (RGBD cameras or cameras coupled with laser range finders) aimed at the target organ allowing for 3D reconstruction of the organ surface and its localisation with respect to known references. Such approaches have the potential for reliably tracking of soft deformable targets although they depend on line of sight and may pose significant challenges in tracking surgical targets deep within the tissue.

### IR-based active marker tracking systems

LEDs[10] emitting in the IR-range[11] are used as markers and mounted on the target. A pair or three linear photosensor units form the tracking camera module, using optical bandpass filters to

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[4] Photo credits : Lap Laser

[5] Photo credits : Claron Technology

[6] Photo credits : Ray A. Lathrop, "Minimally Invasive Holographic Surface Scanning for Soft-Tissue Image Registration" [162]

[7] Photo credits : NDI

[8] Photo credits : Accuray

[9] Photo credits : Brainlab.com

Figure 3.3: *Left: Polaris Vicra optical tracking system capable of following passive and active IR targets* [7]*; Centre: Boulder Innovation Group Flashpoint active optical camera used in the Accuray Cyberknife system* [8]*; Brainlab Curve optical tracking system for neurosurgery.*[9]*;*

remove ambient light with wavelengths outside the IR-range. The LEDs fire in a given sequence, allowing the central unit to compute the position of the target thanks to a combination of this known sequence and triangulation. At least three non-collinear LEDs are required to determine 6-DoF[12] position and orientation information. Active systems are usually more accurate, robust and fast than their passive counterparts but require on-board sterilizable electronics and a power supply, limiting their applications in certain cases. A noteworthy example of active tracking systems is the Atracsys accuTrack, which boasts errors below 0.25mm RMS[13] with frame rates up to 4kHz.

calculated as the square root of the arithmetic mean of squares of differences between actual and measured positions.

### IR-based passive marker tracking systems

A simpler tracking camera module than the one described in the previous paragraph, usually comprised of an IR illuminator and a 2D camera, is used to track reflective spheres mounted on the target. The spheres are illuminated by the camera module in the near-IR spectrum. A unique geometric configuration of markers is used for each target to be tracked so as to allow unambiguous identification within the recorded 2D images. Since the markers are entirely passive reflectors, they have the advantage or being wireless and requiring no power, but are often more sensitive to dirt or wear and provide slower and less accurate position estimates than their active counterparts. The NDI Polaris, which we used in the experiments presented in the following, is a system capable of using both passive and active IR markers, achieving errors below 0.30mm RMS with frame rates up to 60Hz.

### Laser tracking systems

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[10] LED : Light-Emitting Diodes

[11] IR-range : Infrared light range, i.e. wavelengths between 700nm and 1mm. Optical trackers usually operate in the near-IR range, i.e. at wavelengths close to 700nm.

[12] DoF : Degrees of Freedom

[13] RMS (Root-mean-square positional errors

An array of photosensors is mounted on a carrier while a group of two or three laser light fans are emitted towards rotating mirrors, allowing a sweep of the sampling body by the laser light fans. The position of the target is estimated by combining the knowledge of the sweep fan positions and the signals obtained by the photosensors. An example of such a tracker is the laserBIRD2 by Ascension Technology. Such systems have however not found widespread applications in the domain of surgery.

Optical tracking was largely successful in clinical applications thanks to the combination of its relatively large workspace, high accuracy and reliability. These systems are usually subject to little interference with other medial equipments present in the operating room. This is how optical tracking systems have become the current standard in most clinical applications despite their line-of-sight limitation.

### 3.1.3 Electro-Magnetic Tracking Systems (EMTS)

Figure 3.4: *Left: NDI Aurora AC-driven electromagnetic tracking system with planar emitter* [14]*; Centre: Ascension Tech Trakstar and Drivebay DC-driven systems* [15]*; Varian Technologies Calypso transponder-based tracker*[16]

Magnetic trackers are also a common option for instrument tracking in space as they do not require line of sight and allow for precise position estimation. Several earlier studies have been based on custom-built EMTS: Woloert et al. [312] present the design of a custom-built magnetic tracker for laparoscopic instruments developed in order to evaluate movement trajectories of laparoscopic tools during surgeries. Similarly, Ikuta et al. [137] present a system for recording force and position information during laparoscopic surgeries, using a custom built magnetic tracker to obtain the 3D position of instruments. Others have made use of the increasing number of commercially available EMTS, such as the NDI Aurora™or Ascension Technology TrakStar™, the latter which we used in some of our experiments presented in the following.

#### Alternating current (AC) driven tracking

This technology represents the earliest developed electromagnetic tracking technology. Systems usually consist of an emitter housing at least three perpendicular coils emitting an elec-

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[14] http://www.ndigital.com/medical/products/aurora/ Photo credits : NDI

[15] http://www.ascension-tech.com/medical/index.php Photo credits : Ascension Tech

[16] Photo credits : Varian Technologies Calypso

tromagnetic field composed of three dipole fields. A probe housing small coils measures the induced voltage which is proportional to the flux variation of the magnetic field, allowing for an estimation of the probe position and orientation in the emitter frame of reference. Kuipers et al. [157] provide a detailed description of the function principle of AC tracking systems.

#### Direct current (DC) driven tracking

Though their structure is somewhat similar to AC-driven systems, these trackers use a quasi-static DC-driven magnetic fields. Miniature active or passive sensors measure the magnetic induction after establishment of a stationary magnetic field. DC tracking systems are usually more robust to the presence of metallic objects close to the emitter or sensor. Ferromagnetic materials in the electromagnetic field can however still significantly affect the measurement accuracy.

#### Transponder-based systems

Permanent magnets or transponders are built into instruments or implanted in order to track target. An external coil excites the transponders at fixed resonant frequencies, following which each transponder responds with a decaying magnetic field whose waveform allows for computation of the current transponder position with respect to the source coil. The use of such systems is relatively recent and therefore limited, with a notable example being the Calypso 4D system (see fig.3.4) used for tumour position tracking during radiation therapy. These systems have the advantage of unambiguous transponder localisation at relatively high frame rates. However, they are still sensitive to interference from metallic objects or conductive materials and have a relatively limited workspace for bulky equipments.

The lack of any line-of-sight limitation and the ability to track flexible endoscopes and catheters are the main advantage of electromagnetic tracker systems. They do not compete with optical tracking systems in terms of robustness and accuracy, although from an application point of view, electromagnetic tracking systems are usually closer to the target, often resulting in comparable overall performance.

Magnetic tracking technology's adoption for medical applications has been relatively slow, partly because of the distortion factors previously mentioned and the lack of compensation methods. Only the introduction of miniaturized electromagnetic tracking systems which allowed for embedding in surgical instruments such as conventional tools, needles or even catheters (see fig.3.4 centre for the example of available sensor sizes for the TrakStar system) gave electromagnetic trackers an advantage over other tracking technologies in terms of tracking flexible instruments and tracking within the patient's body.

### 3.1.4 Tracking using imaging systems

While optical and magnetic tracking are well established methods for recording the instrument position in space, there is a certain amount of research done in the field of tracking the instruments within the endoscope image (e.g. [299], [298], [11]) in order to remove the need for additional sensors.

### Tracking in the endoscopic image

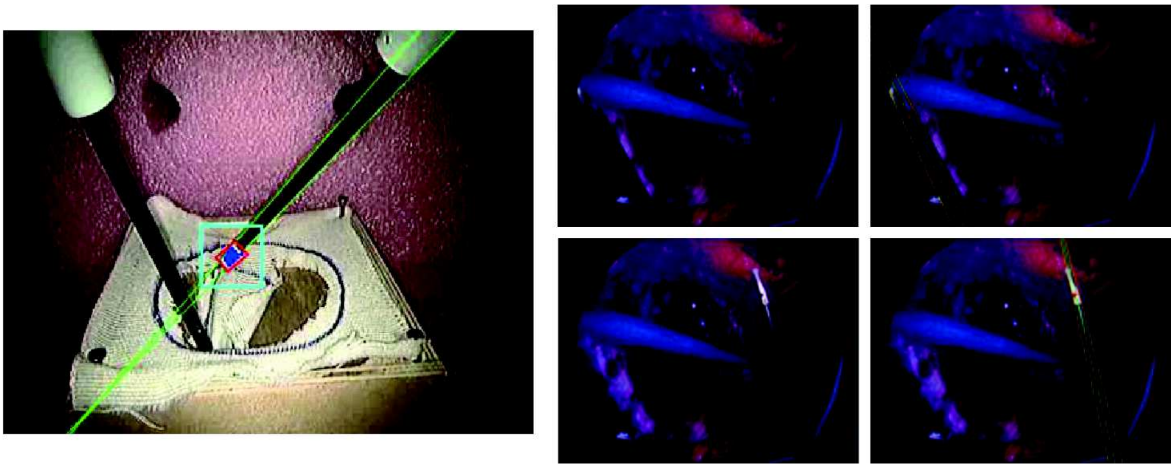


Figure 3.5: *Left : Instrument pose estimation in the endoscopic image from Loukas et al. [175]; Right : 3D Tracking of laparoscopic instruments using statistical and geometric modelling from Wolf el al. [311]*

As laparoscopic surgery requires the use of an endoscope, there is a relatively strong interest in attempting to acquire instrument positional data directly from the endoscopic image, which would be a low-cost alternative to other tracking systems that would not interrupt the surgical workflow or require any additional costly hardware. Therefore, quite some work has been performed on the subject (e.g. [311], [175]) with moderate success due to several difficulties, most notably the robustness to total or partial occlusions of the instruments.

### Tracking in other medical imaging modalities

There is a growing trend towards making medical imaging an integral part of the intra-operative process, as evidenced by research and development of hybrid operating rooms. There are thus a certain number of applications where dedicated instrument and surgical target tracking systems may be replaced by image processing of either CT, MRI, fluoroscopy or ultrasound images. The possibilities in this domain are many, each with their respective advantages and drawbacks, and an exhaustive discussion would go beyond the scope of this manuscript.

## 3.2 Feeding back the tool tip position to the surgeon

### 3.2.1 A short survey of conventional approaches for surgical tool navigation

Conventional approaches for surgical tool navigation that have found their way into operating rooms are mainly systems for neurosurgery, followed by orthopaedic surgery and more recently vascular surgery and needle-insertion procedures.

Navigation systems evolved as “image-based,” meaning that for example preoperative CT or MRI images are acquired and used for navigation in the operating room, with or without highlights of specific features. An alternate approach often found in orthopaedic surgery due to the rigid nature of the surgical targets are "model-based" navigation systems, which dispense with the preoperative imaging and use a computer-generated model of the target and environment to assist in navigating the instrument. Instruments are then tracked using one of the systems previously mentioned and the information on relative positions of instruments to targets is shown to the surgeon visually.

The navigation systems using visual feedback usually only simultaneously display the image or position of the instrument and the pre-operative plan, with certain more recent systems resorting to augmented reality features so as to blend the instrument, pre-operative plan and relevant anatomical features.

In all these cases, display of navigation information usually requires additional displays, ranging from rather costly and bulky multiple screen systems (such as e.g. the Brainlab for neurosurgery or CASone for open hepatic surgery) to hand-held displays or in more recent academic work, augmented reality thanks to projections or headsets. Surgeons are therefore required to focus on multiple screens or hide parts of the surgical scene through augmented reality overlays. This is both an issue in terms of clutter in the operating room, surgeon’s visual cognitive load and safety.

As previously explained, the present work will however focus on the use of haptic feedback for assisting navigation of laparoscopic surgical tools. In the following we therefore begin by presenting a state of the art for haptic feedback applied to navigation problems in general, followed by a more detailed state of the art on haptic feedback for navigation of surgical tools.

### 3.2.2 Haptic feedback for navigation - A state of the art

Haptic feedback has been explored as a means for improving performance in gesture guidance and navigation for all manner of tasks, with varying levels of success. In the following, I aim to give an overview of these studies on potential applications, highlighting implementations, results and general conclusions that may be of use in the study of haptic feedback for instrument navigation in MAS.

#### Haptic feedback for gesture guidance and learning

Haptic feedback has been investigated for improved gesture performance and learning. Concerning tactile feedback, Bark et al. [25] explore the effect of feeding back proprioceptive information in fast arm movements using visual and vibrotactile information. Users are presented with feedback on the deviation of their arm position with respect to a target position which rapidly changes. In this scenario, vibrotactile feedback yields no significant improvements except for user comfort. They conclude that at high speeds, high refresh rates are required for tactile feedback in order to see improvements in performance, and that graded tactile feedback (i.e. feedback proportional to errors) may benefit users for error correction. These paradigms have been exploited in rehabilitation scenarios, with Causo et al.( [51], [52]) exploring the use of combined visual and vibrotactile cues in guiding arm rehabilitation tasks. Their initial experiments validate the usability of the system but its performance is not yet compared to alternative guidance methods. The use of haptic feedback has also been explored in guiding musical gestures (e.g. [196], [110], [132]). In particular, Holland et al. [132] present the use of vibrotactile guidance for percussion learning, raising a number of interesting points about the design of vibrotactile guidance in a learning settings. Another obvious application of gesture guidance is sports: Ruffaldi et al. [237] explore the idea of using vibrotactile cues for guiding hand gestures in rowing. Providing users with visual, vibrotactile and combined cues indicating the deviation from the optimal hand trajectory, concluding that congruent visual and vibrotactile feedback improves the quality of gestures during training, whereby vibrotactile feedback alone allows for faster responses than when visual feedback is present, probably because of the lower cognitive load.

### Haptic feedback for precise aiming

Focussing less on the actual gesture and more on improving precision and execution speed of targeted movements, Oron-Gillad et al. [203] analyse the use of vibrotactile cues for a 2D target acquisition task. Vibrotactile cues seem successful at directing the users attention towards given targets and accelerating task completion. Also they obtain better performance when the vibrotactile cues indicate deviation than when they indicate target acquisition (i.e. no vibration on target and increasing vibration with deviation from the target performs better than vibration increasing with proximity to the target). Provided vibrotactile cues were vibration bursts at fixed amplitude, frequency and duration with varying inter-stimulus intervals. Kinaesthetic cues have also been employed for such targeting tasks: Asque et al. [16] use a 3DoF haptic interface to assist a user in a 2D target pointing task. They conclude that less constraining feedback leads to highest performances, citing haptic cones (i.e. the targets are highlighted by being placed at the apex of a "cone" in the virtual surface scanned with the interface, which is less intrusive as no pulling or friction forces are applied to the interface handle) as the most beneficial.

### Haptic feedback for 3D navigation

Combining aspects from the previously examined cases, a few works have focussed on haptic feedback for navigating 3D space. Rodriguez et al. [234] evaluate visual, haptic and combined visuo-haptic feedback for learning 3D trajectories. They conclude that the best learning effect in terms of accuracy is obtained by congruent visual and haptic feedback. Noting that continuous feedback presents the risk of creating a dependence on feedback in certain users, they propose a *"feedback on request"* scheme, for which they however note the risk of users creating an incorrect mental model of the movement in the absence of feedback. Bark et al. [23] explore the use of visual, vibrotactile and skin stretch feedback in feeding back proprioceptive information when guiding a robot arm. Haptic feedback leads to overall better performances (accuracy, speed) than visual feedback, and skin stretch is shown to be superior to vibrotactile information in this case. Concerning the design of kinaesthetic guidance cues, Abbott et al. [2] present the concept of *hard* and *soft guidance virtual fixtures* as well as *forbidden region virtual fixtures* for robot-assisted manipulation and provide certain design considerations for their implementation.

#### Haptic feedback for pedestrian and vehicle navigation

In an alternative to the conventional kinaesthetic and vibrotactile feedback schemes, Horschel et al. [133] and Gleeson et al. [99] develop a system for communicating directional cues to a users fingertip using skin stretch. When encoding four directions, they observe recognition accuracy above 95% for displacements as small as 0.2mm and speeds as low as 2mm/s. Gleeson et al. [100] study the effect of presenting directional cues via skin stretch which are misaligned with their real-world meaning. Tactile directional cues that are misaligned with the world are still interpreted (though in varying manners) correctly at little cost for large misalignments, but smaller misalignments impact user performance negatively. Their findings are then compared to audio and vibrotactile cues in a device for pedestrian navigation in [154].

Concerning pedestrian navigation, Elliott et al. ( [77], [76]) present studies aimed at GPS-based guidance of soldiers on foot in complex terrain using vibrotactile cueing. Initial experiments comparing with compass and traditional visual GPS guidance show equal performances to visual GPS. However, the second study examines performance in the present of concurrent tasks and high visual cognitive load (i.e. searching for targets, navigating in the dark), concluding that in such cases, tactile guidance outperforms traditional GPS. However, such feedback for navigation is not always as beneficial, e.g. Ertan et al. [79] present a concept of a 4x4 vibrotactile array for communicating navigational cues to a pedestrians back, but initial tests do not clearly show any improvement in performance. These paradigms are also extended to vehicle navigation: Ege et al. [75] use vibrotactile feedback embedded in a steering wheel for vehicle guidance with the aim of reducing cognitive load over the use of auditory cues. Their results show that when auditory distractions are present, tactile guidance performs better than auditory guidance. Van Erp et al.( [78], [288]) test a vibrotactile waist belt for assisting navigation on foot and in vehicles. They conclude that in such task, encoding direction improves performance but encoding distance to a waypoint does not. Tests in vehicles where strong environment vibrations are present lead to similar results, guidance with the belt is concluded to be highly intuitive.

### 3.2.3 Haptic feedback for surgical instrument navigation - A state of the art

#### Kinaesthetic feedback in surgical navigation

Haptic feedback for surgical tool navigation has been explored mostly in the context of RMAS, using kinaesthetic feedback. To cite a few, Park et al. [210] present an implementation of forbidden region virtual fixtures for catheter navigation. Li et al. [170] present virtual fixtures generated based on anatomical features for applications to sinus surgery, i.e. on rigid bodies. Feng et al. [81] propose forbidden-region virtual fixtures for laparoscopic surgery, with audio, visual and haptic feedback. The forbidden regions are defined by extracting organ outlines in the laparoscopic image, with the aim of preventing unwanted collisions with the organs. Usability and performance tests are however still pending. Prada et al. [221] describe the design and performance of virtual fixtures used to train surgical cutting. They compare *attractive virtual fixtures* that pull the instrument towards given points in a predefined path against *forbidden region virtual fixtures* that push the instrument away from unauthorized limits. Both paradigms yield an improvement in cutting performance, however forbidden region virtual fixtures do not significantly improve Task Completion Times (TCT) whereas attractive virtual fixtures significantly reduce TCT compared to no virtual fixtures. Pezzementi et al. [216] explore a novel solution to guidance virtual fixtures in RMAS, suggesting that in movements where proper dynamics are important, virtual fixtures may be implemented to guide tool speed and not only its position.

### Tactile feedback in surgical navigation

However, tactile feedback has also been explored as a viable solution, either for comanipulation ( [235], [317]) or as a form of sensory substitution to avoid stability issues in teleoperation settings. Bluteau et al. [38] study the use of vibrotactile cues for guiding a tool along a 3D trajectory in traditional (open) computer assisted-surgery (CAS). They study the use of vibrotactile and visual cues, refining the tactile cues into positional and angular error feedback. Information on angular errors turns out to be unusable, whereas positional errors are intuitively corrected. Adding functional vibrotactile feedback did not significantly affect task duration, however it lead to a significant decrease in spatial errors, mean velocity and reliance upon the visual feedback. In an even more experimental idea, Robineau et al. [233] suggest using Bach-y-Rita's tongue display unit (an electro-tactile array dispensing cues to a user's tongue) to inform surgeons of deviations with respect to a planned trajectory during needle insertion tasks. From their initial experiments, they conclude that such an approach is feasible and simple from a cognitive point of view, although a practical implementation still faces some hardware problems. Brell et al. ( [40], [41]) review work and design considerations for tactile feedback to augment surgical gestures based on preoperative information. They note that tactile feedback is a promising alternative to visual guidance as the cues are private, usually intuitive and can easily code complex spatial information. They present the development of conTACT, a multi-modal CAS navigation system using optical tracking capable of providing visual-tactile feedback. Tactile cues are provided to the back of the surgeon's hand using vibration motors. Registration between preoperative planning, current patient position and tracked tools is presented only for a milling task on rigid structures. While purely visual feedback yields lower errors than purely tactile feedback, it also significantly prolongs TCTs. The best results are achieved through visual+tactile feedback, with extremely low error rates although TCTs are longer than for tactile feedback alone.

The work of Brell et al. highlights the issue of registration between pre-operative medical data and per-operative imaging, instrument and organ tracking. This issue remains largely unresolved for deformable and moving organs, although there is some promising work towards solutions. To cite a few, Ryd et al. [240] present a potential solution to matching forbidden-region virtual fixtures to known anatomical motion of organs with focus on cardiac surgery. Kuroda et al. [158] present a concept for registering non-rigid target positions in the human body for surgical navigation purposes, as well as a tactile guidance system which thereby takes advantage of pre-operative data. The tracking of targets is done by registering vessels neighbouring target bodies. An implementation showing visual feedback based on patient data is presented, and a concept for tactile guidance using electro-stimulation is shown. The effectiveness of the tactile feedback system is however not evaluated quantitatively, nor is it tested in a MAS setting. Gibo et al. [97] present two concepts for moving virtual fixtures for teleoperation on organs subject to physiological motion, one using predicted position and the second using the current organ position. Initial tests show an improvement in movement accuracy and applied forces using these paradigms.

### 3.2.4 Concluding remarks on the state of the art

Our analysis of the state of the art leads us to conclude that surgical navigation systems available in the operating room currently exclusively rely on visual feedback. This can be relatively costly and bulky (because of additional displays), increases the visual cognitive load for surgeons and can be problematic in terms of complexity and safety (again because of divided attention between multiple displays or masking of visual information when using overlays).

The growing use of robots as co- or tele-manipulators in surgery has led to a spike in research on kinaesthetic feedback for guidance, which could circumvent the problem of additional display hardware while still presenting intuitive information. Such systems however require a costly RMAS set-up and still face a certain number of challenges, most notably in terms of safety of shared control between surgeon and robot.

Tactile feedback has been explored to a very limited extent for open surgery navigation but has shown some potential. These benefits may be extendible to laparoscopic surgery, providing an avenue for relatively cheap and unobtrusive feedback which could relieve some of the surgeon's visual cognitive load.

The remainder of this chapter will therefore present our work on evaluating the potential of tactile feedback and its combination with visual feedback in laparoscopic instrument navigation. We begin by quantifying the degradation in performances between open and laparoscopic surgery and evaluating the respective benefits obtainable through simple visual, tactile and kinaesthetic feedback (section 3.2.5). This is followed by a more in-depth analysis of the manner in which tactile and combined visual and tactile feedback help improve performances in navigation tasks (section 3.2.6) and an early attempt at applying the insights gained to navigation assistance in an actual laparoscopic training task (section 3.2.7).

### 3.2.5 Initial exploratory experiments

Here, we discuss a pair of experiments focussing on assistance for guiding the tip of a laparoscopic instrument towards a target plane. This situation could arise for example during a laparoscopic hepatectomy, during which the surgeon must delineate a plane bisecting the liver and cut the organ along said plane while ensuring the best accuracy and planarity of the cut ( [86]). Inaccurate cuts pose potential health hazards through insufficient resection of pathological tissue or through excess resection of healthy tissue. Non-planar cuts on the other hand are dangerous due to the resulting poor vascularisation of protruding liver tissue, which may lead to post-operative complications.

#### 3.2.5.1 Materials & Methods

In the following, we present the experimental set-up and procedures for both experiments evaluating the benefits of haptic and visual feedback in laparoscopic instrument navigation.

##### Experimental set-up and task

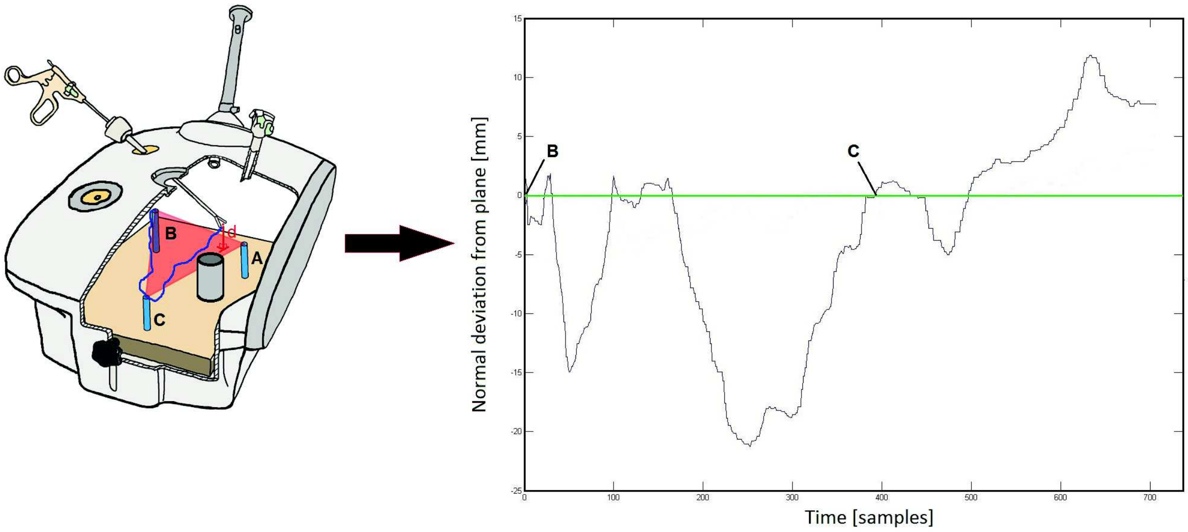


Figure 3.6: *Schematic of the laparoscopic trainer containing the three pegs (A, B and C) forming an inclined plane with their tips. The subject attempts to follow a given trajectory between the peg tips (dark blue line) without deviating from the target plane.*

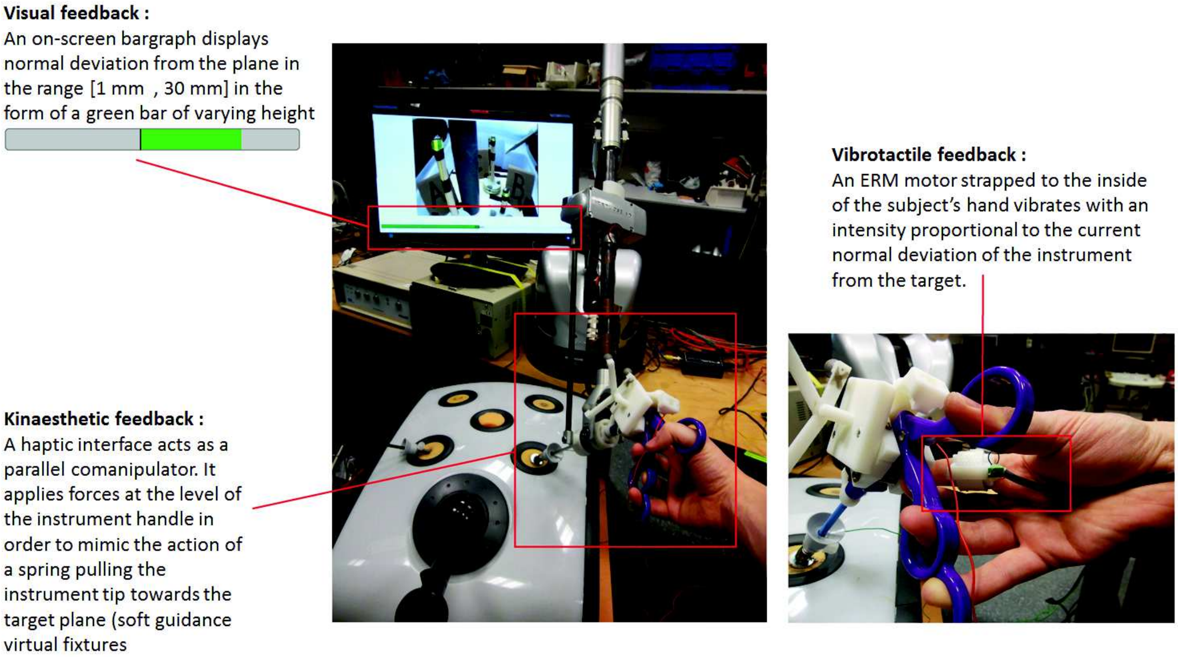
We placed subjects in front of a laparoscopic trainer (EndoSim LaproTrain, see figures 3.6 and 3.7 for details) and let them manipulate standard laparoscopic forceps inserted through 5mm trocars while observing the endoscopic image on a 24" screen placed directly in front of them. Three different sized pegs (A, B and C respectively - see figure 3.6) were set up vertically within the trainer so that their tips formed a steeply inclined plane similar to a resection plane for a hepatectomy.

Subjects were tasked with following random trajectories beginning at one peg, passing through both other pegs before returning to the peg of origin (see figure 3.6). They were instructed to thereby keep the tip of their instrument as close as possible to the target plane while trying to finish the trial as quickly as possible. Normal deviation from the target (d, in [mm]) is computed at every instant and fed back to the subject as per the current feedback condition. The plot on the right shows an example of a deviation curve obtained for the blue trajectory drawn on the left. A fixed cylindrical obstacle is placed on the [AC] trajectory segment to prevent straight line movements between both pegs and complicate the task for the user.

The laparoscopic forceps were fitted with passive optical markers allowing for tracking of the instrument handle position in space thanks to an NDI Polaris optical tracking system (25Hz frame rate, accurate to <1mm). For experimental conditions involving a robotic co-manipulator (see section 3.6 for a detailed listing of experimental conditions), the instrument handle was attached to the wrist of a 6-Degrees of Freedom (DoF) haptic interface (Haption Virtuose 6D) capable both of applying forces to the instrument and recording its position in space. Instrument handle position data were recorded through custom software, which allowed for real-time computing of the instrument tip position in space thanks to a prior calibration step which provided us with the transformation matrix between instrument handle and tip.

The positions of the three peg tips in the laparoscopic trainer as well as the position of the insertion point (trocar position) were recorded prior to the experiments, allowing for computation of the normal deviation of the instrument tip with respect to the target plane and thus enabling the generation of appropriate feedback signals indicating this deviation to the subject.

At the end of the experiments series, the instrument tip position data and the computed deviations were analysed using Matlab as per evaluation metrics presented in the following in section.


**Visual feedback :**
An on-screen bargraph displays normal deviation from the plane in the range [1 mm , 30 mm] in the form of a green bar of varying height

**Vibrotactile feedback :**
An ERM motor strapped to the inside of the subject's hand vibrates with an intensity proportional to the current normal deviation of the instrument from the target.

**Kinaesthetic feedback :**
A haptic interface acts as a parallel comanipulator. It applies forces at the level of the instrument handle in order to mimic the action of a spring pulling the instrument tip towards the target plane (soft guidance virtual fixtures

Figure 3.7: *Setup as seen from the point of view of the subject, with detail of the three means for providing feedback*

### Evaluated forms of feedback

Feedback informed the users of their normal deviation to the plane in various manners. We consider conditions as being "*without feedback*" when the user is presented with only the endoscopic image. Table 3.6 lists the feedback conditions relevant to our current analysis.

Visual feedback was provided in the form of a horizontal bargraph displayed on the screen (see figure 3.7 top left). The bargraph consisted of a horizontal grey container displayed beneath the endoscopic image, within which a green bar changed length either to the left or right starting from the centre so as to display the current deviation magnitude, which was also shown as a numerical value in [mm] at the centre of the bargraph. The absence of a green bar signalled the fact that the user was "on target", i.e. at a deviation between -1 mm and +1 mm from the plane. Otherwise, the green bar length varied continuously between zero and its maximum length (i.e. half the grey container length) to indicate deviation.

Cutaneous vibrotactile feedback was provided to the user via an Eccentric Rotating Mass (ERM) motor (Precision Microdrives$^{TM}$Pico Vibe 307-100 [191]) strapped to the inner side of the index finger holding the instrument (see figure 3.7 right). This placement is interesting in the context of integration of vibrotactile feedback to the handle of serial co-manipulators for laparoscopic surgery. The distance to the target plane was encoded as a linear increase in vibration intensity, proportional to the magnitude of the deviation (range: 0g to 7g for deviations from 0mm to 30mm). For ERM motors, vibration amplitude and frequency are inherently linked, so that the frequency of the vibrotactile feedback varied almost linearly between 25Hz and 260Hz (see [191] for detailed information on the amplitude/voltage and frequency/voltage relationships for the employed ERM motor).

We also implemented soft guidance virtual fixtures using a Haption Virtuose 6D$^{TM}$haptic interface set up as a parallel co-manipulator (see figure 3.7 bottom left). The haptic interface was attached to the instrument just below the handle held by the user and applied forces in order to guide the instrument tip towards the plane. These forces were calculated as per equation (3.1) in order to simulate a spring (k = 400N/m) attached between the instrument tip and the plane.

$$\vec{F_{wrist}} = l_{out}/l_{in} \cdot (-k \cdot \vec{n} \cdot d) \tag{3.1}$$

where $l_{out}$ and $l_{in}$ respectively denote the lengths of instrument shaft inside and outside of the point of insertion (calculated based on the robot wrist position, the known instrument length and the trocar position defined in the robot coordinate system prior to the experiment), d is the current deviation from the plane and $\vec{n}$ is the plane's normal vector. The choice of a relatively low stiffness (i.e. soft virtual fixtures) was made with the clinical imperative of leaving the surgeon in control of their action in mind, as minor deviations from the pre-operative plan may sometimes be necessary. This also has the advantage of keeping the virtual fixtures mainly informative at low deviations, for better comparison with the other forms of feedback.

We evaluated forms of feedback listed in table 3.6 below, along with two unlisted tactile feedback conditions in the laparoscopic block (omitted for lack of any positive results) and two conditions in the robot-assisted block (inactive haptic interface, with and without visual feedback, with the purpose of verifying the transparency of the haptic interface with regards to task execution).

**Table 1.** Evaluated feedback conditions

| Block | Condition | Description |
|---|---|---|
| Open Surgery | Open | Reference : Subjects were placed before the LaproTrain$^{TM}$with the cover removed so as to simulate an open surgery situation. The instrument used was a standard needle-holder fitted with markers for optical tracking |
| Laparoscopic surgery | NoFeed* | Laparoscopic surgery : Subjects manipulated a standard laparoscopic forceps tracked using optical markers inserted into the closed LaproTrain$^{TM}$through a 5mm trocar. The endoscope image was shown on a 24" screen placed directly in front of the subjects. This set-up remained basically the same for all following conditions. |
| | Visual* | Laparoscopic surgery + visual feedback : Identical to NoFeed, but subjects were given visual feedback on their current deviation via an on-screen bargraph (see section 3.2.5.1 for details) displayed below the endoscopic image. |
| | TacCont* | Continuous vibrotactile feedback : Identical to Nofeed, but subjects were provided with continuous vibrotactile feedback proportional to their current deviation. |
| | TacCont+Visual* | Continuous vibrotactile + Visual feedback : Identical to TacCont, with the addition of visual feedback as described above. |
| Robot-assisted laparoscopic surgery | RobInact | Inactive comanipulator arm : A Virtuose 6D (Haption) haptic interface is attached to the instrument just below the handle. It is entirely passive and applies no forces to the instrument handle. |
| | Robinact+Visual | Inactive comanipulator arm + Visual feedback : Identical to RobInact, with the addition of visual feedback as described previously. |
| | Kin | Soft guidance virtual fixtures : A Virtuose 6D (Haption) haptic interface is attached to the instrument just below the handle. It applied forces so as to guide the tip towards the target plane upon deviation, as described previously. |
| | Kin+Visual | Soft guidance virtual fixtures + Visual feedback : Identical to Kin, with the addition of visual feedback as described previously. |

#### Feedback thresholds

Pilot tests showed that maximum deviations around 30mm were attained when performing

**Table 2.** Questionnaire filled out by subjects after performing the task in each condition. (*) marks statements only presented for conditions with feedback, i.e. NoFeed, Visual, TacCont+Visual and RobInact+Visual. Answer range from "Strongly disagree = 1" to "Strongly agree = 5". See figure 3.11 for quantitative results.

| Statement : | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1) I felt the task was difficult to perform in this condition | | | | | |
| 2) I believe I performed well in this condition | | | | | |
| 3) I understood the feedback * | | | | | |
| 4) I felt the feedback helped me in accomplishing the task * | | | | | |
| 5) I thought the feedback was intuitive * | | | | | |
| 6) I was disturbed by the feedback * | | | | | |
| 7) I felt the feedback was easy to use * | | | | | |

the task in a laparoscopic setting without feedback (NoFeed), hence the choice of this value as the maximum displayed deviation, be it for the bargraph or tactile feedback. The optical tracking system provided us with measurement accuracies just below 1mm around the instrument tip position, thus any deviation computed as below 1mm was considered as on-target. Over the resulting range between 1mm and 30mm deviation from the target, the feedback levels varied linearly from minimum to maximum. To allow for good comparison, the stiffness of the virtual spring implemented by the haptic interface was chosen so as to not allow any deviation beyond 30mm.

### Evaluation metrics

Resulting trajectories were analysed both in terms of precision and time criteria. Relevant precision criteria encompassed both:

(1) on-target precision (using a "*relative Time on Target*" (rToT) score, defined as the percentage of TCT (Task Completion Time) during which the instrument tip was under 1mm normal deviation from the target plane),
(2) and amplitude of deviations (i.e. maximum peak-to-peak normal deviations).

The evaluated time criterion was :

(3) TCT (Task Completion Time) which serves as an adequate measure of task completion speed since the nominal trajectory length did not vary between trials.

In experiment 2, a questionnaire (see table 3.2) presented as a five point Likert scale was filled out by subjects after performing the task in each feedback condition. The results are detailed and discussed in the following section and shown in the form of graphs in figure 3.11.

### Sample populations and trial randomisation

### First experiment (Experiment 1 in the following)

This experiment, discussed in part in [134], had 23 (16 male, 7 female) novice right-handed subjects performed 5 repeats of the task presented previously for the 11 different feedback conditions (i.e. a total of 55 trajectories per subject) partially listed in table 3.6. For practical reasons, conditions were grouped in three blocks: open surgery (1 condition), laparoscopic surgery (6 conditions) and robot-assisted laparoscopic (4 conditions) (see table 3.6 in the following for details). Subjects began with the open surgery block, the order of the subsequent blocks was randomized and the order of the conditions within the blocks was fully randomized. This procedure was chosen in order to minimize bias from learning effects and fatigue, under the assumption that the task ergonomics sufficiently differed from one block to another to not require full randomization of all 11 conditions.

### Second experiment (Experiment 2 in the following)

A second experiment was conducted to take a closer look at improvements observed in experiment 1 when providing visual feedback, continuous vibrotactile feedback and their combination (only six of the initial 11 conditions were analysed further - these are marked with a (*) in table 3.6. As the number of conditions was reduced, subjects were able to complete 6 trajectories per condition. The order in which subjects performed the six conditions was fully randomized in order to minimize potential influence of short-term learning effects on our results. For this experiment, we recruited a new sample of 11 (8 male, 3 female) novice, right-handed subjects, with no previous experience in laparoscopy or with our experiments).

### Exploratory results for an expert intern

For exploratory purposes, an intern with extensive laparoscopic surgery training (male, right-handed, age 28) was asked to complete 10 trajectories respectively for all conditions (see table 3.6 for details) in order to gain insights into the generalizability of our results to a population of surgeons.

All subjects received detailed explanations on the experimental protocol and presented forms of feedback prior to beginning the experiments and provided written informed consent for their participation.

### Statistical analyses

We studied mean performances of each subject for each feedback condition, providing us with 23 observations per condition for experiment 1 and 11 observations per conditions for experiment 2. As a general rule, data for each condition were not normally distributed but only slightly skewed and sample variance was large enough for us to assume unequal population variances. Although samples are relatively small, the limited skew led us to provide t-intervals for our estimation of 95% confidence intervals for population means (shown as blue vertical lines in figures 3.9, 3.10 and 3.8) and calculate statistical significance of observed differences in means using paired-sample t-tests with subsequent Bonferroni correction of the obtained p-values.

#### 3.2.5.2 Results

The RobInact and RobInact+Visual conditions served the purpose of verifying transparency in the co-manipulated setting, i.e. the fact that they did not differ from conditions NoFeed and Visual, so as to be able to attribute effects observed in conditions Kin and Kin+Visual to the presence of virtual fixtures. The lack of significant differences observed between RobInact and Nofeed as well as between RobInact+Visual and Visual tend to confirm this hypothesis.

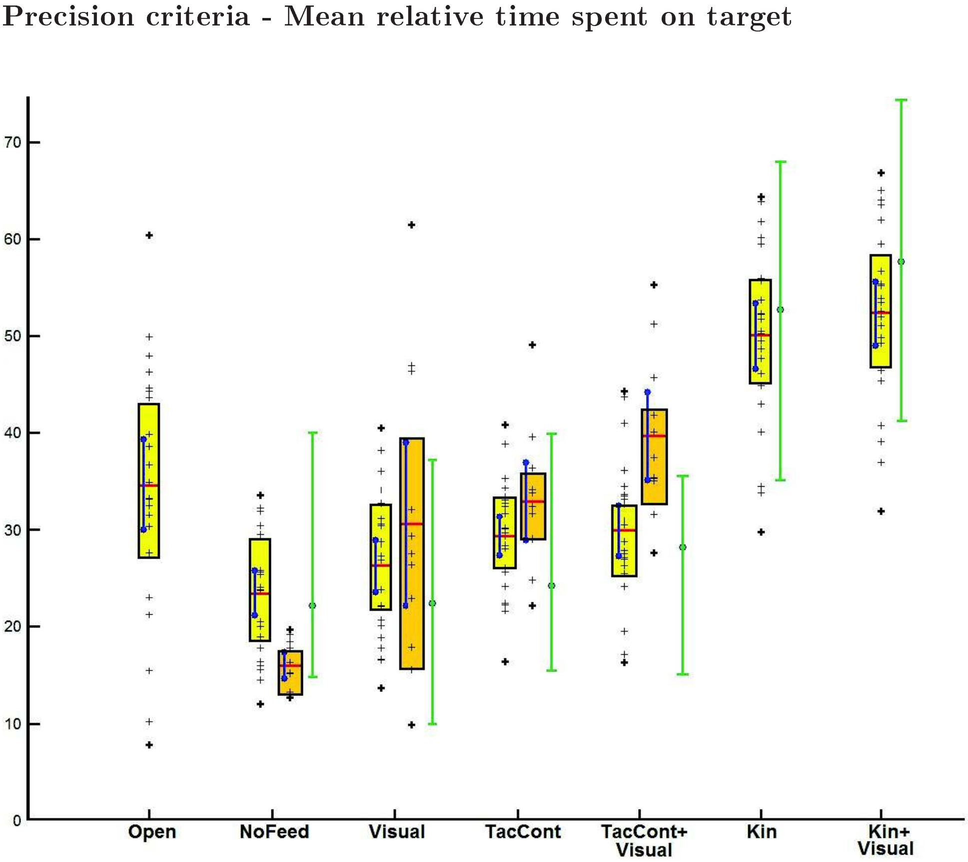


Figure 3.8: *Mean subject rToT (in [%]) for each condition. Results from experiment 1 are shown in yellow, results from experiment 2 in orange, performances for the intern in green; data points shown as black crosses, interquartile range shown by coloured boxes, sample means as horizontal red lines and confidence intervals for population means as vertical blue lines. The spread of the intern's performances is shown by the vertical green bars, his mean performance by the green circle with blue contour.*

Figure 3.8 shows the results obtained for on-target precision, measured by the percentage of TCT spent at deviations below 1 mm (rToT). Results are coherent between experiments, although subjects performed worse in the mean for condition NoFeed in the second experiment, leading to greater relative improvements obtained from feedback.

**Table 3.** Differences in mean relative Time on Target (rToT) between conditions and associated statistical significance. Lack of significance below $\alpha$=0.1 is shown by NS (Not Significant). For the relevant conditions, results from experiment 1 are highlighted with ($^1$), and those from experiment 2 with ($^b$).

| | NoFeed | Visual | TacCont | TacCont +Visual | Kin | Kin +Visual |
|---|---|---|---|---|---|---|
| Open | -11.1%<br>(p<0.01) | -8.28%<br>NS | -5.23%<br>NS | -4.56%<br>NS | +13.52%<br>(p<0.01) | +15.76%<br>(p<0.01) |
| NoFeed | | +2.83%$^a$<br>+14.58%$^b$<br>NS<br>(p<0.05) | +5.87%$^a$<br>+16.93%$^b$<br>(p<0.05)<br>(p<0.01) | +6.56%$^a$<br>+23.69%$^b$<br>(p<0.05)<br>(p<0.01) | +24.62%<br>(p<0.01) | +26.83%<br>(p<0.01) |
| Visual | | | +3.04%$^a$<br>+2.35%$^b$<br>NS | +3.72%$^a$<br>+9.11%$^b$<br>NS | +21.8%<br>(p<0.01) | +24%<br>(p<0.01) |
| TacCont | | | | +0.7%$^a$<br>+6.76%$^b$<br>NS | +18.75%<br>(p<0.01) | +20.96%<br>(p<0.01) |
| TacCont +Visual | | | | | +18.08%<br>(p<0.01) | +20.28%<br>(p<0.01) |
| Kin | | | | | | +2.2%<br>NS |

In condition Open, subjects perform the task with moderate precision (around 35% time spent on target). Precision is greatly reduced for the task in condition NoFeed (between 15% and 25% time spent on target), and introduction of solely informative visual, tactile or combined feedback (Visual, TacCont, TacCont+Visual) tends to improve precision without returning on-target precision to levels obtained in the Open setting.

The use of soft guidance virtual fixtures greatly increases on-target precision (around 50% of TCT spent on target), with performances significantly improved even over that of condition Open.

Concerning the intern, it is surprising to note that for all conditions except Kin and Kin+Visual, he shows performances close yet below average of those of novice subjects despite his experience in laparoscopy. However, his performances in conditions with feedback tend to follow a similar trend to those observed in novice subjects, and improvements from soft guidance virtual fixtures are particularly marked in his case. Of course these results remain purely anecdotal in comparison with those presented for our novice subjects.

Table 3.3 sums up the observed differences in means between conditions along with associated statistical significance.

### Precision criteria - Mean deviation amplitude

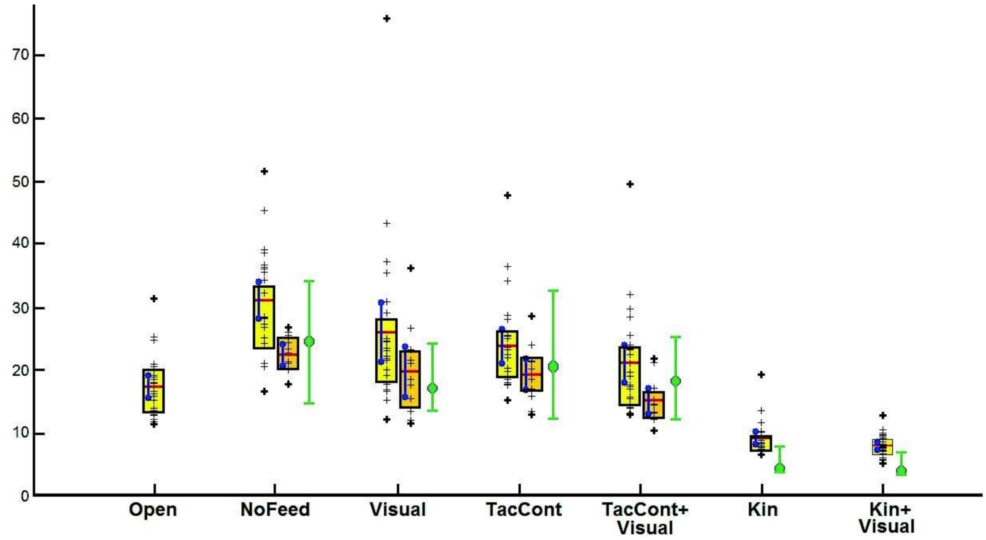


Figure 3.9: *Mean subject DA (in [mm]) for each condition. Results from experiment 1 are shown in yellow, results from experiment 2 in orange, performances for the intern in green; data points shown as black crosses, interquartile range shown by coloured boxes, sample means as horizontal red lines and confidence intervals for population means as vertical blue lines. The spread of the intern's performances is shown by the vertical green bars, his mean performance by the green circle with blue contour.*

Figure 3.9 shows the results obtained for our second precision criterion - mean deviation amplitudes (DA). As expected, the passage from open to laparoscopic surgery leads to a great degradation in precision (increase in deviation amplitudes). Providing solely informative feedback (conditions NoFeed, Visual and TacCont+Visual) tends to improve performance over the reference laparoscopic condition (NoFeed), although this is only consistently significant for combined visual and tactile feedback (TacCont+Visual). Surprisingly, deviation amplitudes are generally smaller for condition NoFeed in experiment 2 despite the fact that subjects tended to move at higher speeds (see following section on Task Completion Times (TCT)) and had worse on target precision (see section on relative Time on Target (rToT)) than in experiment 1. This is not the case for the conditions with feedback (Visual, TacCont, TacCont+Visual), where the lower deviation amplitudes also came at the cost of prolonged TCT. The use of soft guidance virtual fixtures significantly improves performance both over the reference laparoscopic condition (NoFeed) and even the reference open surgery condition (Open).

Again, the intern performs more or less on par with novices regarding this criterion, with his mean performances either at or slightly above those of novice subjects, except for conditions Kin and Kin+Visual where his deviation amplitudes are exceptionally low.

Table 3.4 sums up the observed differences in means between conditions along with associated statistical significance.

### Speed criteria - Time to complete task

Performances in terms of speed (evaluated as TCT - Task Completion Time) are shown in

**Table 4.** Differences in mean Deviation Amplitudes (DA) between conditions and associated statistical significance. Lack of significance below $\alpha$=0.1 is shown by NS (Not Significant). For the relevant conditions, results from experiment 1 are highlighted with ($^{a}$), and those from experiment 2 with ($^{b}$).

| | NoFeed | Visual | TacCont | TacCont +Visual | Kin | Kin +Visual |
|---|---|---|---|---|---|---|
| Open | +14.76 mm<br>($p<0.01$) | +8.66 mm<br>($p<0.1$) | +6.43 mm<br>($p<0.05$) | +3.68 mm<br>NS | -8.13 mm<br>($p<0.01$) | -9.36 mm<br>($p<0.01$) |
| NoFeed | | -5.1 mm$^{a}$<br>-2.68 mm$^{b}$<br>NS | -7.32 mm$^{a}$<br>-3.1 mm$^{b}$<br>($p<0.05$)<br>NS | -10.08 mm$^{a}$<br>-7.37 mm$^{b}$<br>($p<0.01$) | -21.88 mm<br>($p<0.01$) | -23.12 mm<br>($p<0.01$) |
| Visual | | | -2.22 mm$^{a}$<br>-0.42 mm$^{b}$<br>NS | -4.98 mm$^{a}$<br>-4.69 mm$^{b}$<br>NS | -16.78 mm<br>($p<0.01$) | -18.02 mm<br>($p<0.01$) |
| TacCont | | | | -2.75 mm$^{a}$<br>-4.27 mm$^{b}$<br>NS | -14.56 mm<br>($p<0.01$) | -15.8 mm<br>($p<0.01$) |
| TacCont +Visual | | | | | 11.8 mm<br>($p<0.01$) | -13.04 mm<br>($p<0.01$) |
| Kin | | | | | | -1.24 mm<br>NS |

figure 3.10. Once again, results appear coherent between experiments, though subjects performed the task faster in the mean for condition NoFeed in experiment 2, which may explain the difference in performance between experiments with regards to precision for this condition.

In condition Open, subjects naturally performed the task at high speeds (12.5 s mean Task Completion Time (TCT)), and moving to laparoscopic setting greatly reduced task execution speed (mean TCT between 33.2 s and 42.4 s in condition NoFeed). The addition of solely informative visual, tactile or combined feedback (conditions Visual, TacCont, TacCont+Visual) again reduced task execution speed when compared with the reference laparoscopic condition (NoFeed). Finally, the use of soft guidance virtual fixtures both without and with added visual feedback (conditions Kin, Kin+Visual) slightly increased mean task execution speeds, although these were still far from those obtained in the reference Open condition.

The intern however performed the task notably faster than novice subjects in all conditions. Also, the reductions in speed observed when providing visual, tactile or combined feedback (conditions Visual, TacCont and TacCont+Visual) are very limited when compared to novice performances. As with both previous criteria, these results remain anecdotal and do not carry the same significance as those obtained with the novice subjects.

Table 3.5 sums up the observed differences in means between conditions along with associated statistical significance.

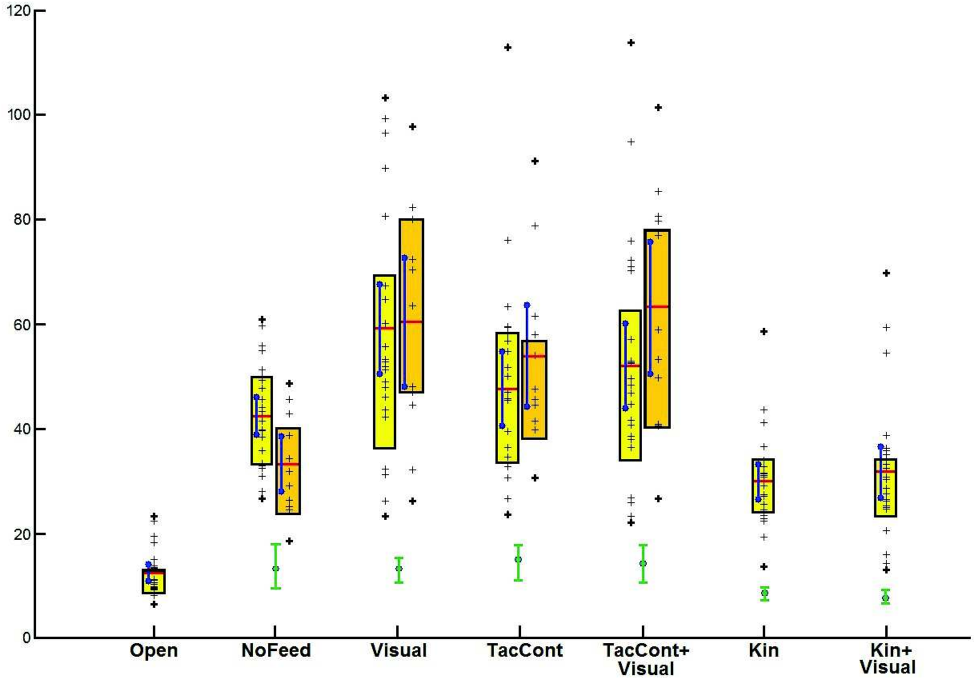


Figure 3.10: *Mean subject TCT (in [s]) for each condition. Results from experiment 1 are shown in yellow, results from experiment 2 in orange, performances for the intern in green; data points shown as black crosses, interquartile range shown by coloured boxes, sample means as horizontal red lines and confidence intervals for population means as vertical blue lines. The spread of the intern's performances is shown by the vertical green bars, his mean performance by the green circle with blue contour.*

### Subjective user assessment

Based on our questionnaire evaluating user perception of the benefit of this feedback (see figure 3.11 for complete results), combining vibrotactile with visual feedback (TacCont+Visual) seems to significantly correlate with a drop in self-assessed performance (mean score drop by 0.1 ($p<0.05$)) despite the improvement in measured performance. These results may indicate a negative effect from a perceived excess of information in condition TacCont+Visual, leading to more mental fatigue and perceived confusion for the user. The Visual feedback condition was evaluated as being significantly clearer than the tactile feedback condition TacCont (mean score difference of 0.18 ($p<0.05$)), which in turn outperformed condition TacCont+Visual (though not significantly). Condition TacCont+Visual was evaluated as significantly easier to use than condition TacCont (mean score difference of 0.1 ($p<0.05$)), but harder to use than the Visual condition (mean score difference of 0.27 ($p<0.01$)). This result could also reflect the perceived complexity of dealing with tactile and visual cues simultaneously.

### Confounding factors

As we are aware of evidence supporting possible influence of factors such as musicianship and experience with video games and Virtual Reality (VR) ( [176]) on performances in laparoscopic surgery or similar tasks, we compared performances for each of the metrics used while grouping subjects respectively by gender, musicianship, experience with video games and prior experience

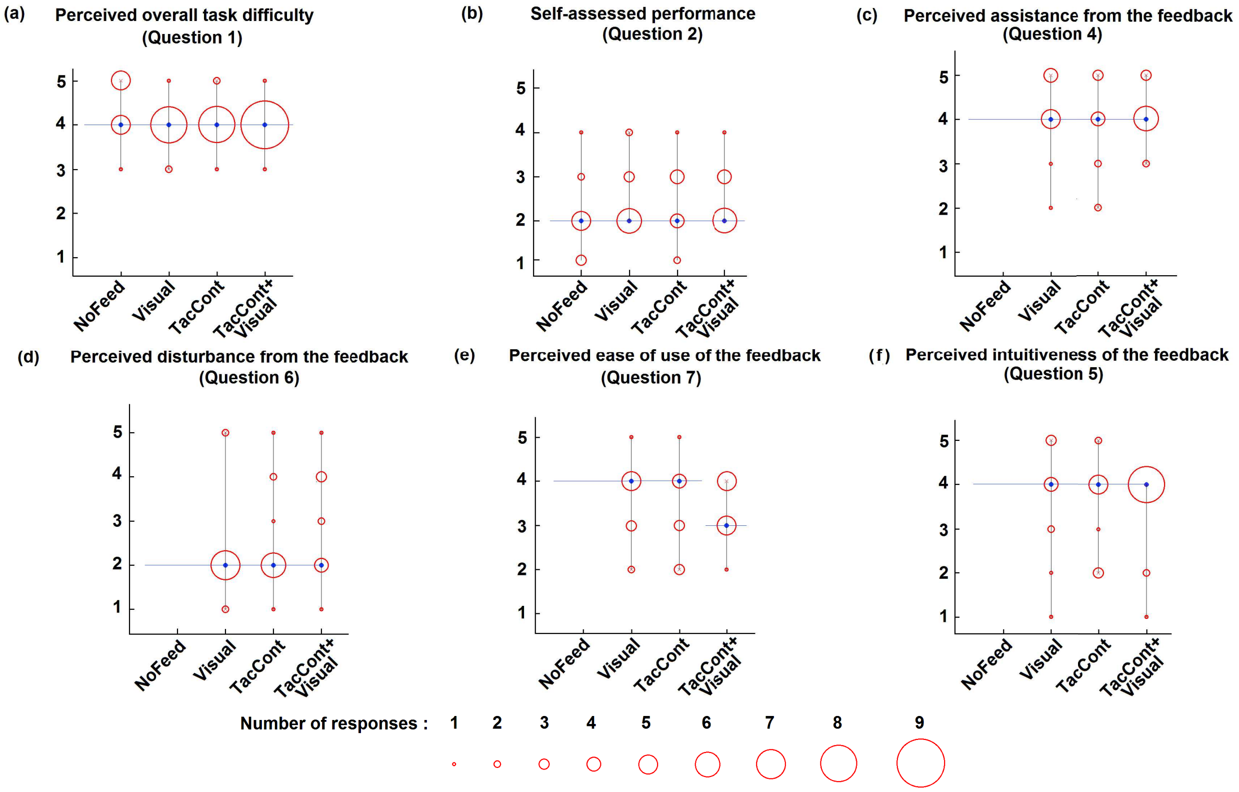


Figure 3.11: *Subjective evaluation of feedback and performance as per the questionnaire described in table 3.2. The results for question 3 "Did you understand the feedback" are omitted as the question served the purpose of evaluating the reliability of other results and was consistently answered with "Agree"(4) or "Strongly agree"(5). Median responses for each condition are shown in blue, and the distribution of responses is shown through red circles varying in diameter proportionally to the number of responses collected at each response level for each condition (the larger the circle, the more responses collected - see legend on figure for precise numeric significance)*

**Table 5.** Differences in mean Task Completion Time (TCT) between conditions and associated statistical significance. Lack of significance below $\alpha=0.1$ is shown by NS (Not Significant). For the relevant conditions, results from experiment 1 are highlighted with ($^a$), and those from experiment 2 with ($^b$)

| | NoFeed | Visual | TacCont | TacCont +Visual | Kin | Kin +Visual |
|---|---|---|---|---|---|---|
| Open | +29.9 s<br>($p<0.01$) | +46.5 s<br>($p<0.01$) | +35.1 s<br>($p<0.01$) | +39.4 s<br>($p<0.01$) | +17.4 s<br>($p<0.01$) | +19.2 s<br>($p<0.01$) |
| NoFeed | | +16.6 s$^a$<br>+27.08 s$^b$<br>($p<0.05$)$^a$<br>NS$^b$ | +5.2 s$^a$<br>+20.63 s$^b$<br>NS | +9.6 s$^a$<br>+29.84 s$^b$<br>NS$^a$<br>($p<0.01$)$^b$ | -12.5 s<br>($p<0.01$) | -19.2 s<br>($p<0.05$) |
| Visual | | | -11.4 s$^a$<br>-6.45 s$^b$<br>NS | -7.1 s$^a$<br>+2.75 s$^b$<br>NS | -29.1 s<br>($p<0.01$) | -27.3 s<br>($p<0.01$) |
| TacCont | | | | +4.3 s$^a$<br>+9.2 s$^b$<br>NS | -17.7 s<br>($p<0.01$) | -15.9 s<br>($p<0.05$) |
| TacCont +Visual | | | | | -22.1 s<br>($p<0.01$) | -20.2 s<br>($p<0.01$) |
| Kin | | | | | | +1.8 s<br>NS |

with haptic interfaces.

Our sample populations were distributed as follows according to the criteria mentioned above:

### Experiment 1

- Gender : 16 male, 7 female;
- Experience with video games and VR : 11 experienced, 12 inexperienced;
- Musicianship : 6 musicians, 17 non-musicians;
- Experience with haptic interfaces : 14 experienced, 9 inexperienced;

### Experiment 2

- Gender : 7 male, 4 female;
- Experience with video games and VR : 7 experienced, 4 inexperienced;
- Musicianship : 3 musicians, 8 non-musicians;

- Experience with haptic interfaces : 6 experienced, 5 inexperienced;

No notable differences were observed between groups for the three metrics we considered, i.e. relative Time on Target (rToT), Deviation Amplitudes (DA) and Task Completion Times (TCT). Thus, we treated our populations as homogeneous in the following analysis of results.

#### 3.2.5.3 Discussion

##### Differences in performances between experiments

The most notable differences observed between experiments are those in the baseline performance in laparoscopic surgery (NoFeed) : In experiment 2, subjects perform the task faster in the mean (lower Task Completion Times) but with less on-target precision (lower relative Time on Target) than in experiment 1. This can be explained by differences in the distributions of speed-accuracy trade-off – which however does not amount to the claim that subjects in experiment 2 consistently chose a different speed-accuracy trade-off when compared to experiment 1 as the datasets for both experiments significantly overlap.

A surprising observation in condition NoFeed however is the fact that although subjects in experiment 2 performed the task faster than in experiment 1, they also displayed far less spread in their Deviation Amplitudes (DA), resulting in better precision than for experiment 1 concerning this criterion. We therefore believe that there may have been fatigue effects or a possible negative after-effect from performing in the reference Open surgery beforehand in experiment 1 (it should be noted that the number of task repetitions was only 5 in experiment 1, so any after-effect would probably have consequences visible in the results). These factors could negatively influence the spread in deviation amplitudes and rToT in experiment 1, and the redesign of the protocol in experiment 2 would have remedied this.

The improvement patterns in the means between conditions NoFeed, Visual, TacCont, TacCont+Visual (respectively: laparoscopic surgery without, then with visual, tactile and combined feedback) are consistent between both experiments for all three criteria (rToT[17], DA[18] and TCT[19]) despite being quantitatively different, leaving us confident that they are a good basis for the conclusions drawn in the present paper.

Concerning the quantitative nature of these differences, the general trend is towards spread in performance being equal or lower in experiment 2 compared to experiment 1 for any given condition and criterion pair. Furthermore, differences in means between condition pairs for a criterion are also larger or equal in experiment 2 when compared to experiment 1. This is why we believe the protocol in experiment 1 introduced a significant fatigue bias, which would tend to increase spread in subject performances and thereby mask observable differences in mean performance introduced by the differences in the provided feedback.

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[17] rToT : relative Time on Target

[18] DA : Deviation Amplitude

[19] TCT : Task Completion Time

### Degradation in performance between open and laparoscopic surgery

Relative Time on Target (rToT) is significantly worse in all laparoscopic conditions (except robot-assisted laparoscopic without and with visual feedback - Kin and Kin+Visual) than in the reference Open condition though spread is largely reduced. In laparoscopic settings, whether informative feedback is presented or not, it is significantly harder for a novice subject to maintain the tip of the instrument close to the target while moving than it is in open surgery. This is understandable when considering the limitations in dexterity discussed in the introduction. The larger spread in condition Open can be attributed to the fact that though it is easier to maintain the instrument tip on target, condition Open also allows faster movement between pegs, which can easily exacerbate errors in on-target accuracy. The reduction in possible movement speeds between open and laparoscopic surgery appears particularly clearly in the significant increase in Task Completion Times (TCT) between conditions Open and condition NoFeed (1.65x in Experiment 1 and 2.38x in Experiment 2) which cannot be explained by additional attention to precision (significant reductions in relative Time on Target (rToT) as well as increases in Deviation Amplitudes (DA)).

### Improvement of performance through tactile and visual feedback

The introduction of solely informative visual, tactile and combined feedback (conditions Visual, TacCont and TacCont+Visual) leads to consistent improvements in terms of precision but at the cost of reduced task execution speeds for novice subjects. This is to be expected as the availability of feedback leads subjects to pay more attention to their deviation and take the time necessary in correcting the movement of their instrument.

Deviation Amplitudes (DA) are significantly reduced in laparoscopic settings thanks to provision of combined visual and tactile feedback (TacCont+Visual). This leads us to conclude that both forms of feedback either effectively communicate information allowing for correction through redundancy over different sensory channels, or that both forms of feedback somehow compensate for each other's weaknesses when combined. The observed minor drop in task execution speed observed in condition TacCont+Visual when compared to the tactile feedback condition (TacCont) or the visual feedback condition (Visual) is associated with better performances in terms of both precision criteria, thus hinting at a greater focus on precision objectives rather than speed objectives when redundant multi-modal feedback was available.

The intern showed improvement patterns comparable to those observed in novices yet with only a very limited degradation in task execution times. This would seem to indicate that although the intern favoured a speed-accuracy trade-off where task execution speed was prioritised, he was able to take advantage of the provided information to improve his precision without negative impacts on his speed. As such, it would appear that exclusively informative feedback may be of most use to experienced laparoscopic surgeons.

### Improvement of performance through co-manipulation

The use of a parallel co-manipulator implementing soft virtual fixtures improved both novices and the intern's performance in terms of speed and accuracy. This is understandable as subjects are physically limited in their deviation from the target and may relinquish a degree of control to the robotic co-manipulator in order to achieve high precision without needing to slow their movements.

The addition of visual feedback to the robotic assistance through virtual fixtures (condition KV) led to insignificant improvements over condition Kin (robotic assistance without visual feedback), leading us to believe that in such a setup virtual fixtures are sufficient and there is little to be gained from multimodal feedback.

For both conditions Kin and Kin+Visual, the intern showed greater relative improvements in performance (both for speed and accuracy) than those observed with novice subjects, hinting at a possible greater benefit of robotic assistance for experienced users.

Although performance was far better in conditions Kin and Kin+Visual than in all other feedback conditions, it should be noted that providing such feedback in the operating room is limited by the cost of the devices used, potential safety issues raised through the shared control between robot and surgeon and problems of clutter and installation times in the operating room. If the necessary hardware becomes available in operating rooms and the safety issues that arise are dealt with, there is no doubt that such assistance is optimal, but until then forms of feedback similar to those presented in conditions Visual, TacCont and TacCont+Visual (visual, tactile and combined feedback)) may be interesting low-cost and easily implemented alternatives for improving surgeon performance.

#### 3.2.5.4 Conclusion on our initial experiments

We confirm previous results indicating that in a 1D guidance task, visual and cutaneous vibrotactile feedback as well as their combination leads to improved performances in terms of precision at the cost of increased TCTs. Our shortened and fully randomized experimental protocol minimized contributions from learning effects in the observed differences.

We also compared data for novice subjects with an intern's performances, showing no significant differences in terms of precision but a significantly lower Task Completion Times (TCT) at equal precision. Overall, the patterns of improvement over the reference condition obtained in novice subjects for conditions Visual, TacCont, TacCont+Visual, Kin and Kin+Visual can be found again in the intern's performance, leading us to believe in a good chance of our results being generalizable to a population of surgeons with similar results. Interestingly, the intern performed better in the tactile conditions TacCont and TacCont+Visual than in condition Visual , which may indicate a lower cognitive load when using feedback presented though tactile cues instead of visual cues. Similarly to our previous experiments, we note that visual feedback still seems beneficial, particularly in avoiding larger deviation amplitudes. Finally, the intern's TCTs seemed much less affected by the provision of feedback, which stands out as a particularly interesting feature when considering clinical applications of such feedback.

Analysis of novice subject's perception of the usability and impact of the provided feedback on their performance revealed that presence or lack of feedback does not seem to have any significant effect on the perceived difficulty of the task. The self-assessed performance of the users is however significantly improved in the visual feedback condition Visual over the combined visual and tactile feedback condition TacCont+Visual, indicating a potentially disturbing effect from the excess of information provided in condition TacCont+Visual. Overall, the subjects seemed to understand the feedback well in all conditions, with significantly better understanding reported for the visual feedback condition Visual when compared to the tactile feedback condition TacCont. We believe this to be linked to the fact that our visual feedback through the bar-graph provided additional directional information whereas the vibrotactile feedback only provided information on the magnitude of the deviation from the target and was harder to interpret. When comparing perceived assistance from the various forms of feedback, all conditions seem to do equally well. All forms of feedback are perceived as equally easy to use, with the exception of the combined visual and tactile feedback condition TacCont+Visual, which scores significantly lower than the tactile feedback condition TacCont, hinting at complexity arising from an excess of information. This is reflected in the perceived intuitiveness of the provided feedback, where TacCont+Visual again scores significantly lower than the visual feedback condition Visual. When asked about potential disturbances in task execution arising from the feedback, subjects tend to be undisturbed, with no significant differences between forms of feedback.

These promising initial results for the use of cutaneous feedback are leading us to consider extending the evaluation of such forms of feedback to more complex guidance tasks (i.e. 2D and 3D trajectories), while performing a comparative evaluation of various forms of tactile feedback in order to improve performance and intuitiveness of the feedback. Furthermore, there was little to no contact between the instrument and structures placed within the trainer in this study. In order to assess the viability of such forms of feedback for clinical applications, we are currently working on evaluating their use in tasks involving physical interaction within the trainer, e.g. dissection or suturing tasks. Developing an experimental protocol around a more complex task involving actual interaction with the environment within the laparoscopic trainer will also require subjects to focus more on the task at hand and the laparoscopic image, thus highlighting potential effects of various forms of feedback on the attention given to the task being performed. Finally, we aim to test generalizability of our results to a population of surgeons.

### 3.2.6 Quantifying user reactions to tactile and visual feedback components

#### 3.2.6.1 Introduction

The initial exploratory experiments on haptic and multi-modal assistance to instrument navigation have shown the potential of various forms of feedback in improving overall gesture quality, mainly in terms of precision criteria. However, it remains to be determined whether the measured improvements are due to an improvement in the reaction to deviation movements, an improvement in the capability of aiming for a target or a combination of both.

To attempt to better understand this and the role of the various information components (indication of deviation direction, distance or both) in assisting parts of the gesture (initial reaction to a deviation, correction and final stabilisation around the target), we designed a simplified guidance experiment described in the following.

#### 3.2.6.2 Materials and methods

##### Experimental set-up and task

Subjects were once again placed in front of a laparoscopic trainer [20] equipped with a centred marker indicating the rest position between trials. Subjects manipulated laparoscopic forceps fitted with a magnetic tracking probe[21] at the handle and observed the scene on a 24" monitor placed directly in front of them (see fig 3.12).

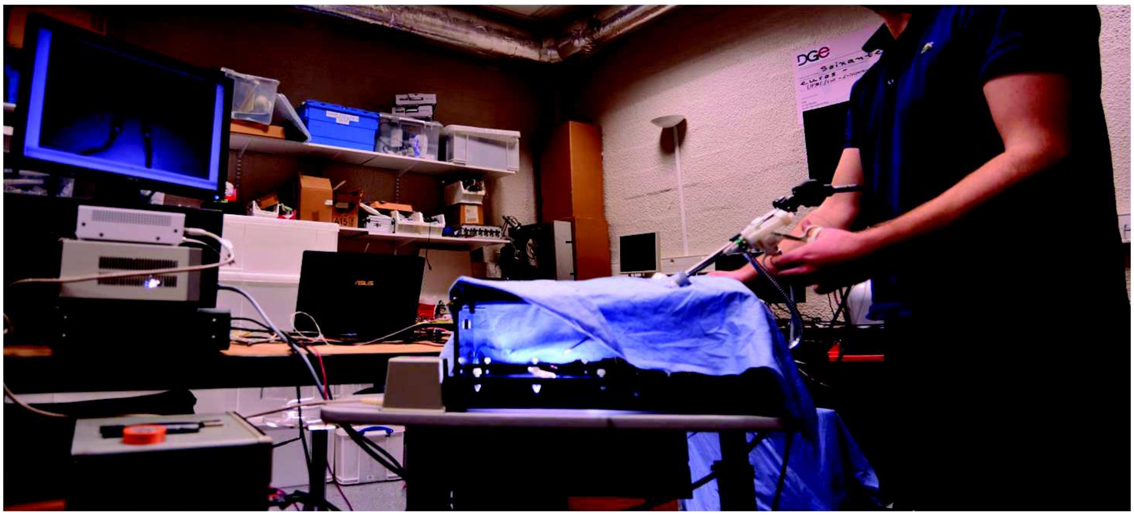

Figure 3.12: *Experimental set-up: The subject (right) manipulates standard laparoscopic forceps fitted with a magnetic tracking probe allowing to compute the instrument tip position in real time while observing the endoscopic camera image on a 24" screen placed directly in front of him.*

Subjects were tasked with maintaining the tip of their instrument within a target plane that would stay parallel to their sagittal plane. They initially positioned the instrument tip on a physical reference point coinciding with the target plane's resting position (see fig.3.13 left). The experimenter then launched the trial, upon which a short visual indication of the future direction of movement of the target plane was After a random delay time, the target plane would shift to the left or right as per the prior indication. The distance d of the shift was randomly selected between 20mm and 120mm. As soon as the target plane shifted, the subjects started receiving feedback on their current deviation from the plane. Using said feedback, they were to move the instrument tip back to the new position of the plane as quickly and precisely as possible (i.e. minimizing overshoot and oscillation around the target).

Positional data on the instrument tip were obtained by fitting the instrument handle with a magnetic tracking probe whose position was recorded in space by placing the tracker base unit just behind the laparopscopic trainer (see fig. 3.12). Positional data were recorded at approx 250Hz through custom software.

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[20] STORZ Szabo-Berci Pelvitrainer

[21] Ascension TrakStar

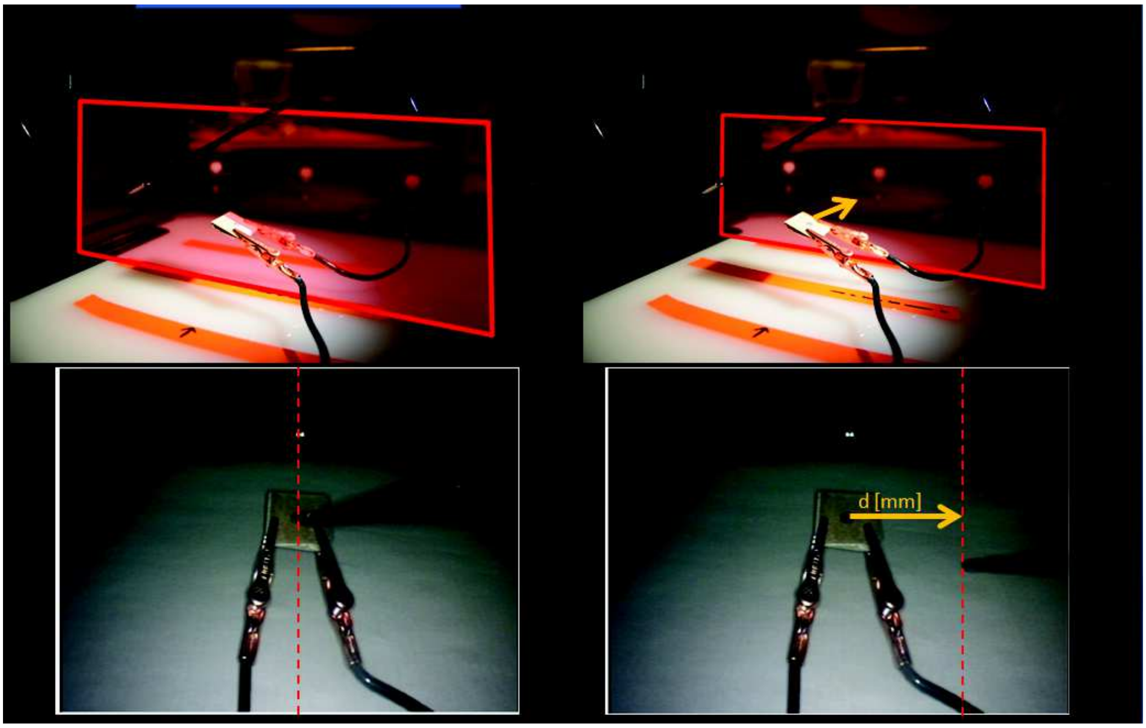

Figure 3.13: *Experimental task: Initial (resting) position shown on the left. The instrument is aligned with the physical reference by the user, corresponding to no deviation from the target plane's initial position. After a randomly varying delay, the target plane shifts to the final position (to the left or right) in a step randomly varying between d=20mm and d=120mm.*

**Table 6.** Evaluated feedback conditions

| Condition | Description |
|---|---|
| TacPuls-f | Pulse vibrotactile feedback : Identical to NoFeed, but subjects were provided with continuous vibrotactile feedback proportional to their current deviation. |
| TacPuls-f + Visual | Pulsed vibrotactile + Visual feedback : Identical to TacCont, with the addition of visual feedback as described above. |

### Evaluated forms of feedback

In addition to performing the tasks in the conditions NoFeed, Visual, TacCont and TacCont+Visual as described for the previous experiment (section 3.2.5), subjects performed the present experiment with a variation of the tactile feedback scheme as described below.

Three sub-experiments (blocks) were conducted :

- Only amplitude information was provided, using a single ERM motor as in the previous experiment or one-sided bargraph with continuously varying height.
- Only direction information was provided, using a two-sided bargraph as in the previous experiment, but with only a binary state (full or empty) or a pair of ERM motors vibrating in a fixed manner.

- Both amplitude and direction information were provided, using a two-sided bargraph with continuously varying height or a pair of ERM motors vibrating proportionally to the deviation as per the chosen vibrotactile encoding scheme.

### Sample population and trial randomization

Nine novice subjects took part in the experiment, performing fully randomised sequences of all experimental conditions in each of the three blocks. The order of the three blocks was also randomly assigned.

### Evaluation metrics

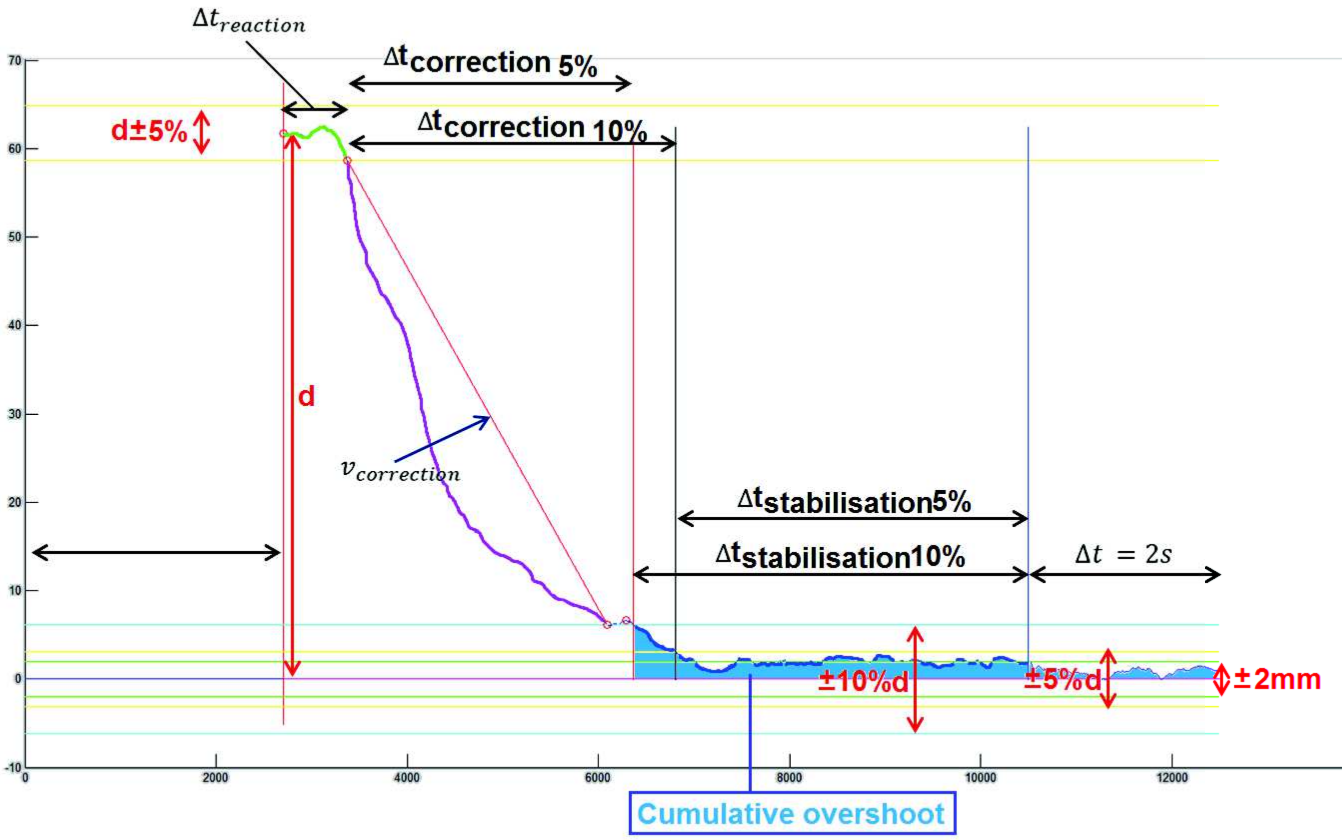

Figure 3.14: *Example of a deviation curve with indication of the measured values and evaluation metrics. The initial movement of the target plane, increasing the deviation to an amplitude of d[mm], takes place after a random waiting time. As long as the subject's deviation from the target stays within d ± 5%, we assume the correction phase has not begun. Once this threshold is reached, the reaction time is deduced and the correction phase begins. Two further thresholds are defined : The first moment from which deviation permanently stays below ± 10% of d and the first moment from which deviation permanently stays below ± 5% of d. These allow us to calculate the correction and stabilisation times, which in turn allow calculation of the correction speed, cumulative overshoot and number of peaks during stabilisation.*

Figure 3.14 graphically shows the various metrics chosen to evaluate the efficiency of the evaluated forms of feedback and their components on performances in the three stages of the corrective movement: The initial reaction to a deviation (green part of the deviation curve), the corrective movement itself (purple part of the deviation curve) and the final stabilisation around the target (blue part of the deviation curve). The definition of the various metrics is given in the following discussion.

### 3.2.6.3 Results and discussion

#### Initial reaction to a deviation

The critical criterion for optimal reaction to feedback indicating a deviation is the reaction time, i.e. the time between onset of the deviation and the beginning of corrective action. The lower the reaction time, the more efficient the feedback in preventing large deviations and allowing for swift correction. Reaction times were evaluated using $\Delta t_{reaction}$ (see fig.3.14), calculated as the time (in ms) elapsed between onset of the deviation and the reaction instant defined as the first time the deviation value goes outside of the [0.95d ; 1.05d] range.

#### Reaction time (speed criterion)

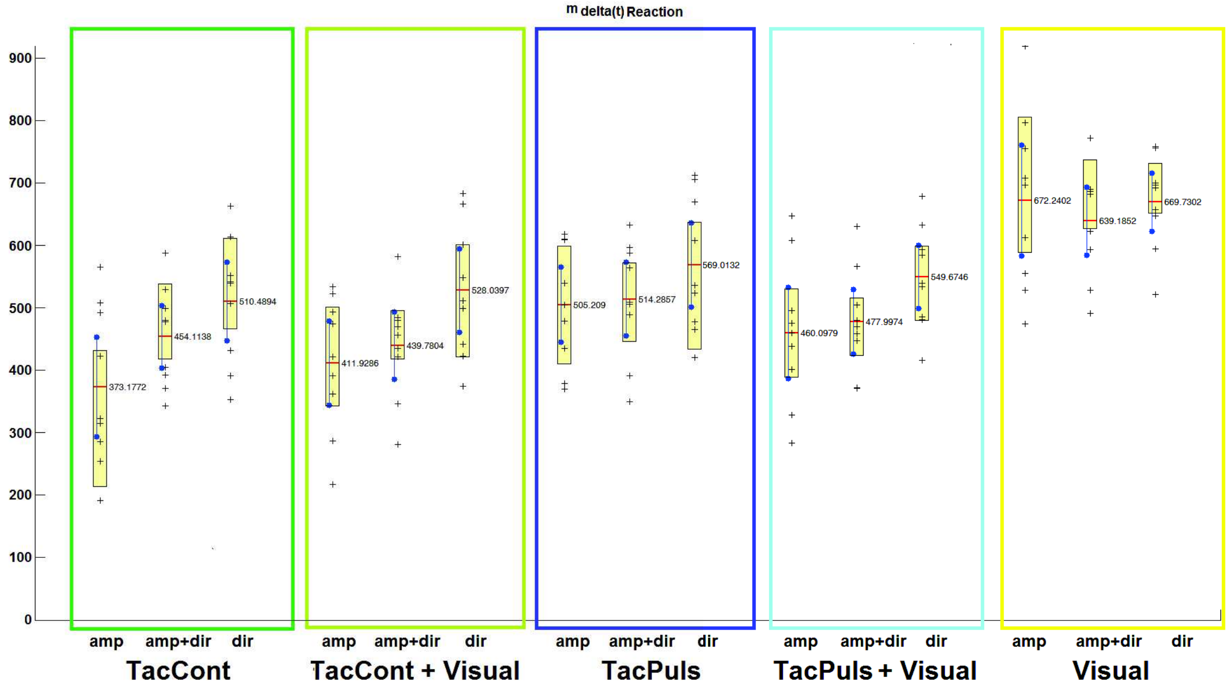

Figure 3.15: *Reaction times : delay between shift in target position and beginning of corrective movement, as defined by the first instant where a movement is made in the direction of the target with an amplitude above* 5%. *The shorter the better (indicate feedback is rapidly detected and clear enough to allow quick correction). Performances are grouped in boxes by condition. For each condition, performances are differentiated depending on whether only deviation amplitude information is provided (amp), only direction information is provided (dir) or both direction and amplitude information are provided (dir+amp). Data points are indicated as crosses. Sample means are indicated by horizontal red bars, the confidence interval for the mean by dark blue vertical blue bars, and the interquartile range by the orange filled box.*

Subjects performed worst of all in the visual feedback condition, with no notable differences between in performance depending on the information components provided.

Subjects performed best of all in the continuous vibrotactile condition (TacCont), with a noticeable edge when only amplitude information was provided. Providing direction information alone or in combination with amplitude information does not make a significant difference. The addition of visual feedback (Condition TacCont+Visual) seems to yield no change, positive or negative, except a slight deterioration when only amplitude information is provided. This would seem to indicate that when multi-modal feedback is provided, subjects react to the continuous vibrotactile feedback with highest priority. The improvement in performance when only amplitude information is provided may be due to the fact that as subjects had prior knowledge of the direction in which the target would move through the arrow presented visually before each trial, they skipped an interpretation step which is present when directional information is also provided.

Pulsed vibrotactile feedback and combined visual and pulsed vibrotactile feedback (Conditions TacPuls and TacPuls+Visual) yielded slightly worse performances than continuous vibrotactile feedback, with no notable differences observable between the provided information components.

### Deviation correction phase

During the deviation correction phase, interesting evaluation criteria are the speed (measured by the movement speed) and precision (measured by the overshoot upon first reaching the target) of the correction movement. Correction speed was using $V_{corr,10pct}$ and $V_{corr,5pct}$ for speed, respectively calculated as the ratio $0.85d/\Delta t_{correction,10pct}$ and $0.9d/\Delta t_{correction,5pct}$ (see fig.3.14). In terms of speed and precision during the corrective movements, no notable differences were observed between conditions or between information components. Overall, subjects were slower and more imprecise when using pulsed vibrotactile feedback alone (condition TacPuls), which may be due to the fact that close to the target the inter-pulse interval grows large and can be confused with the lack of vibration indicating the "on-target" state.

### Stabilisation around a target

Once the target was reached, the quality of stabilisation around it was evaluated in terms of speed (using the times needed to stabilise below the $0.1d$ and $0.05d$ limits respectively), accuracy (by measuring cumulative overshoot beyond given thresholds around the target) and efficiency (by evaluating stabilisation movement smoothness).

#### Speed

The fastest stabilisations are clearly achieved in the continuous tactile (without or with visual feedback) condition, which also have the fastest transition between large and small oscillations

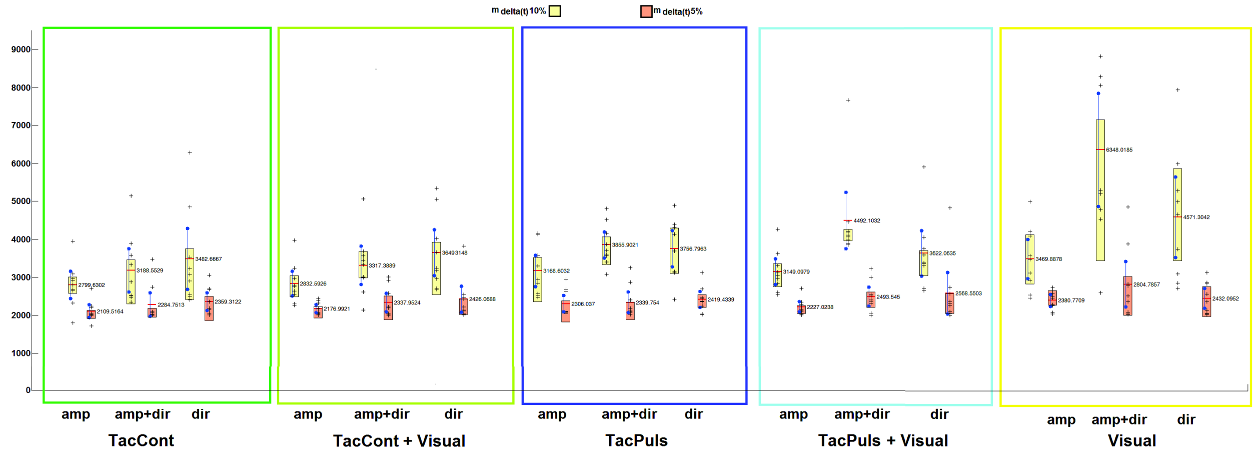

Figure 3.16: *Stabilisation times, respectively for the 0.1d range around the target (light orange) and the 0.05d range around the target (light yellow). The shorter the better, indicating swift stabilisation on the target. The closer the orange boxes are to the yellow boxes, the lower the overall oscillation amplitudes during the stabilisation phase. Performances are grouped in boxes by condition. For each condition, performances are differentiated depending on whether only deviation amplitude information is provided (amp), only direction information is provided (dir) or both direction and amplitude information are provided (dir+amp). Data points are indicated as crosses. Sample means are indicated by horizontal red bars, the confidence interval for the mean by dark blue vertical blue bars, and the interquartile range by the orange filled box.*

around the target. No significant difference is observable between different information components, with only a slight advantage observable when only directional information is provided. This could indicate the fact that the higher speed of information delivery when compared to TacPuls combined with the fact that tactile feedback draws attention to cues more than visual feedback are powerful contributors to efficient stabilisation. The worst performances are achieved using visual feedback alone, with significantly longer times spent oscillating widely around the target. Pulsed vibrotactile feedback yields intermediary performances, close to those obtained with continuous vibrotactile feedback but slightly worse. The previously discussed differences mainly affect the large oscillation component in the stabilisation phase (0.1d threshold). The amplitude information (amp) component seems to be the most effective overall, though not by far. This seems to indicate that during stabilisation users rely more on notification-type information indicating either a "deviation" or "no deviation" state, rather than trying to obtain information on the direction in which to correct their deviation. Combinations of visual and tactile feedback yield no improvements, indicating that the visual component was probably ignored in the presence of tactile feedback, or may even have acted as a distractor seen as the performances slightly worsen, though the significance of these differences does not allow for more than speculation on this point.

### Accuracy

The best performances are observed for continuous tactile feedback combined with visual feedback (Condition TacCont+Visual), with slightly lower cumulative overshoots during the stabilisation phase than continuous tactile feedback alone. In both cases, there is little difference between the provided information components (dir, amp or amp+dir), with a slight edge to the performances obtained with amplitude information alone, mirroring the observations made for the

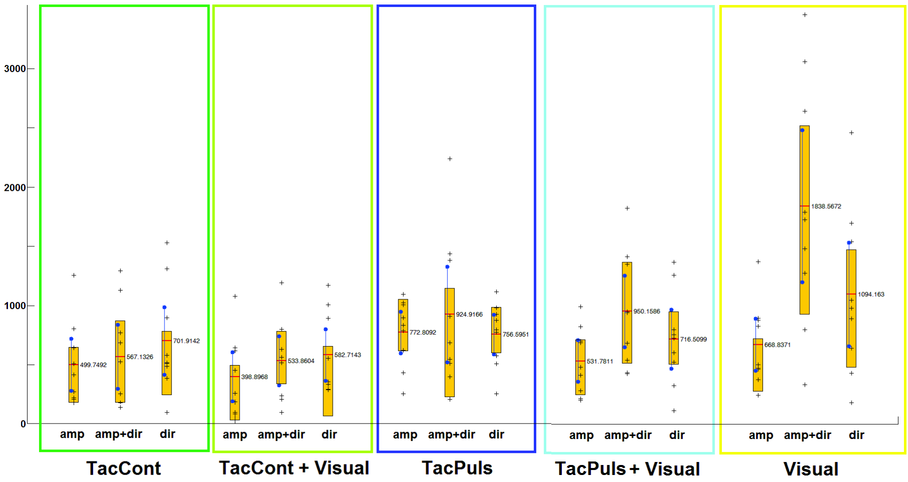

Figure 3.17: *Cumulative overshoot during the stabilisation phase : integral of deviations beyond the 2mm tolerance around the target over the stabilisation period. The lower the better, indicating short stabilisation times at low oscillation amplitudes around the target. Performances are grouped in boxes by condition. For each condition, performances are differentiated depending on whether only deviation amplitude information is provided (amp), only direction information is provided (dir) or both direction and amplitude information are provided (dir+amp). Data points are indicated as crosses. Sample means are indicated by horizontal red bars, the confidence interval for the mean by dark blue vertical blue bars, and the interquartile range by the orange filled box.*

speed criteria. The switch between motors in the direction information (dir) component may have acted as a disturbance to the users, preventing them from properly limiting oscillation around the target. Pulsed vibrotactile feedback (with or without visual feedback) yields performances close to those obtained with continuous vibrotactile feedback, with slightly longer large oscillation times. Overall the main differences observed are in the duration of large oscillations around the target, and all forms of feedback more or less perform on par for the small oscillations around the target.

#### Efficiency

The smoothest stabilisation movements are obtained using pulsed tactile feedback combined with visual feedback (TacPuls+Visual) closely followed by visual feedback alone, with little differences between provided information components - except in the case of visual feedback and large oscillations, where amplitude alone yielded better performances than its counterparts. In tactile feedback conditions, especially in the absence of visual feedback, the direction component seems decisive in improving the smoothness of the stabilisation movement.

### Concluding discussion

Continuous vibrotactile feedback yields the best reaction times in the event of a deviation, probably because of the immediate nature of the signal and the fact that tactile feedback forces

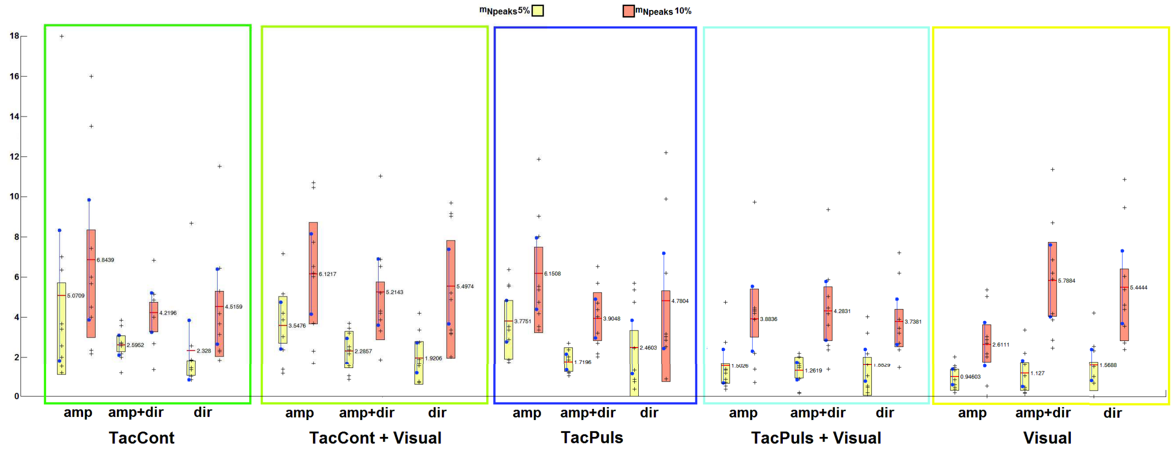

Figure 3.18: *Number of oscillation movements around the target during the stabilisation period, as indicated by peaks of the thresholded deviation curve respectively at 0.1d (light orange) and 0.05d (light yellow). The lower the better, indicating a smoother stabilisation around the target. Performances are grouped in boxes by condition. For each condition, performances are differentiated depending on whether only deviation amplitude information is provided (amp), only direction information is provided (dir) or both direction and amplitude information are provided (dir+amp). Data points are indicated as crosses. Sample means are indicated by horizontal red bars, the confidence interval for the mean by dark blue vertical blue bars, and the interquartile range by the orange filled box.*

attention to the presence of a deviation. This is coherent with continuous tactile feedback yielding the best results during the stabilisation phase. Visual feedback seemed to play a beneficial role in smoother movements, both during the transition from corrective motion to stabilisation motion around the target.

### 3.2.7 Haptic and multi-modal feedback for assistance to navigation during a cutting task

Our prior experiments have led us to conclude that feeding back 1D information on positional error with respect to a target has been shown to improve accuracy in moving towards targets in free space when no concurrent task is distracting the user. However, this leaves a certain number of crucial open questions when considering applications to laparoscopic surgery. If the user is engaged in a visual-motor task such as precise cutting or suturing, can we still expect to achieve such improvements in accuracy from the provided feedback? When feedback is provided, would the beneficial effect obtained be amplified as the task grows harder? Or on the contrary, would the concurrent task have a distracting effect, diminishing the feedback's effectiveness? And finally, what is the effectiveness of feedback (in particular tactile feedback provided at the hand) when the user is actively engaged in complex motor tasks with the hands manipulating the instruments ?

To attempt to provide some insights into these open questions, we developed an experiment on a navigation task closer to clinical training reality, based on the Fundamentals of Laparoscopic Surgery (FLS) cutting task (FLS Task II) [84]. The FLS provides a series of training and evaluation exercises on basic motor skills required for laparoscopic surgery (Grasping and transferring objects between hands, cutting, ligation, suture throwing and knot tying). Each exercise uses a standardized setup (see fig.3.19) and is accompanied by a pre-defined ideal execution procedure and evaluation metrics.

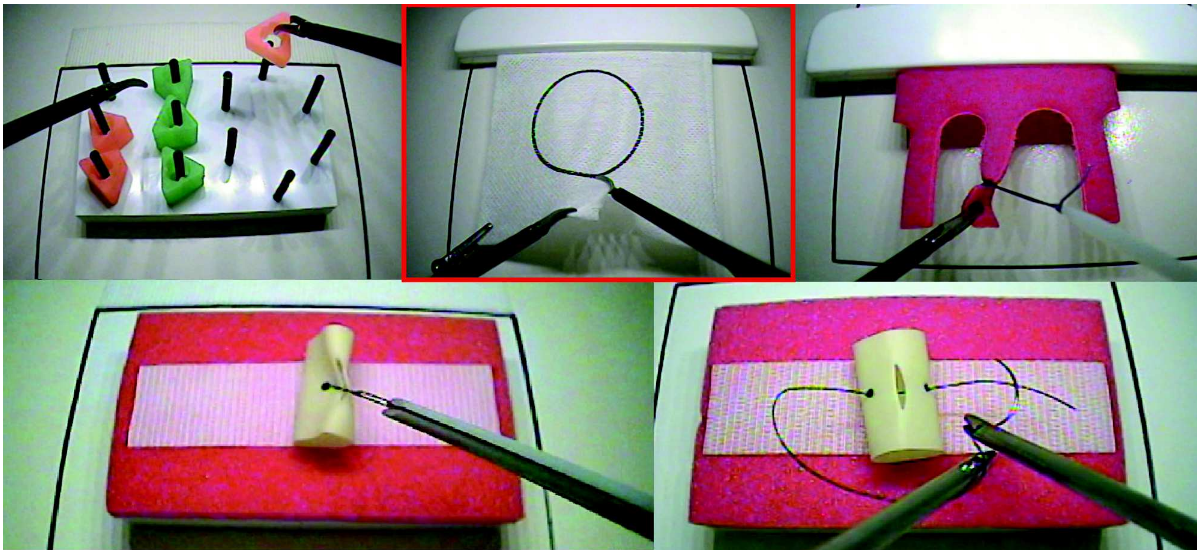

Figure 3.19: *The five modules (tasks) in the fundamentals of laparoscopy training and evaluation programme. From left to right : Task 1 - Peg transfer task with the objective of training bi-manual dexterity; Task 2 - Pattern cut, with the objective of training cutting proficiency; Task 3 - Ligating loop; Tasks 4 and 5 - Suture knot tying with extra-corporeal and intra-corporeal knots respectively.*

For the cutting task (see fig.3.19), the objective is to precisely cut out a pre-marked circle from two-ply gauze within a time limit of 300 seconds. Evaluation of performance is solely based on completion time and maximum deviation from the target circle. Although the FLS guidelines do not specify any imposed sequence for the cutting task and does not specifically evaluated the cutting method used, there is a consensus on the optimal way of cutting to achieve lowest cutting times with minimum effort (see fig. 3.20).

We based our task on this exercise and provided subjects with various forms of feedback in the hopes of assessing the impact of feedback on performance improvement both in the short term and over a training period.

#### 3.2.7.1 Materials and methods

##### Experimental set-up and task

As shown in fig.3.21, subjects were placed in front of a laparoscopic trainer fitted with a holding clamp for installation of the gauzes. Subjects manipulated the gauze to apply adequate tension for cutting using a Storz Maryland dissector in their non-dominant hand. Subjects cut the gauze using a pair of disposable laparoscopic scissors in their dominant hand. The 100 mm x 100 mm gauzes were prepared prior to the experiments and featured a centred 600 mm diameter circle. Subjects observed the scene on a 32 inch monitor placed directly in front of them, while the projected endoscopic image was recorded at a rate of 30Hz by our custom experimental software. The laparoscopic scissors were fitted with passive infrared markers at the handle and tracked using an NDI Polaris tracking system.

Cut gauzes were collected, scanned and processed using custom software that allowed us to

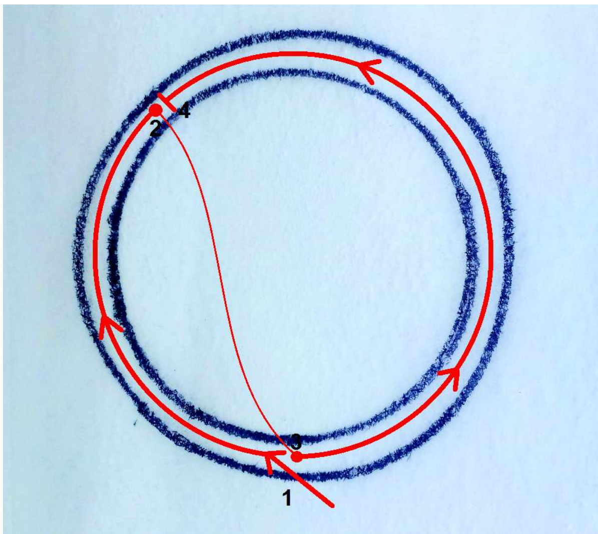

Figure 3.20: *Optimal cutting path for the FLS pattern cut exercise. Cutting begins closest to the surgeon at the bottom centre, along the circle towards the left (segment 1-2). Once the surgeon reaches approximately 11 o'clock position on the gauze, he moves the scissor back to the starting position (movement 2-3) and resumes cutting towards the right (segment 3-4) until the inner part of the gauze comes loose, concluding the trial.*

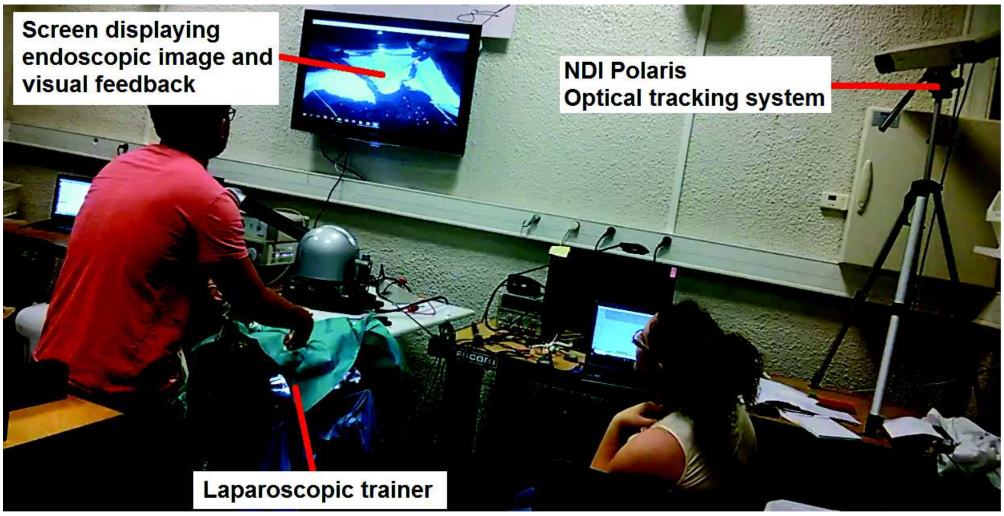

Figure 3.21: *Experimental set-up*

compute the accuracy metrics discussed below.

Subjects were instructed to cut the gauze along the target circle following the sequence shown in fig. 3.20 and discussed above. Their main objective was to cut as close to the target circle as possible, while their secondary objective consisted in attempting to complete the task in the shortest time possible. Subjects were informed that we considered deviations within a 2 mm margin around the target circle as on-target and that the feedback would indicate this accordingly.

### Evaluated forms of feedback

The daily initial and final trials were performed without feedback regardless of the evaluated condition, in order to obtain baseline and progression measurements. Based on our previous findings and for practical reasons, we limited the experimental conditions to a total of four :

- Reference condition without feedback (NoFeed) :
  Subjects performed the required number of repetitions of the task without any feedback provided. This condition served to establish reference performance levels for each session and a reference learning curve (much like that which would be observed for surgeons in training).
- Visual feedback (Visual) :
  Subjects performed the task while receiving visual feedback on their current deviation from the target circle. Visual feedback was provided in the form of an on-screen coloured circle roughly following the instrument tip in the endoscopic image, whose diameter varied continuously proportionally to the computed absolute value of radial deviation from the target circle. When within the 2mm tolerance margins around the target, the circle was coloured green. When deviating outside of the margins towards the exterior of the circle, the circle turned red, and when deviating outside of the margins towards the interior of the circle, the circle turned yellow. The visual feedback thus provided both an indication of magnitude and direction of deviation in a manner that was minimally distracting from the endoscopic image and the task at hand.
- Continuous vibrotactile feedback (TacCont) :
  Subjects performed the task while receiving continuous vibrotactile feedback provided by a pair of ERM[22] vibration motors attached to the subject's hand. When within the 2mm tolerance margin around the target, the motors did not vibrate. When deviating towards the outside of the circle, the top motor vibrated with an intensity proportional to the magnitude of radial deviation. Similarly, when deviating towards the inside of the circle, the bottom motor vibrated with an intensity proportional to the magnitude of radial deviation.
- Combined visual and continuous vibrotactile feedback (TacCont+Visual) :
  Subjects performed the task while receiving a combination of visual feedback (Visual) as described above and of continuous vibrotactile feedback (TacCont) as described above.

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[22] Direct-current driven Eccentric rotating mass motors - Model: Precision Microdrives PicoVibe 307-100

#### Sample population and trial order

For practical reasons, this experiment was only initially performed with three subjects for each of the four conditions. As subjects were to be engaged for repeated tasks over a 10 day period and initial uncertainties remained as to the effectiveness of the protocol, we chose not to recruit a too large sample population for this initial experiment.

Each subject was therefore assigned one of the four evaluated feedback conditions for the entire 10 days of the experiment: No feedback (NoFeed), Visual feedback (Visual), Continuous vibrotactile feedback (TacCont), and combined visual and continuous vibrotactile feedback (TacCont+Visual). For each daily session, the subject began with a trial without feedback to assess baseline performance, followed by one to three trials with feedback, depending on the time spent on each trial. At the end of each session, a final trial without feedback was performed in order to assess residual improvements over the session with feedback removed.

#### Evaluation metrics

Although the evaluation metrics for the FLS cutting task are only two-fold - Maximum deviation from the circle and task completion time - and provide binary results (i.e. acceptable or unacceptable), we chose to go beyond these in our evaluation to better quantify the impact of feedback on performance and the learning process. Subject performances were evaluated according to the following metrics:

- Speed criterion - Task Completion Time (TCT)

  TCT was measured as the total time in [ms] elapsed between the moment where the subject first reached the circle with the approach cut and the moment the cut-out gauze disc became detached from the surrounding gauze. TCT for each trial was measured in our trajectory recording software.

- Accuracy criterion - Incorrectly Resected Area (IRA)

  The Incorrectly Resected Area is the surface area in [mm$\hat{2}$] of gauze cut outside of the tolerance margin of 2 mm surrounding the target circle. IRA is further subdivided into the incorrectly resected outside area IRA+ and incorrectly resected inside area IRA-. IRA was measured using the same software for analysing the gauze scans as mentioned for the measurement of Deviation Amplitudes.

### 3.2.7.2 Results and discussion

#### Speed criterion - Task Completion Time (TCT)

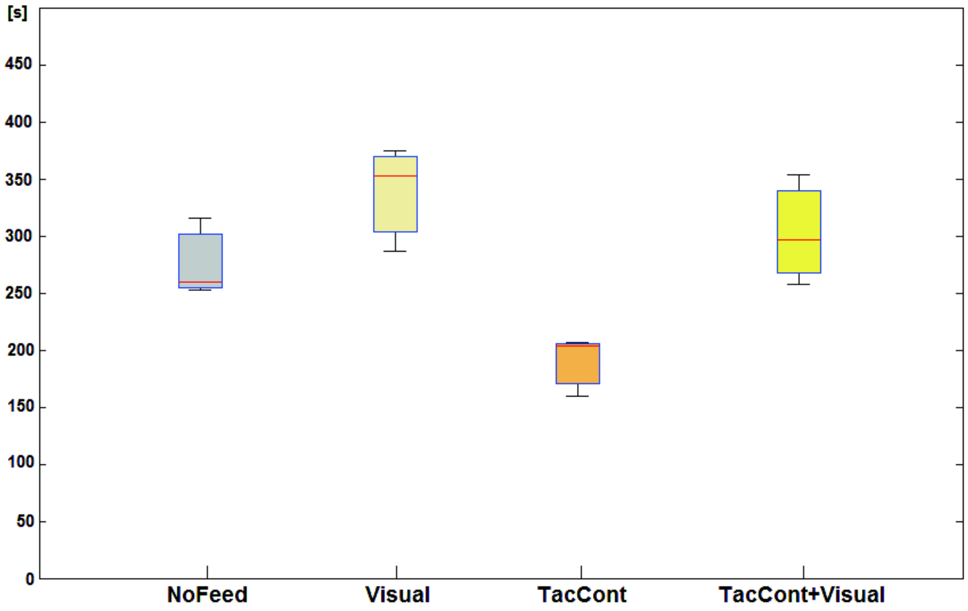

Figure 3.22: *Comparison of mean subject Task Completion Times (TCT) in [s].*

Regarding speed, lower Task Execution Times indicate better performances. Differences in TCT between conditions are not extremely marked, however visual feedback seems to slow task execution while continuous vibrotactile feedback yielded improved task execution times. The combination of both forms of feedback seems to even out, yielding comparable task execution times to the NoFeed condition.

### Accuracy criterion - Incorrectly Resected Area (IRA)

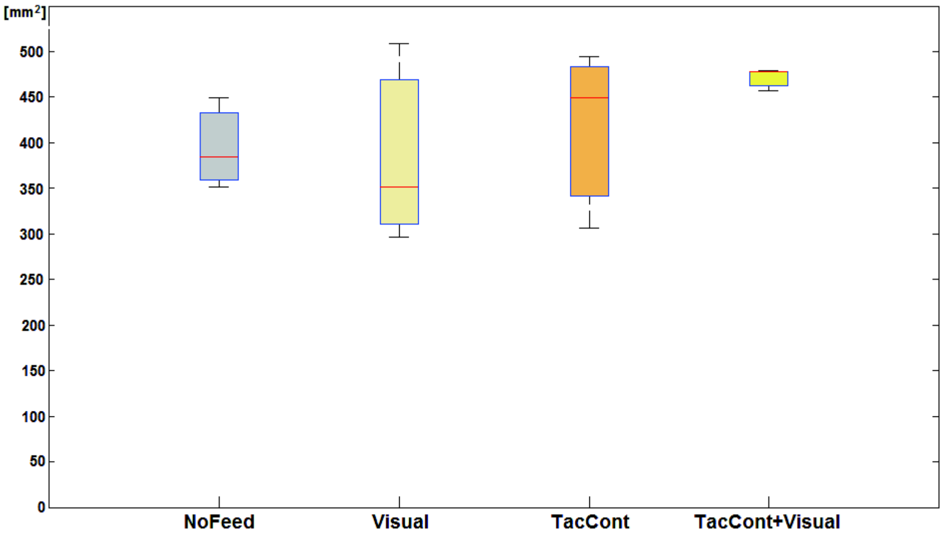

Figure 3.23: *Comparison of Incorrectly Resected Areas (IRA) in [mm2].*

In terms of precision as assessed through the Incorrectly Resected Area, visual feedback seems to yield slight improvement in median precision. This is consistent with previous experiments as well as the fact that in the Visual condition subjects tended to perform the task slower. Both continuous vibrotactile feedback conditions led to degraded performances in terms of precision, especially in the case of condition TacCont+Visual. Considering the faster performances in the TacCont condition and the lack of difference between the TacCont+Visual and NoFeed Task Execution Times, this seems to indicate that combined visual and tactile feedback is detrimental to task performance.

#### Influences of feedback on learning

Initial analysis of learning curves over a one-week period showed no positive or negative after-effect of providing feedback on task performance. Improvements in performance after one week appeared very similar for all four subjects. It is possible that this initial training period was too short to observe possible positive impacts of feedback on speed of learning and that, similarly to what we previously hypothesised concerning the better performance of a skilled intern when using the feedback, subjects require a certain familiarisation both with the task to be performed and the handling of laparoscopic instruments for feedback on their precision to be used effectively.

### 3.2.7.3 Conclusion on haptic feedback for navigation in a cutting task

Our exploratory experiment on using tactile feedback in a cutting task yielded mixed results. On the one hand, there may be a benefit in using the tactile modality rather than the visual modality in this task as indicated by subjective feedback and the drop in speed when visual feedback was provided. Observed improvements were however very limited in magnitude, contrary to the simpler navigation tasks in free space studied previously. Also, the combined Visual+Tactile condition yielded very bad results compared to previous experiments in this new task. This would seem to indicate limitations in the applicability of such feedback to complex trajectories and tasks requiring interaction with the environment.

## 3.3 General conclusions on haptic feedback for assisting surgical tool navigation

In the present chapter, we discussed our work on the use of haptic and multi-modal feedback systems for assisting navigation of laparoscopic instruments towards known surgical targets.

Despite the significant challenges posed by the problems of tracking both surgical instruments and surgical targets, especially in the case of soft, deformable and moving tissue, the growing scientific literature on the subject and early systems appearing on the market make it sensible to pose the question of the best way to provide surgeons with intuitive and usable navigation information.

In this regard, we chose to evaluate the potential for tactile and combined visual and tactile feedback of deviation information with respect to known surgical targets in improving gesture accuracy and efficiency.

To gain initial insights into the improvements that may be obtained through such feedback compared to more conventional methods of navigation such as on-screen visual feedback and virtual fixtures in co-manipulated RMAS, we designed an initial experiment comparing performances in a simple free space navigation task. Subjects attempted to move their instrument tip between fixed targets while not deviating from a given target plane. We first compared performances in an open surgery setting to those in a laparoscopic surgery setting to evaluate the magnitude of performance degradations due to the ergonomics of the laparoscopic approach. We then evaluated the respective benefits obtained over conventional laparoscopy when information on the deviation was provided through visual, tactile and kinaesthetic feedback as well as the combinations of the latter two with visual feedback. **The experiment showed that in a 1D guidance task, all evaluated forms of feedback led to improved performances in terms of precision, with the best results obtained when using virtual fixtures. However, visual and cutaneous vibrotactile feedback and their combinations yielded promising results, with improved accuracy at the cost of prolonged task execution times.**

Our initial exploratory experiments on haptic and multi-modal assistance to instrument navigation demonstrated the potential of various forms of feedback in improving overall gesture quality, mainly in terms of precision criteria. However, it remained unclear how the visual, tactile and multi-modal feedback in particular affected user behaviour during corrections. We designed a second simplified guidance experiment to attempt to better understand this and the role of the various information components (indication of deviation direction, distance or both) in assisting parts of the gesture (initial reaction to a deviation, correction and final stabilisation around the target). Subjects were instructed to track a target plane with their instrument tip as it suddenly shifted in position while being provided with vibrotactile, visual or combined feedback on the deviation amplitude, direction or both. **Continuous vibrotactile feedback yielded the best reaction times in the event of a deviation**, probably because of the immediate nature of the signal and the fact that tactile feedback forces attention to the presence of a deviation. This is coherent with continuous tactile feedback yielding the best results during the stabilisation phase. **Visual feedback seemed to play a beneficial role in smoother movements, both during the transition from corrective motion to stabilisation motion around the target.**

Both these experiments used set-ups which remained quite far from actual laparoscopic clinical practice. This left a certain number of crucial open questions when considering applications to laparoscopic surgery. In particular, the effectiveness of feedback while the user is engaged in complex visuo-motor tasks such as precise cutting or suturing remained to be verified. To attempt to provide some insights into these open questions, we developed a final experiment on a navigation task closer to clinical training reality, based on the Fundamentals of Laparoscopic Surgery (FLS) cutting task. Subjects were to cut a circular pattern from a piece of gauze under provision of visual, vibrotactile and combined feedback. **This exploratory experiment yielded mixed results. On the one hand, there may be a benefit in using the tactile modality rather than the visual modality in this task. On the other, observed improvements were however very limited in magnitude, contrary to the simpler navigation tasks in free space studied previously. This would seem to indicate limitations in the applicabil-**

**ity of such feedback to complex trajectories and tasks requiring interaction with the environment.**

**Prospects for future work** The drop in observed improvements in performances obtained through feedback when navigation tasks were complicated would suggest that an evaluation of the effectiveness of feedback on non-novice populations would be of interest. Therefore further work should rapidly address the question of whether experts are able to effectively use such feedback in more complex guidance tasks and environments or whether the feedback inherently becomes ineffective in these conditions.

Beyond that, it would be interesting to train subjects to use feedback for a certain task to evaluate whether this may be a way of improving a given person's performance.

And finally, the forms of feedback that have shown promising results here may be beneficial in the learning process for medical students. A more in-depth evaluation of the improvements in learning curves obtainable through use of feedback during training could potentially yield highly interesting results.

Chapter 4

# Haptic force feedback for laparoscopic tools

Part of the work presented in this chapter has been published in the following

- Howard, T., & Szewczyk, J. (2016). Assisting Control of Forces in Laparoscopy Using Tactile and Visual Sensory Substitution. In New Trends in Medical and Service Robots (pp. 151-164). Springer International Publishing.

## Contents

In the following chapter, we focus on feeding back tool tissue interaction forces to the surgeon. Some work, such as [303], has already shown the potential added benefit of this form of information, confirming the outcome of our discussion with surgeons on areas where haptic feedback may be of interest in MAS[1]. Force information is useful in the case of palpation, grasping and manipulation tasks. When sensing and feeding back forces, a distinction can be made between grasping forces and interaction forces between tool and tissue in cases such as suture needle insertion, knot tying and palpation. In each case it is necessary to apply a minimum amount of force so as to achieve the task at hand without exceeding certain limit forces depending on the task, tool and tissue involved in order to avoid unnecessary trauma and associated complications.

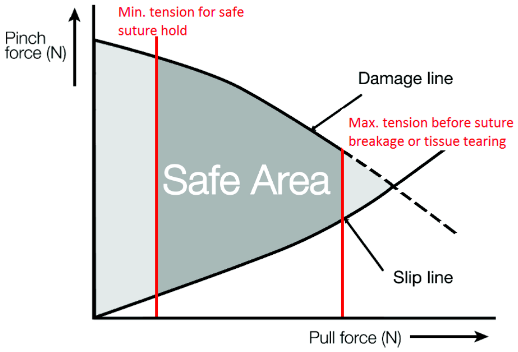

Figure 4.1: *Safe area for grasping forces (in grey). Above the damage line, the tissue or suture wire is at risk of tearing. Below the slip line, they are at risk of slipping out of grasp. Specificities of suturing are shown in red: A safe suture is achieved once the minimum tension in the wire is attained to ensure a safe suture hold, however exceeding a certain tension level puts the wire or tissue at risk of breaking or tearing the tissue*[2]

### The case of palpation

In laparoscopy, the process of palpation consists in feeling an anatomical structure in the body to determine its size, shape, firmness, or location. This is done either using dedicated laparoscopic palpation probes or with graspers, either by prodding the tissue with the jaws closed or by grasping the tissue to assess the firmness of the grasped tissue. As explained in chapter II, the degradation in haptic perception limits palpation in laparoscopy to experts palpating superficial structures which are relatively large or present serious differences in stiffness to their surrounding tissue. Palpation therefore requires exerting sufficient force to create a displacement or strain of the tissue, while at the same time limiting said force so as not to damage the tissue (see section 4.1 for force ranges).

### The case of tissue grasping and manipulation

Beyond palpation, the main use of grasping is in tasks requiring tissue manipulation, either

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[1] Minimal Access Surgery
[2] Adapted from Westebring et al. [303]

to displace tissue so as to gain access to a surgical site, to bring it within reach of other surgical tools or to visually inspect it. Correct grasping also plays a role in suturing so as to ensure a good hold of the suture thread and needle without damaging them. In both cases, the aim is to obtain a good and stable hold of the grasped object without applying excess force which may lead to damages (suture breakage in case of thread, ischemia and injury in case of tissue).

#### The case of suture knot tying

In the case of suturing, there is great potential benefit to be obtained from better control of interaction forces at the tool-tip. Similarly to grasps, sutures are safe for the patient as long as they exceed a minimum tension when tied which ensures good closure of the wound and secures against reopening. On the other hand, excess suture tension leads to tissue damage or suture breakages and associated complications (see figure 4.1). Therefore it is important that surgeons be able to feel both thresholds for safe suture hold and dangerous suture tension in order to ensure the greatest possible level of safety and efficiency in suturing.

## 4.1 Defining our needs

According to Vinatier et al. [219], the resulting tool-tissue interaction forces are in the [0N ; 12N] range in laparoscopic surgery. Furthermore, the authors measure interfering forces at the trocar with magnitudes up to 4.5N. The designed force sensing instrument should be robust to these interfering friction forces. In [305], the authors used the *Red Dragon* system for measuring grasping forces and durations during laparoscopic gestures, recording mean forces applied to the tool handles at 8.52 N +/- 2.77 N with maximum force up to 68.17 N. Average measured grasp times were around 2.29 s +/- 1.65 s, with 95% of all grasps held for under 8.86 s +/- 7.06 s. The average of maximum grasp times was 13.37 s +/- 11.42 s. Westebring et al. [304] compared laparoscopic tissue lifting against barehanded lifting, measuring greater pinch forces in barehanded lifts (at 2.63 N average pull forces) than when lifting laparoscopically (at pull forces between 0.77 N and 1.08 N). Safe grasps were consistently achieved in barehanded lifts, whereas in laparoscopic lifts excessive force (up to 7.9 N) and slippage (up to 38% of the trials) were observed. With these empirical values for the interaction forces during laparoscopy, we have an idea of the force ranges in which our sensors should be capable of resolving the minimum necessary number of distinct force levels.

## 4.2 Measuring grasping interaction forces at the tool tip

In order to adequately feed back information on forces to the surgeon, these forces must also first be measured with a sufficient degree of accuracy and reliability. As force sensing in conventional and robot assisted laparoscopy has been an area of interest of many studies (e.g. [10], [318], [131], [255], [246], [321], [228], [213]) without yet attaining results leading to off-the-shelf force sensing instruments, we first focus on measuring tool-tissue interaction forces in accordance with our needs.

The problem of measuring interaction forces at the tool tip has been addressed in several works in the past, mainly because of its potential applications to RMAS. We begin by presenting a state of the art on the subject in order to show the feasibility of such measurement, then proceed to define and discuss our needs with respect to clinically relevant force data. Similarly to the work presented in chapter III, for practical reasons, we do not tackle the issue of acquiring the force information in the work presented here, instead focussing on the evaluation of feedback methods for this information.

### 4.2.1 State of the art

Pungmali et al. [223] provide a good in-depth review of force sensing technologies as well as the current state of their applications in MAS. Here we go over the basic technologies, highlighting those that may be of interest to us.

#### Displacement-based sensing

Considering the test body as a spring with known stiffness, elements allowing the measurement of the test body displacement can be used in force sensing. Using the known force-displacement relationship then allows deduction of the applied force from the measured displacement. Several technologies for accurately measuring displacements are available, such as potentiometers, digital encoders or linear variable differential transformers (LVDT) which use the displacement of a ferromagnetic core inside a coil. LVDT has the potential to resolve mN forces, however its practical implementation remains complex for space reasons, lack of EMI[3] immunity as well as the requirement for precisely characterizing the elastic element.

#### Current-based sensing

Force sensing can also be performed at the level of the actuation mechanism in case of motorized elements. The value of the drive current in a motor is usually proportional to the current motor torque, allowing deduction of forces applied at driven joints. Tholey et al. [274] evaluated this approach for the design of a laparoscopic grasper with motorized jaws, concluding this method is simple yet relatively inaccurate. More recently, Kim et al. [149] investigated the use of indirect force sensing for the DaVinci using motor torque measurements. Though it is easily applicable to RMAS, an obvious limitation of this approach is that it relies on the use of electrical actuators and therefore cannot be applied to manual actuation such as in a conventional laparoscopic grasper.

#### Pressure-based sensing

The use of pressure-sensing equipment, either in the actuation mechanism in case of pneumatic or hydraulic actuation or directly at the location of measurement, is also a valid method of force measurement, pressure being defined as force applied over a given surface area. Tadano et al. [263] investigate the approach of sensing actuation pressure for force sensing in a 4DoF pneumatic driven forceps, obtaining good accuracy (O,1N resolution) at the cost of high complexity. Other notable works are those of Tenzer et al. [270], who present a low-cost tactile sensor based on a

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[3] EMI : Electro-magnetic interference

MEMS[4] barometer chip, and Vogt et al. [291], who developed a micro 3-axis force sensor based on microfluidic channels.

### Resistive-based sensing

This approach is probably the most widespread, especially due to long lasting experience from various industrial applications. Resistive strain gauges are glued to flexible test bodies (flexures). The application of external forces deforms the flexures and strain gauges, leading to a variation in electrical resistance in the strain gauge wiring which can then be measured. In this sensing method, there is always a trade-off to be made between sensing accuracy (which requires high strain at a given force level, i.e. lower stiffness of the flexure) and structural stiffness. This sensing method also requires appropriate acquisition electronics in order to obtain satisfactory measurements, raising concerns in terms of sterilizability and EMC[5]. Many works have dealt with equipping conventional instruments ( [272], [1], [69], [137]) as well as RMAS instruments [37] with strain-gauge force sensors.

### Capacitive-based sensing

Capacitive-based sensing is particularly appropriate for the detection of extremely small deflections of structures with low temperature interference. Capacitive sensing is of particular interest in the development of tactile arrays. In [135] and [136], the authors present an overview of the potential of capacitive sensing for remote palpation applications. Capacitive sensors are however limited in two aspects, the first being the complexity of their implementation and limited availability, and the second being the fact that their high resolution comes at the cost of a limited sensing range.

### Piezoelectric-based sensing

Piezoelectric materials generate voltages under the application of mechanical stress, making them good candidates for the fabrication of force sensors. Since they autonomously generate voltage, no external power supply is required. Piezoelectric-based sensing also provides excellent sensitivity and response to dynamic loading. However, their application in static loading conditions is limited (charge leakages over time lead to measurement drifts), their cost and complexity is often prohibitive, a certain number of piezoelectric materials have very low resistance to shear stress and piezoelectric materials are usually highly sensitive to temperature effects. In MAS applications, the most commonly found piezoelectric materials are PVDF (polyvinylidene fluoride) and PVF2, which are often used in the design of tactile sensing elements [254].

### Piezoresistive-based sensing

Piezoresistive materials are metals or semiconductors whose resistivity changes under the application of mechanical stress. Applying the approach for standard resistive strain gauges also makes these materials good candidates for forces sensing. The technology has been applied for force sensing in catheters ( [266]) as well as laparoscopic instruments ( [277], [18], [68], [65], [66], [67])

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[4] MEMS : Micro-Electomechanical System

[5] EMC : Electro-magnetic compatibility

### Optical force sensing

Optical force sensing relies on fibre optic wave guides to convey force information. The optical fibre acts as a light transmission element up to a transducer element which modulates the light when subject to strain. The transmitted or reflected light can then be analysed in order to recover information on strain and thereby applied force. They can be further divided into two broad categories of sensors :

#### Extrinsic sensors

Extrinsic sensors are usually based on the analysis of reflected light intensity off a deformable reflective surface. For example, Arain et al. [15] present a tactile sensor using interferometry with applications to MAS.

#### Intrinsic sensors

Intrinsic sensors can be based on several physical phenomena (e.g. Rayleigh, Brillouin etc.) but the most common available intrinsic optical sensors are probably Fibre-Bragg-Grating (FBG) strain gauges. Chung et al. [57] present the development of a highly sensitive 1D force sensor based on FBG technology. Ahmadi et al. ( [4], [5]) present an intrinsic optical fibre sensor (not FBG) for a palpation instrument which is MRI[6] compatible and shows good performance under static load.

Optical sensors offer the advantages of high measurement precision, low signal loss over long distances as well as immunity to EMI. However, their cost and complexity remain prohibitive, there is still little industrial and research experience with such sensors and optical fibres are usually less flexible than electrical wires in resistive strain gauges, making them more prone to damage.

### Combined sensing methods

Knowing the respective shortcomings of various sensing technologies, it is also possible to combine them in order to obtain better overall performances and compensate for said shortcomings. However, this comes at the expense of higher system complexity, and in the case of MAS, a more complex integration with regards to the small available space. Fattahi et al. [80] consider the option of combining piezoresistive and FBG sensing technologies to compensate for temperature as well as creep phenomena.

### Placing the sensors

#### Grasping force measurement :

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[6] MRI : Magnetic resonance imaging

Measurement of the grasping force in a laparoscopic instrument can theoretically take place either directly in the grasper jaw, with the advantage of potentially high fidelity measurements, or anywhere along the mechanical transmission between the tool handle grips and the grasper jaws, simplifying integration but introducing complexity due to potential interference by play, backlash, friction and mechanical coupling with other interaction forces.

**Tool-tissue interaction force measurement :**

Similarly to the measurement of grasping forces, the measurement of tool-tissue interaction forces can be performed by placing sensors at various locations along the instrument. Placement of the force sensing elements close to the tool tip has the advantage of potential high precision and little impact of interfering forces on the measurement, but comes at the cost of complexity due mainly to the very limited available space, sterilizability constraints, and constraints on the flexures (with regards to overall instrument stiffness) in case of the use of strain gauges. Other options include sensorizing the trocar and instrument handle such as in works by Zemiti et al. [321] and Ortmaier et al. [204] in order to deduce the tip forces. This comes at the cost of higher overall system complexity but almost eliminates all size-related constraints. Measuring the forces applied on the instrument outside of the trocar is not robust to interference by friction forces in the trocar and instrument mechanism and therefore usually a poor technological choice, as shown by Sukthankar et al. [259], who measure forces at the instrument tip and instrument handle during laparoscopic surgeries, noting significant differences in force magnitudes and patterns.

## 4.3 Force feedback

### 4.3.1 Force feedback in MAS - A state of the art

Among the most cited problems in MAS, distorted and partially lost haptic perception of forces is a major cause for concern ( [252], [219], [198]), prompting us to seek solutions for assisting surgeons in better controlling them. Haptic perception of forces is also a major issue in robotically assisted minimal access surgery (RMAS), as teleoperation has only worsened the situation compared to MAS, exacerbating the problem of excessive applied forces.

An interesting overview of force feedback in RMAS is given by Weber et al. [297], who perform a meta-analysis of 21 studies comparing surgical task performance with and without force feedback. They conclude that force feedback has a moderate effect on accuracy, a strong beneficial effect on the control of average and peak forces and no effect on task completion times. However, technical difficulties in implementing force feedback for RMAS have prompted research in alternate methods for presenting force information, in particular through sensory substitution.

Both audio ( [151], [31], [26]) and visual feedback in RMAS ( [151], [229]) and MAS (e.g. [303]) have proven effective in reducing mean and peak forces during suturing and tissue manipulation. However, implementing audio feedback in the operating room where ambient noise is high and it may impede communication remains challenging. Visual feedback requires a possibly distracting display alongside the endoscopic image, and increasing the already high visual cognitive load. For this reason, tactile feedback has been considered as an option for displaying interaction forces, with the advantage of not competing with other important information passing through the same perceptual channel, and providing immediate, private and non-disruptive cues.

When analysing virtual reality suturing tasks, Bleuen et al. [242] conclude that force feedback improves suturing performance independently from the operator's experience. The degree to which such results may apply in MAS or RMAS is however disputable, as on the one hand, natural haptic feedback is still available though degraded, and on the other hand the surgeons experience would quite likely affect his/her use of real visual feedback to estimate applied forces.

A number of studies have focussed on the development of various RMAS platforms with force feedback capabilities, e.g. [179], [235]. The number of studies evaluating the effectiveness of force feedback for improving surgical task performance in RMAS is however more limited. Reiley et al. [229] present an experiment to evaluate the contribution of visual force feedback on suturing performance using an RMAS system. Visual force feedback resulted in reduced suture breakage, lower applied forces, and decreased force inconsistencies among novice robotic surgeons, without affecting knot quality or TCT. This beneficial effect was not replicated in surgeons already experienced with the RMAS system. Similarly, Akinbiyi et al. [9] present an implementation of force and tissue oxygenation sensing in DaVinci® instruments with visual feedback of the information to the surgeon. Visual force feedback seems to generally improve quality as well as consistency of quality in robotic suturing. Wagner et al. ( [295], [294]) examine RMAS performances of novices and experts with and without force feedback. Lack of force feedback increased applied mean force magnitudes by over 50%, peak force magnitudes by over 100%, and tripled the error and damaged tissue rates. Speed and precision of dissection tasks however remained unaffected. Pitakwatchara et al. [220] analysed RMAS cholecystectomy in order to selectively amplify forces in a task specific manner for forceps manipulation. Force magnification has the positive impact of reducing the mean of applied force magnitudes. Concerning the trade-off between accurate control of forces and task completion times in RMAS, Wagner et al. [294] show that force feedback has a beneficial effect on control of interaction forces, however only experienced surgeons are capable of taking full advantage of this without increasing task completion times. Furthermore, Tirmizi et al. [275] show that vibrotactile force feedback can adequately substitute for natural force feedback in RMAS, leading to improved performance over no feedback.

In [303], the author presents work on using feedback on haptic information in order to enhance the surgeon's control of laparoscopic grasp force. Conclusions of this work are that the instruments disturb the available tissue information. Visual and kinaesthetic feedback are available although disturbed and tactile information is not present. Feeding back information on grasp force and tissue slippage either visually or through tactile feedback both improved performance, with tactile feedback leading to faster reaction times in case of tissue slippage for subjects of all previous expertise levels. Schoonmaker et al. [243] present an experiment at evaluating phantom tissue probing using a laparoscopic grasper providing vibrotactile feedback to inform the user about the applied tool-tip interaction forces. All three evaluated forms of tactile feedback improve overall performance, resulting in lower probing depth error and lower maximum applied forces. The authors therefore conclude it is a viable form of sensory substitution for force feedback in MAS. Zhou et al. [324] present the use of vibrotactile feedback for palpation assistance in MAS. By modulating amplitude, frequency and duty-cycle of the vibrations as a function of applied force, they show improved accuracy and confidence in subjects during palpation tasks, with lower peak forces and smaller force ranges during the execution of the task. They also show that this vibrotactile feedback tended to be more efficient as more parameters were modulated simultaneously. Stetten et al. [258] present an interesting concept for force amplification in a serially co-manipulated surgical instrument using a brace at the level of the handle to apply forces to the user's hand.

These improvements are also noted in other surgical areas, e.g. Payne et al. [211] analyse the effectiveness of force feedback in catheterization tasks, showing a 73% reduction in mean applied forces and a 55% reduction in peak applied forces when force feedback was present when compared to manual catheterization.

To the best of our knowledge, most work on tactile feedback for MAS has focussed on cutaneous feedback of grasping forces and tissue palpation forces with promising results. Here, we propose a series of experiments aimed at determining whether it is possible to represent tool-tip interaction forces through haptic and/or visual cues in a manner that is intuitively usable to better control them, seeking insight into the best form for representing forces.

### 4.3.2 Objectives

Our study of the potential assistance provided by feeding back information on interaction forces follows three steps :

I Only information on the force magnitudes is provided, without any prior definition of a target force or computation of a force error. This is done with the aim of obtaining a reliable perception of interaction forces, which may initially contribute to a finer and more repeatable control of tool-tip interaction forces. In the long run, use of tools with such feedback capability may reduce excess force as learning allows for feedback to be incorporated into the sense of force.

II A target force for the given action is defined and information on the force magnitude is completed with highlighting of the target force. Though applications using such a feedback scheme would require prior knowledge and definition of the ideal target force, these may not only allow finer and more repeatable control of tool-tip interaction forces, but also efficient reaching of known ideal target forces.

III A variation on the scheme presented previously would consist in using the information on the target force to compute a force error and feed information about this error directly back to the surgeon.

### 4.3.3 Initial experiment: feeding back absolute force information

#### Materials and methods

Our first experiment focussed on the manipulation of a suture thread attached to the end of a laparoscopic instrument, with the aim of subjecting it to given levels of tension forces. 16 Subjects (10 male, 6 female, all novices in laparoscopy) performed a sequence of force reach and

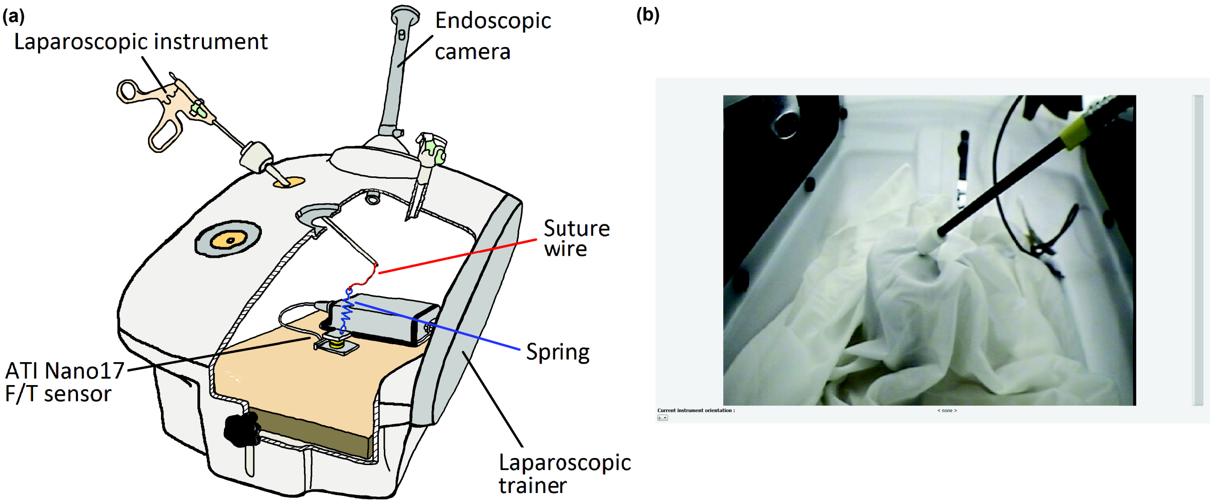

Figure 4.2: *(a) Experimental setup; (b) Endoscopic image as seen by the subject*

hold tasks for a selection of 10 feedback conditions.

### Hardware

Subjects were placed in front of a laparoscopic trainer (EndoSim LaproTrain) containing a plate equipped with a force sensor with a fixture for holding a suture wire (3-0 gauge Braun Novosyn 90/10), as shown in fig. 4.2 left. They manipulated standard laparoscopic forceps with the suture wire attached so as to avoid time losses associated with novices attempting to grasp a suture thread. Fig. 4.2 left highlights the force sensor (ATI Nano17E 6-axis force/torque sensor, sensing range [0N-12N], force values acquired at 40Hz) in yellow, the spring between the force/torque sensor and suture thread in blue and the suture thread in red. The role of the spring was to introduce a relatively low stiffness elastic component between the highly stiff wire and force sensor, mimicking the natural elasticity of tissue during suture knot tying or tissue manipulation. Subjects observed the scene on a 24" LCD monitor placed directly in front of them, and manipulated the laparoscopic forceps through a 5mm trocar, observing the inside of the laparoscopic trainer as shown in Fig. 4.2 right. Loose white sheets were placed over the force/torque sensor and spring so as to minimize visual cues that could aid in assessing the thread tension. Vibrotactile feedback was provided using an ERM motor (Precision Microdrives PicoVibe 307-100 [191], vibration intensity range laparoscopic tool handle. New feedback commands were generated at a frequency of 40Hz, following the acquisition of the force data.

### Feedback conditions

**Reference - No feedback (NoFeed) :** Subjects received no feedback about the suture thread tension $F_{tension}$ and relied solely on the visual information from the endoscope and natural tactile information from the instrument.

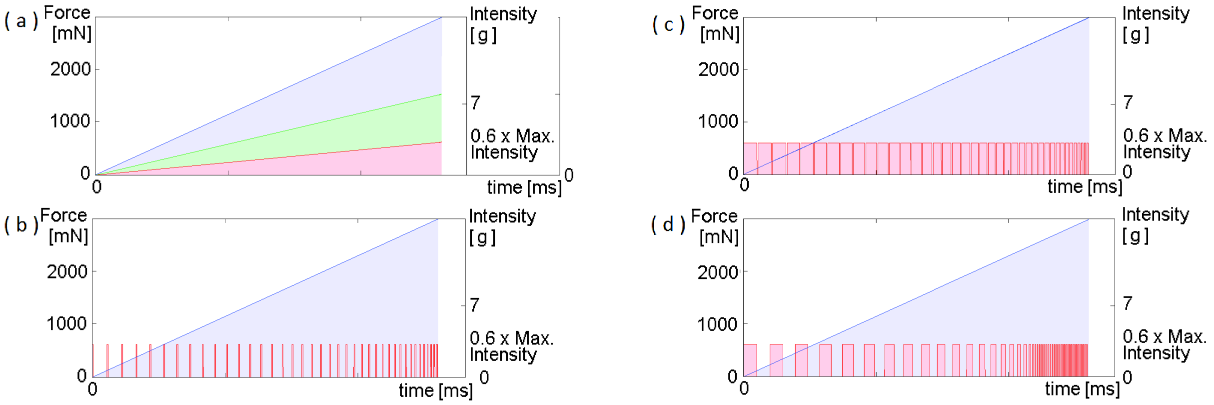

Figure 4.3: *Feedback levels depending on the magnitude of force to be displayed. From the top left to bottom right : (a) Visual (Visual) and continuous vibrotactile feedback (TacCont); (b) Pulsed vibrotactile feedback (TacPuls-f); (c) Pulsed vibrotactile feedback (TacPuls-q); (d) Pulsed vibrotactile feedback (TacPuls-p). The blue curve indicates the force magnitude, the green curve the associated bargraph height and the red curve the vibration intensity.*

**Visual feedback (Visual) :** Subjects received visual feedback about $F_{tension}$ in the form of a vertical bar-graph displayed next to the endoscopic image. The bar-graph displayed forces in the range [0N-3N]. We did not highlight the target force in any way. The feedback level as a function of $F_{tension}$ is shown in green in fig. 4.3 (a).

**Continuous vibrotactile (TacCont) :** Subjects received tactile feedback about $F_{tension}$ through an ERM vibration motor. The tension force $F_{tension}$ was displayed through a linearly proportional variation of vibration amplitude (0g to 5.2g), as shown in red in fig. 4.3 (a).

**Pulsed vibrotactile - fixed pulse length (TacPuls-f):** The same vibration motor as for condition TacCont displayed the suture tension $F_t$ though series of vibration pulses at a fixed amplitude (3.4g) and length (45ms) with a spacing inversely proportional to the applied force varying between 525ms and 15ms, as shown in red in fig. 4.3 (b).

**Pulsed vibrotactile - varying pulse length and interval (TacPuls-p):** Identical set-up to TacPuls-f, however this time the length and spacing of the pulses were varied jointly in the same manner as the spacing in TacPuls-f, always keeping spacing and length equal. The pattern of force encoding is shown in red in fig. 4.3 (d).

**Pulsed vibrotactile - fixed pulse interval (TacPuls-q):** Identical set-up to TacPuls-f, however this time the pulse spacing was kept constant at 45ms, and the pulse length was varied between 525ms and 15ms in inverse relation to the applied suture tension, as shown in red in fig. 4.3 (c).

**Vibrotactile and visual conditions (TacCont+Visual, TacPuls-f+Visual, TacPuls-p+Visual and TacPuls-q+Visual):** These four conditions are identical to TacCont, TacPuls-f, TacPuls-p and TacPuls-q respectively, whereby we simultaneously provide visual feedback as in condition Visual.

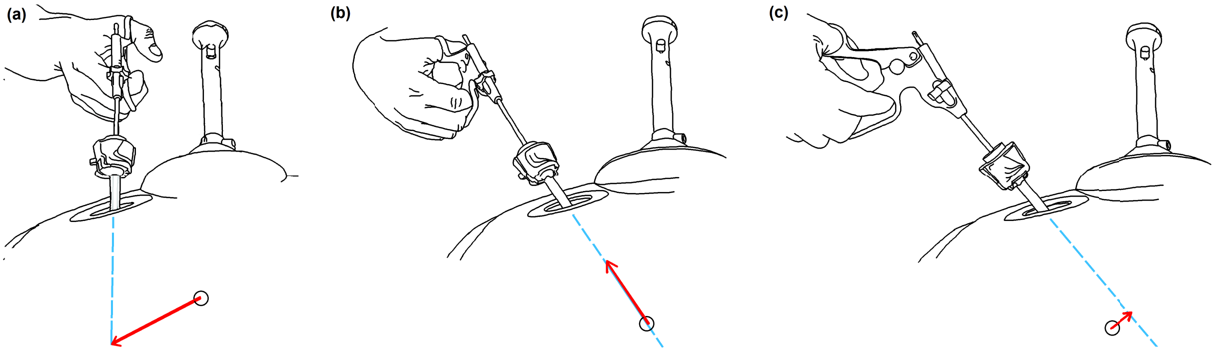

Figure 4.4: *Extreme cases of tool orientations when pulling on the suture wire. The blue dotted line shows the instrument axis, the red arrow the suture thread axis. From left to right : pulling on the wire using lever effect with instrument parallel to the saggital plane (a), directly pulling on the wire with instrument and wire aligned on the trocar axis (b), and pulling on the wire using lever effect with instrument parallel to the coronal plane*

### Task

In chronological order, the task to be performed consisted of:

- **1 definition of a target force** between 1 and 3 N : Subjects pulled on the suture wire while receiving feedback corresponding to the given condition and pressed a button to define the current force as their target for the rest of the task (referred to as the actual target force $F_{tgt}$ in the following). Subjects were under no time pressure to select a target force.
- **1 force reach task**, where the objective was to aim for the previously defined $F_{tgt}$, having changed the instrument's orientation (see fig. 4.4) in order to minimize the impact of visual cues in the endoscopic image on assessment of $F_t$. The subjects pressed a button once they thought they had reached $F_{tgt}$ (in the following, the force applied at the moment of this button press will be referred to as the target force estimated by the subject $F_{tgt,est}$ ).
- **1 force hold task**, where the objective was to hold $F_{tgt,est}$ for a duration of 20s.
- **3 force repeat tasks**, where the objective was once again to aim for $F_{tgt}$ as precisely as possible, changing the instrument orientation every time. For this, the subject pressed a button to begin, pulled on the thread, and pressed the button again once $F_{tgt}$ was thought to have been reached.

To keep the experiment duration manageable, subjects were assigned a randomized sequence of the conditions NoFeed, Visual, TacCont, TacPuls-f, TacPuls-p, TacPuls-q, and one of the four visual+tactile conditions (TacCont+Visual, TacPuls-f+Visual, TacPuls-p+Visual or TacPuls-q+Visual). For each condition, subjects performed two to three repeats of the task previously described. They were each given detailed instructions about the experimental sequence and manipulation of the laparoscopic instrument. Furthermore, they were briefed and given an example for each form of feedback prior to performing the task.

After the experiment, subjects were asked to assess their performance at the task in all the feedback conditions they had experienced, as well as provide their subjective ranking of preference and perceived information content for those conditions. Furthermore, subjects were questioned about their familiarity with video games (5 frequent players, 7 moderate players, 3 non-players) and musicianship (7 musicians, 9 non-musicians) as previous works have shown impacts of these factors on performance in laparoscopic settings ( [193]) and cutaneous perception of forces.

### Evaluation of experimental data

Generally speaking, the objective is to enable repeatable and accurate achieving of desired tool-tip forces, and in some cases such as tissue manipulation, to hold these forces constant - or at the very least within a reasonable tolerance bracket - for a desired length of time. The evaluation criteria described in this section will be used throughout all experiments presented in the present chapter.

**Accuracy criterion - Distance to Target Force (DTF)**

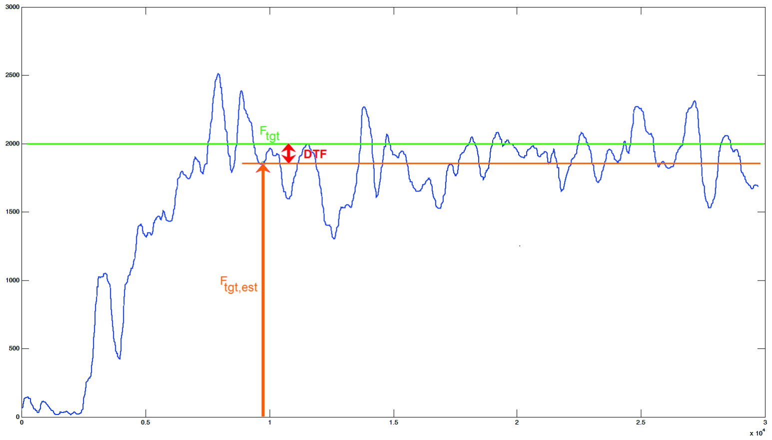

Figure 4.5: *Example of recorded force curve with accuracy metric : DTF. The repeatability metric is the spread of DTF values over several trials.*

The distance to the target force is a good indicator of aiming accuracy. We calculated DTF as the mean of differences between $F_{tgt}$ and $F_{tgt,est}$ for each force reach and force repeat task for each subject.

$$DTF_{Subject} = \frac{\sum_{i=1}^{N}(F_{tgt}(i) - F_{tgt,est}(i))}{N} [mN]$$

where $N = no.\ of\ force\ reaches + no.\ of\ force\ repeats$ performed by the subject.

Values close to 0 indicate higher aiming accuracy. Lower spread indicates greater repeatability. Dividing subject DTF for each condition by the subject's DTF for condition NoFeed highlights improvements (values $<$1) or deteriorations (values $>$1).

#### Repeatability criterion - Spread of DTF

The spread of DTF can be evaluated both through the distance between minimum and maximum distance to target forces as well as the interquartile range for DTF. Lower spread values indicate higher repeatability in aiming towards a given target force.

#### Efficiency criterion - Speed of reaching a target force for a given accuracy - SRF

As the set target forces varied, speed of reaching a given target force (i.e. time spent to reach it divided by target force magnitude) was a better indicator of aiming efficiency than TCT. However, as speed also significantly affected aiming accuracy, we used the speed of aiming at a target force for a given final accuracy (i.e. speed of reaching a target force divided by DTF) as our final metric for efficiency.

$$SRF = \frac{1}{N}\sum_{i=1}^{N} \frac{F_{tgt}(i)}{(TCT(i)*|DTF(i)|)}[s^{-1}]$$

Larger values indicate lower DTF at equal reach speeds or higher reach speeds at equal DTF.

### Constancy criteria

#### Mean force hold error

In holding tasks, the force hold error FHE is the mean of differences between the subject's mean force applied during the force-hold task and $F_{tgt,est}$ from the initial force-reach for a given condition. This is a good measure of cumulative error over the duration of the force hold task.

FHE is the mean of differences between the subject's mean force applied during the force-hold task and $F_{tgt,est}$ from the initial force-reach task for a given condition:

$$FHE = \frac{1}{K}\sum_{i=1}^{K} F_{tgt,est}(i) - mean(F(i))[mN]$$

where K is the number of force-hold tasks performed by the subject.

Lower force hold error is indicative of low drift and efficient correction of drift during the force hold task.

### Drift angles

A second criterion for evaluating the constancy of a force holding task is the drift slope in [N/s] (indicative of the speed of drift). Mean drift for a given condition is calculated by fitting a line to the curve of applied force during the force-hold task and evaluating its slope (the drift angle - D$\alpha$ - in [N/s]). Values further away from zero indicated a marked tendency to drift away from $F_{tgt,est}$. The sign of the drift angles also gives an indication of the direction of drift, with positive values indicating a tendency to apply more force over time and negative values indicating a tendency to reduce applied forces over time.

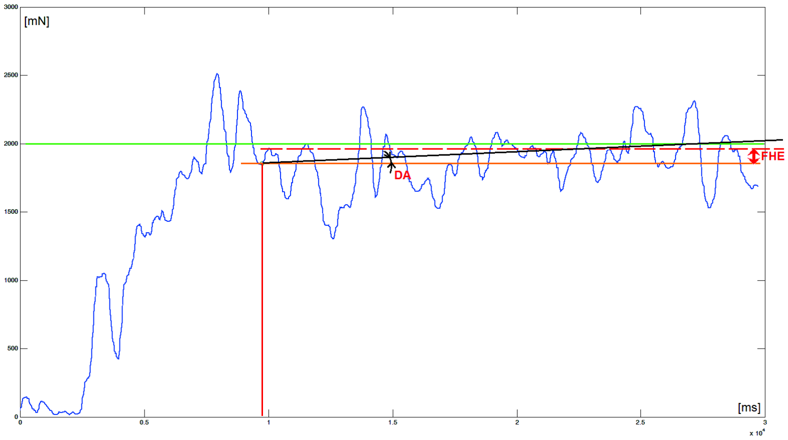

Figure 4.6: *Example of recorded force curve with constancy evaluation metrics FHE and DA.*

## Results and discussion

In the following, we present and discuss the main results obtained for the various evaluation metrics described earlier.

**Precision and repeatability of reaching a target force** Fig. 4.7 shows that providing feedback systematically reduces mean subject DTF for subject mean DTF), all differences in means significant with at least $p<0.05$).

The best performance is obtained for conditions Visual (81.77% reduction in mean error over condition NoFeed, $p<0.01$), TacCont+Visual (85.8% reduction in mean error over condition NoFeed, $p<0.01$), TacPuls-p+Visual (81.98% reduction in mean error over condition NoFeed, $p<0.01$) and TacPuls-q+Visual (83.23% reduction in mean error over condition NoFeed, $p<0.01$), with a systematic improvement of performance over condition NoFeed for all subjects. We believe the better performance obtained through visual feedback can be attributed to the fact that it not only provides information on the current force magnitude but also provides relative distances to the maximum and minimum levels of feedback at any given time, whereas the level of tactile feedback is harder to place on the range of possible feedback levels.

Vibrotactile feedback alone leads to moderate improvements, with the best performance achieved for TacPuls-f (52.21% reduction in mean error over NoFeed, improvements in >75% of cases) and TacPuls-p (55.07% reduction in mean error over NoFeed, improvements in >75% of

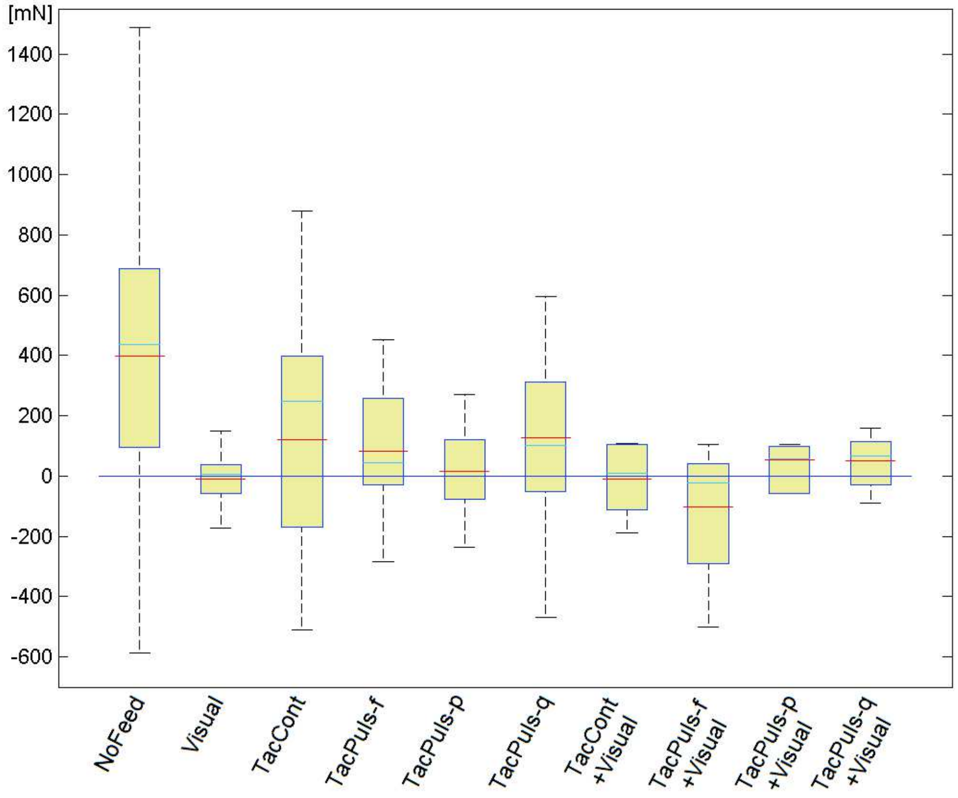

Figure 4.7: *Mean DTF for each subject, grouped by condition [mN]. Medians are indicated by the light blue and means by the red horizontal lines.*

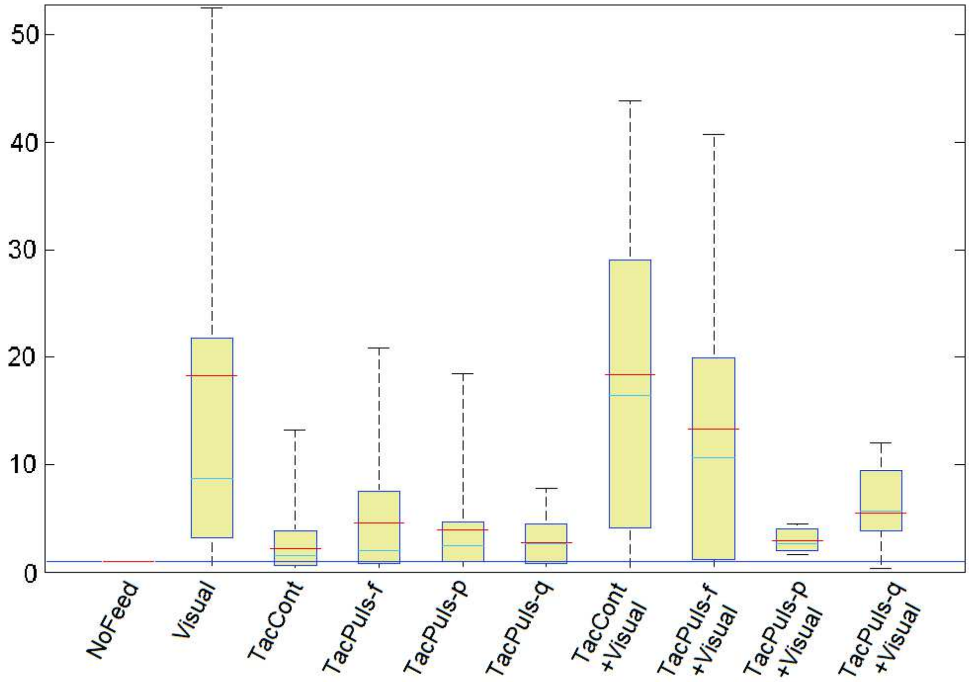

Figure 4.8: *Mean subject speed of reaching a target force (SRF) for a given DTF, relative to subject's performance in condition L [dimensionless].*

cases), although in some rare cases, subjects did not succeed in performing better with them than with visual feedback alone. It seems that vibrotactile pulses yields higher sensitivity to changes than continuous vibration. Also, this difference could relate to greater user comfort when vibration was presented in short bursts. Indeed, condition TacCont shows the worst performance of all tactile conditions, with improvements over NoFeed observed <75% of the time.

In order to further analyse the effect of feedback on errors when aiming for predefined target forces, fig. 4.7 (b) shows the mean DTF values for each condition. In the absence of feedback, there is a marked tendency to not reach the predefined target force. This graph allows analysis of the effect of feedback on repeatability of aiming, shown by the spread of values for each condition. Improvements in mean errors generally hold true for spread, with the best repeatability obtained for conditions Visual (62.8% reduction in SD over condition NoFeed), TacPuls-p (52.4% reduction in SD over condition NoFeed), TacCont+Visual (77.7% reduction in SD over condition NoFeed) and TacPuls-q+Visual (84.7% reduction in SD over condition NoFeed). Conditions TacPuls-f and TacPuls-p+Visual yield moderate improvements in spread (42.2% and 44.7% reduction in SD over condition NoFeed respectively) while the remaining conditions yield only very slight improvements.

In terms of precision, there seems to be no great use in combining visual and tactile feedback (except for the improvement between TacPuls-q+Visual and TacPuls-q, $p<0.05$), as the combination is either detrimental to performance or the tactile feedback is clearly ignored in favour of the visual feedback. The only positive impact that can be noted is a slight improvement in terms of repeatability, which can probably be attributed to the redundancy of information.

**Speed of reaching a target force** Feedback significantly increases SRF at identical DTF ($p<0.05$) except for conditions TacCont, TacPuls-p+Visual and TacPuls-q+Visual. The best improvements are obtained for conditions Visual (18.23-fold increase in mean SRF), TacCont+Visual (18.34-fold increase in SRF) and TacPuls-f+Visual (13.34-fold increase in SRF). Conditions TacPuls-f, TacPuls-p and TacPuls-q+Visual yield moderate improvements (4.55-fold, 3.92-fold and 5.52-fold increase in SRF). The significantly better performance for condition Visual over all tactile conditions (all differences in means significant at $p<0.01$) can be attributed to additional available information we discussed earlier as well as the higher speed of the information delivery. Pulsed vibrotactile feedback requires a certain number of pulse cycles to convey the feedback level, whereas a bargraph provides the same information instantaneously.

If this were the only factor at play, we should expect good performance from condition TacCont. However, the observed bad performance is largely attributable to the low accuracy in condition TacCont due to the poor clarity of the feedback. This conclusion is supported by the TCTs for the force reach and repeat tasks, which are not significantly different for conditions NoFeed, Visual and TacCont.

### Quality of holding a target force

**Mean error** In the absence of feedback, FHE are large and subject to great spread. Condition Visual yields low FHE (35.3 mN mean error) but performs on par with pulsed vibrotactile conditions (no significant differences), with TacPuls-f and TacPuls-q performing moderately better (0.05mN and 10.72mN respectively).

It would seem that tactile feedback performs comparatively well to visual feedback when it comes to avoiding drift from a given value, with an edge to pulsed vibrotactile feedback TacPuls-f. Continuous vibrotactile feedback is of little use in this task, with significantly worse FHE than all other tactile feedback conditions and the visual feedback condition.

Combining visual and tactile feedback yields no significant benefit over visual or tactile feedback alone. Surprisingly, condition TacPuls-q+Visual leads to significantly worse performance, which could be due to the feedback not combining in an intuitive manner. Indeed, subjects tended to report difficulties in using TacPuls-q alone, which could account for a disturbing effect when combined with visual feedback that also demands the subject's attention. Combined feedback TacCont+Visual yields performance on par with condition Visual, leading us to believe that subjects ignored the tactile component of the combined feedback in favour of the visual feedback.

**Drift and cumulative deviation** As expected, the absence of feedback yields a marked tendency to drift from $F_{tgt,est}$, with a tendency to increase the applied force over time (70% of upward drifts against 30% of downward drifts) and a large spread and amplitude of D$\alpha$s.

Visual feedback is more effective at reducing drift amplitude than tactile feedback alone, though not significantly. Concerning tactile feedback alone, the best performance is achieved for conditions TacPuls-f and TacPuls-p (significantly outperforming TacCont and TacPuls-q at

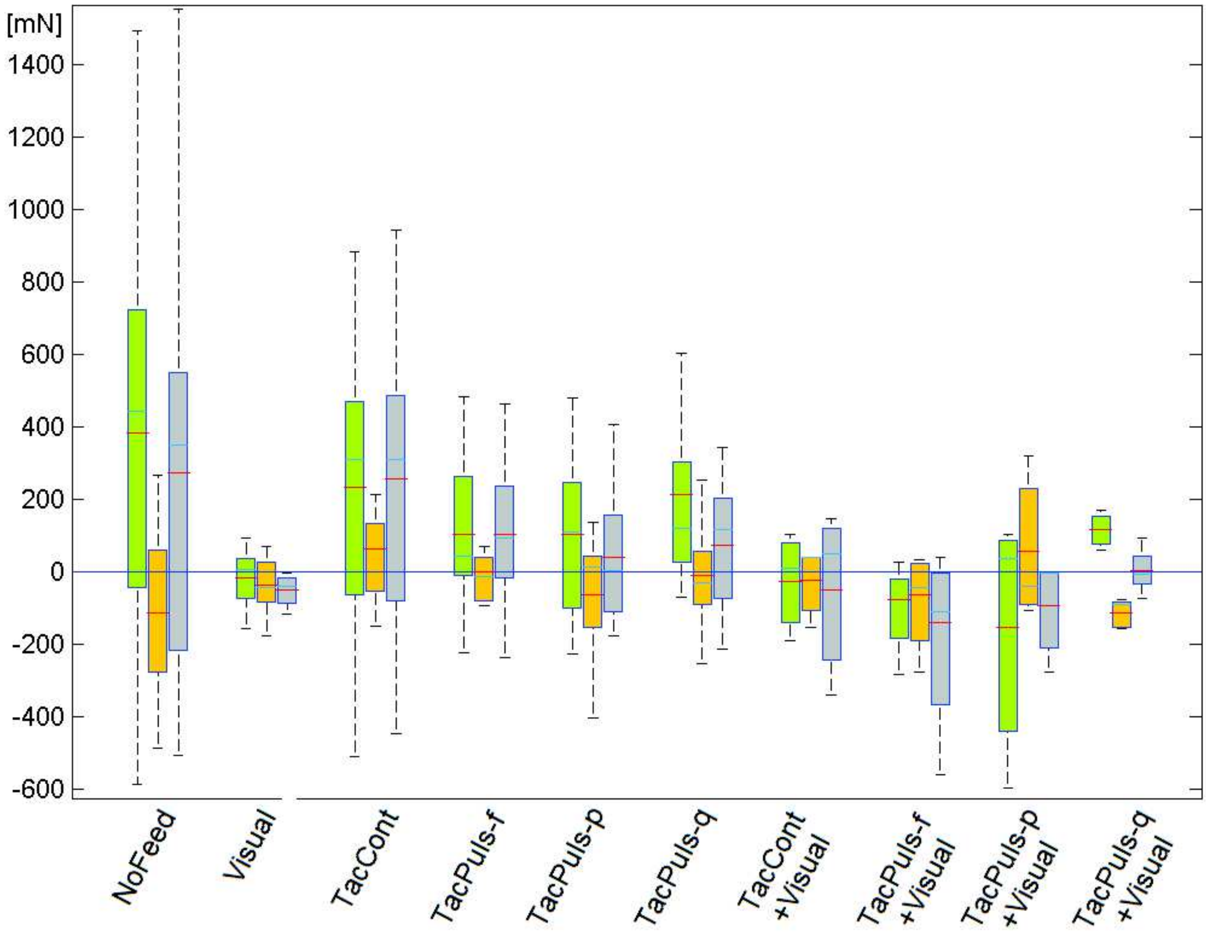

Figure 4.9: *Mean subject FHE (yellow boxplot), against subject DTF from the initial force reach task (green boxplot), and the resulting error (DTF+FHE), grey boxplot.*

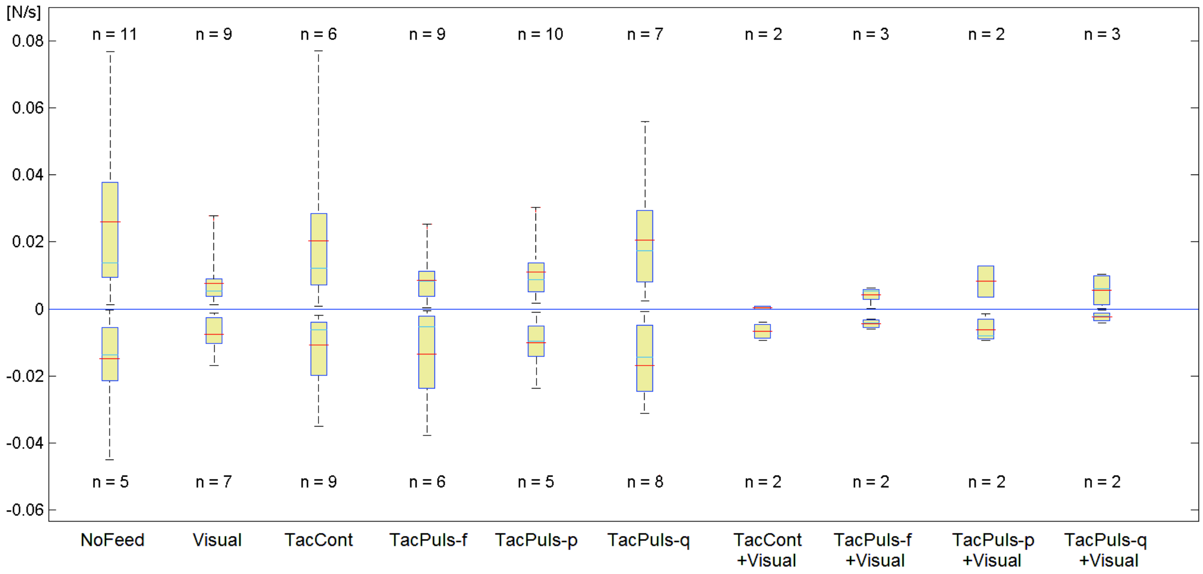

Figure 4.10: *Subject mean drift angles $D\alpha$ for force hold task [N/s]. The $D\alpha$s are separated depending on the drift direction (upwards or downwards), with the number of observations for each being shown so as to give an idea of the distribution of drift directions.*

$p<0.1$).

All combined visual and tactile conditions significantly reduce drift and bring the mean $D\alpha$s close to 0 N/s (equal tendency to increase and decrease force over time, lowest means and spreads of $D\alpha$ values), highlighting a major benefit from combined visual and tactile feedback. In particular, condition TacCont+Visual shows a significant improvement over both conditions Visual and TacCont+Visual ($p<0.05$).

This shows that despite the results obtained from comparison of FHE, visual feedback and its combination with tactile feedback tends to slightly improve performance when it comes to staying close to a target over time. This can probably be attributed to the speed of delivery of the visual information when compared to the tactile information as we already mentioned in section 4.3.3. Once again, when observing performance for TacCont+Visual, it becomes clear that the tactile component was ignored in favour of the visual feedback. Concerning TacPuls-p+Visual, the performance is worsened when compared to either of the individual forms of feedback, which may indicate a poor matching of the visual and tactile feedbacks which confused subjects.

Of the tactile feedback conditions, TacCont (no significant difference to condition NoFeed) and TacPuls-q (difference in mean significant at $p<0.1$) perform worst, which we believe is mainly attributable to the poor understandability of these forms of feedback.

**User assessment of the feedback** Subjects tended to correctly assess their performances in each feedback condition, usually showing greatest self-assessed performances in the conditions Visual and Visual+Tactile conditions. The only discrepancy appeared for condition TacPuls-p, where subjects were unsure about their performance, usually assessing it as much worse than their actual performance. This could indicate that the feedback is indeed intuitive, but that it's unfamiliar nature has a negative impact on user confidence. In terms of information content, subjects consistently rated Tactile+Visual conditions as better than Visual alone which in turn was better than tactile alone conditions. This confirms our belief that visual feedback contains additional information in the form of a reference for the minimum and maximum force value that are available simultaneously to the current force magnitude information, whereas the evaluated tactile feedback alone only provides this last piece of information. Furthermore, it would seem that the tactile feedback in combination with the visual feedback was perceived to provide clearer information of deviation and drift from a target force, reinforcing our hypothesis on the unfamiliarity of tactile feedback by itself. Finally, in terms of usability (comfort and intuitiveness of the feedback), subjects again ranked condition Visual as superior to all others. When it comes to tactile feedback, subjects had a marked preference for conditions TacPuls-f and TacPuls-p, rating conditions TacCont and TacPuls-q as disturbing and confusing.

### Conclusion

In this paper, we describe an experiment aimed at evaluating feedback of tool-tip interaction forces in laparoscopy through haptic and/or visual cues. We compared four forms of vibrotactile feedback, on-screen visual feedback via a bar-graph and their combinations.

Providing no feedback yielded the worst overall performance for precision (strong tendency to not reach the target force, very large errors and low repeatability), speed (slowest for reaching a target force with a given accuracy) and constancy of holding a given force over time (strong tendency to increase the applied force over time, strong oscillations of force and large errors), in line with literature results on forces in MAS.

Visual feedback yielded the best performance overall. Precision and repeatability when aiming at a target force were better than those achieved through tactile feedback, and on par with or better than those achieved for combined visual and tactile feedback. Visual feedback significantly outperformed tactile feedback in terms of speed. When holding a force, it effectively allowed for reduction and correction of drift, with comparable performance to the best of tactile feedback. We believe the overall better performance of visual feedback to be due to additional information provided by the bar-graph when compared to the vibrotactile feedback as well as the comparatively higher speed of delivery of the information to the user. Vibrotactile feedback moderately improved precision. It was shown to be effective in reducing mean force errors and their spread and moderately increasing task execution speed. Concerning the quality of holding a force, the best performance in terms of drift and error reduction were achieved through pulsed vibrotactile feedback. Vibrotactile feedback involving continuous or near-continuous vibration was usually outperformed by pulsed feedback, probably due to greater user comfort.

Condition TacCont+Visual yielded the best results in terms of precision and speed of task execution, outperforming either TacCont or Visual individually. Conditions TacPuls-f+Visual, TacPuls-p+Visual and TacPuls-q+Visual yielded significant improvements over no feedback without reaching those achieved with TacCont+Visual, and not necessarily better than visual feedback alone, though they outperformed pulsed vibrotactile feedback alone. Concerning holding of a target force over time, combined tactile and visual feedback led to comparable errors with Visual and the best performance from tactile feedback alone, but usually significantly reduced drift when compared to Visual and tactile feedback alone respectively. It seems that pulsed vibrotactile feedback in some cases acted as a disturbance when combined with visual feedback, possibly because of discrepancies between their respective information delivery speeds.

Despite the better performance of visual feedback, these results are encouraging for the use of vibrotactile feedback in communicating force information in MAS. Indeed, vibrotactile feedback clearly improves performance over no feedback and retains the advantage that it may prove effective in keeping visual cognitive load for surgeons manageable, though this remains to be investigated.

This study suffers from a few limitations, first of which being that subjects were not familiar with laparoscopy. An evaluation of the best performing forms of feedback in actual suturing trials with laparoscopic surgeons will be required. For practical reasons, the task did not take into account grasping of the thread or needle, which may impact behaviour, especially when using tactile feedback. Surgical suture knot tying is also usually a bi-manual task, so it remains to be seen whether this changes behaviour with regards to the use of feedback with implications for its design. Finally, there was no requirement to focus attention on the endoscopic image, leading to low ecological validity[7] and likely skewing results in favour of visual feedback. Discussion with subjects showed that in conditions with visual feedback, they barely paid attention to the endoscopic image, focussing mainly on the bar-graph. We plan to address these limitations in future experiments expanding on our present work.

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[7] The ecological validity of a study is a measure of the ability of the materials, methods and settings of a study

### 4.3.4 Second experiment : Feeding back absolute force information while highlighting a target

In order to test our hypothesis that the better performance observed when providing visual feedback in our first series of experiments was associated with the fact that the bargraph inherently provided some frame of reference for the current level of visual feedback (bar height) whereas the tactile feedback did not, we modified all feedback provided so that along with absolute force information, there would be a "highlighting" of the target force - which should theoretically put all forms of feedback in an equal position to deliver accurate information on the relationship between the currently applied force and the target force. The modified experimental protocol and results are detailed in the following.

#### Materials and methods

Our experiment focussed on the manipulation of a suture thread using a pair of laparoscopic forceps. Three novice subjects performed a sequence of the tasks listed above for four feedback conditions.

#### Evaluated feedback conditions

Having noted the poor performance of continuous tactile feedback TacCont and the best performance of pulsed vibrotactile feedback with constant pulse length and varying pulse spacing, we limited the evaluated feedback conditions to the following four :

No feedback (NoFeed), Visual feedback (Visual), Pulsed vibrotactile feedback with fixed pulse length (TacPuls-f), Combined visual and pulsed vibrotactile feedback (TacPuls-f+Visual). The feedback types were in no way modified from experiment 1. Highlighting of the target force occurred as follows:

NoFeed No highlighting of the target force as no feedback is provided

Visual The bargraph colour changed from red to green when the applied force was within the tolerance bracket around the target force

TacPuls-f A second motor strapped to the hand of the subject activated identically to the motor displaying the force magnitude when the current applied force magnitude lay within the predefined tolerance bracket around the target force.

TacPuls-f+Visual Both target force highlights described above were combined.

Before beginning the task in each feedback condition, subjects had training session where they freely manipulated the suture wire while receiving the feedback corresponding to the condition, with indication of the target force through an additional auditory cue. This was to ensure

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to adequately approximate the real-world situation being examined.

subjects had a clear idea of how to use the feedback and at the same time simulated the effect of experience with suture thread tension.

**Experimental task** Subjects were to perform two tasks described in the following to allow for evaluation of the various potential benefits and limitations of the studied feedback schemes:

- Force reach task without time pressure (FRF):

  After the training session for the given feedback condition, subjects received a starting signal and were to pull the suture wire so as to achieve the desired target suture tension as precisely as possible while trying to reach if efficiently in terms of task completion time. However the time available to reach the target tension was not limited. Subjects received verbal reminders in case of deviation from the prescribed suture thread orientations. Trials where the subjects failed to comply with this constraint were discarded. The subjects signalled once they thought they had reached $F_{tgt}$ (in the following, the force applied at the moment of this signal will be referred to as the target force estimated by the subject $F_{tgt,est}$ ). Once the target force has been reached, force recordings stop, the trial concludes and the subject releases the thread.
- Force reach and hold task (FRH):

  In this task, subjects reached the target force, then obtained an audio notification signalling the beginning of a 20s holding period during which the subjects were to keep the force as constant as possible until receiving a second audio notification indicating the end of the task. Subjects were informed that no evaluation of the speed of the initial force reach before beginning of the holding task would take place, and that only accuracy would be measured. Subjects received feedback corresponding to the given condition for the entire duration of the trial.

Subjects received feedback corresponding to the given condition for the entire duration of the trial. A total of ten repeats of the FRF task were performed by each subject in each condition. A total of five repeats of the FRH task were performed by each subject in each condition. Subjects were assigned fully randomized sequences of the conditions NoFeed, Visual, TacPuls-f, TacPuls-f+Visual. The order of the sub-experiments FRF or FRH was also randomly assigned. Contrary to the previous experiment, in both tasks, subjects now manipulated the wire with both hands and had to actively grasp the wire so as to bring the task closer to a clinical reality of suture knot tying.

**Hardware**

The fixture previously used for holding the suture wire (4-0 gauge Ethicon Vicryl resorbable suture thread) was modified so as to allow bimanual grasping of the suture thread, as shown in fig. 4.11 left. Both ends of the suture wire were tied to metal rings to be grasped so as to simplify grasping for non-expert subjects and reduce risk of slipping or thread rupture due to inadequate grasping of the thread ends. Subjects observed the scene on a 40" LCD wall-mounted monitor

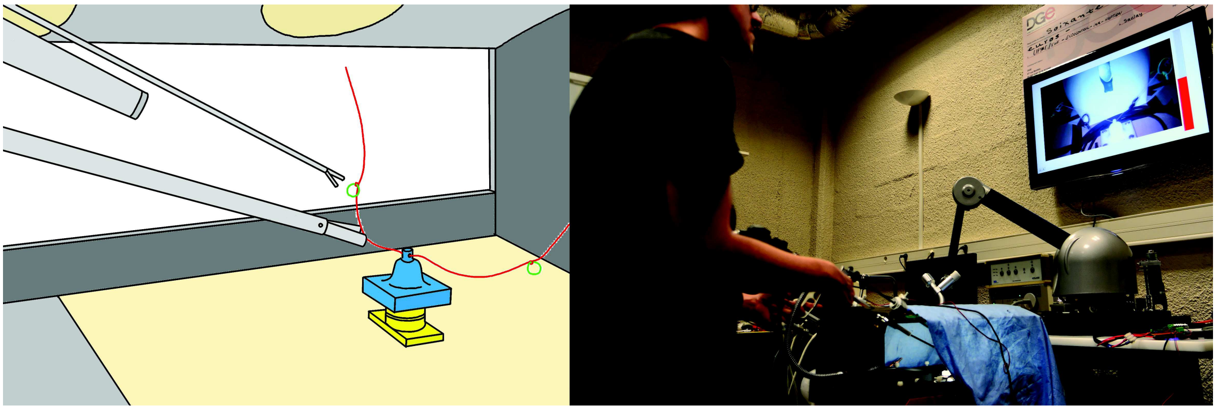


Figure 4.11: *(a) Modified experimental setup; (b) Endoscopic image as seen by the subject*

directly in front of them, similar to a conventional operating room set-up. They manipulated a pair of laparoscopic forceps through 5mm trocars, observing the inside of the laparoscopic trainer as shown in Fig. 4.11 right. Subjects were instructed pull the suture thread strands symmetrically around a vertical plane at approximate angles of $\pi/4$ and approximately at the same vertical height so as to focus user attention on the endoscopic image and hand-eye coordination and allow for calculation of the suture thread tension based on the force sensor measurement. Visual and vibrotactile feedback were provided identically to experiment 1.

### Results and discussion

An overview of the results for each of the three subjects' performances is provided in the following. As these experiments were conducted as preliminary work due to time restraints, we chose to show individual performances beside each other with indications of spread and median performances so as to show emerging trends. Due to the insufficient number of observations for any discussion of statistical significance, the conclusions stated in the following are preliminary and require further investigation.

**Accuracy and repeatability criteria** As in experiment 1, we measured accuracy in aiming through the absolute Distance to Target Force (DTF - see fig.4.12). The lower the observed DTF value, the greater the accuracy in aiming towards a given target force. Repeatability in reaching a target force is measured through the spread of DTF values (both minimum-maximum range - shown as whiskers in fig.4.12 - and interquartile range - shown by the rectangles in fig.4.12). In the reference (NoFeed) condition, subjects showed very large spreads (around 1N interquartile range (iqr)) and median values (around 1200mN) for DTF. All forms of feedback tended to reduce both median DTF to around 250mN and its spread to around 300mN iqr, with particularly good performance in both when using visual feedback. Performances were generally similar for the three feedback conditions, although providing tactile feedback (conditions TacPuls-f and TacPuls-f+Visual) tended negatively affect spread of performances without significantly impacting median performance. Providing feedback therefore increased accuracy and repeatability, with similar performances between tactile, visual and combined feedback although tactile feedback seems slightly less reliable. This is a little surprising as subjects tended to

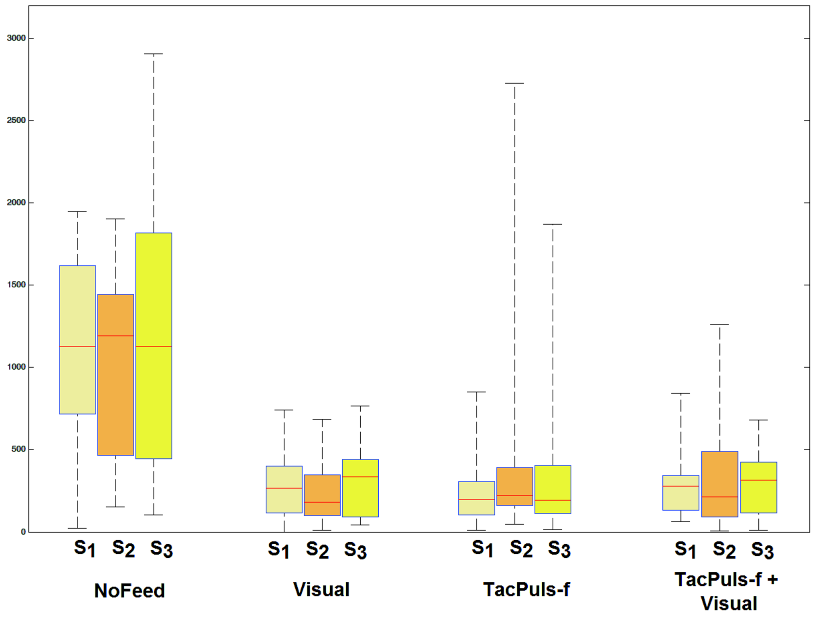


Figure 4.12: ***Feeding back force magnitude with a highlight of the target force :*** *Absolute DTF in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

prefer tactile feedback, finding it less distracting from the task at hand and clearer in indicating the target.

### Speed criteria

SRF was used as a criteria to evaluate the changes in speed-accuracy trade-off when aiming for a target force under provision of various forms of feedback. Higher values indicate better performances, either because similar accuracies were achieved at higher speeds or because higher accuracies were achieved. No notable difference in performances was observed between conditions, leading us to conclude that when feedback was provided, subjects tended to slow their aiming at a given target force. Therefore feedback seems to be beneficial in terms of accuracy but not in terms of efficiency.

### Constancy criteria

The criteria for evaluating the quality of force holds were both the mean force hold error FHE (see fig.4.13) and the drift angles D$\alpha$ (see fig.4.14).

FHE is indicative of the overall error during a force hold task, therefore smaller values indicate better performances. Once again, providing feedback tended to reduce FHE, whereby best performances were achieved using visual feedback alone (Visual) or in combination with tactile feedback (TacPuls-f+Visual). Pulsed vibrotactile feedback improves mean force hold error but

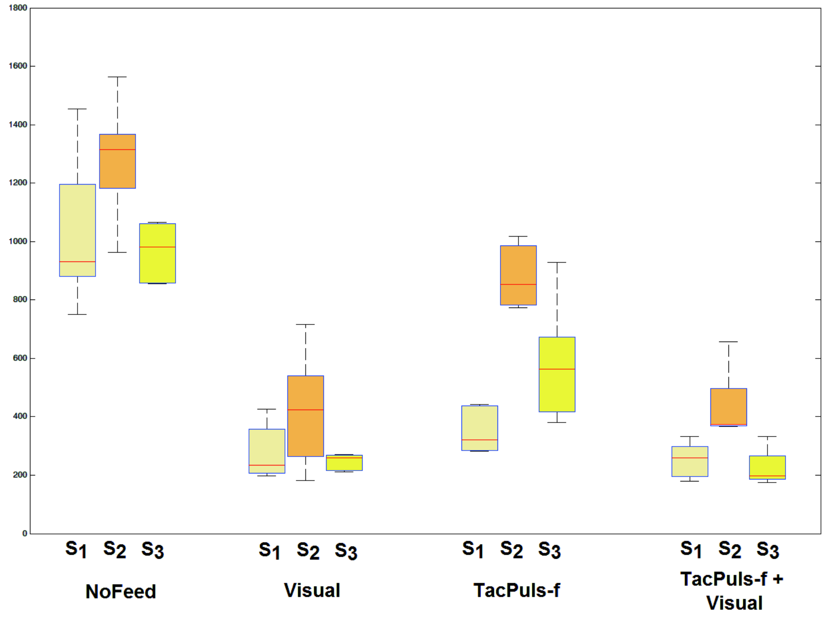


Figure 4.13: ***Feeding back force magnitude with a highlight of the target force :*** *Mean force hold error (FHE) in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

appears less reliable than the other evaluated forms of feedback. The lack in visible differences between visual feedback alone and combined visual and vibrotactile feedback seems to indicate that they do not combine to improve performance and only visual feedback is used.

As expected, in the absence of feedback, there is severe drift from the target force over time, with large variation in drift between trials. The addition of feedback tends to reduce drift amplitude and spread of drift values, with the best results again achieved for visual feedback and combined visual and vibrotactile feedback. However, pulsed vibrotactile feedback alone does not seem to yield significantly worse results over the other forms of feedback despite a slightly increased spread of drift values.

## Conclusion

Overall, changing the feedback scheme from the provision of information on force magnitude to the information on force magnitude combined with a highlighting of the target force tended to bring performances of vibrotactile feedback back on par with visual feedback, although the latter still leads to slightly better performances overall. This would tend to confirm our hypothesis that the main initial advantage of visual feedback stemmed from the availability of reference information simplifying the reaching of a given target force.

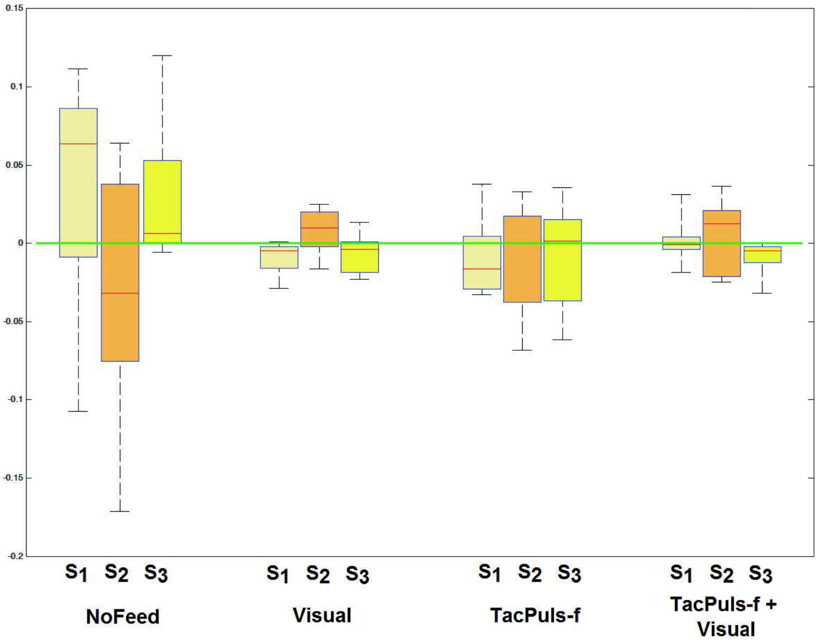


Figure 4.14: ***Feeding back force magnitude with a highlight of the target force :*** *Drift angles during the force hold task ($D\alpha$) in all four feedback conditions, with each subject's performance indicated by a colour. The horizontal green line represents the "ideal" drift value of 0. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

### 4.3.5 Third experiment - part 1 : Feeding back force error information - Amplitude only

As we previously noted, explicit prior knowledge of the desired target force can be used to compute a force error which in turn can be directly shown to the surgeon. The objective of the surgeon is then to simply bring this force error to zero and possibly hold it at this level.

#### Materials and methods

The materials and tasks for the first part of this third experiment remain identical to the previously detailed experiment. However, instead of feeding back absolute force information, we feed back the amplitude of the error between the current force and the target force. No distinction is made between positive and negative force errors, and only error magnitude information is provided to the surgeon.

Concerning the feedback conditions, pilot tests quickly showed that feeding back information on the force error rather than on force magnitude significantly altered the way in which the feedback was used, prompting us to once again investigate the effectiveness of continuous tactile feedback. Thus, the four feedback conditions studied in the previous experiment were expanded to six with the addition of the following two conditions:

TacCont Continuous vibrotactile feedback of the magnitude of the force error was provided using an ERM motor strapped to the inside of the subject's hand, as in experiment I.

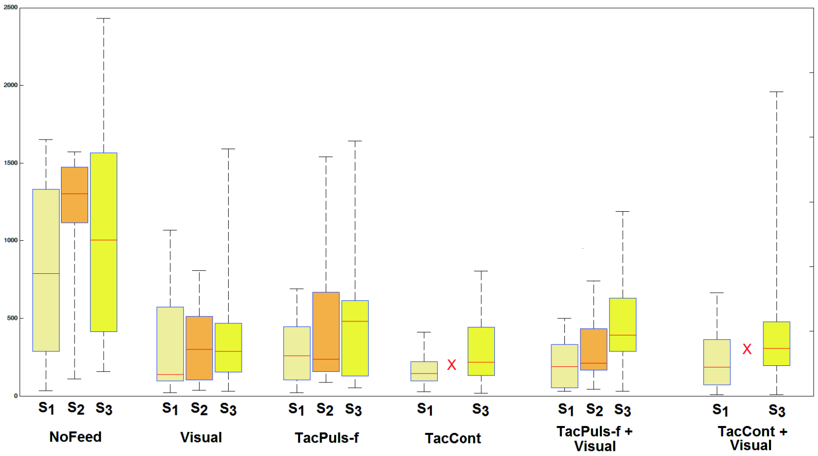


Figure 4.15: ***Feeding back the magnitude of force error :*** *Absolute DTF in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

TacCont+Visual The above tactile feedback was presented simultaneously with visual feedback through an on-screen bargraph indicating the magnitude of the force error.

Again, three novice subjects performed random sequences of both force reach (FRF) and force reach and hold (FHE) tasks in the six feedback conditions. Analysis of the results follows the previously described criteria and procedure.

### Results and discussion

Data for subject 2 in conditions TacCont and TacCont+Visual was corrupted and thus omitted in the discussion and figures 4.15, 4.16 and 4.15.

#### Accuracy and repeatability criteria

As in previous experiments, the reference condition yielded similar large median Distances to the Target Force (DTF) and spreads (see fig.4.15). Providing feedback of any kind greatly reduced median DTF values for all subjects, with similar trends in performance improvements from one subject to another. However no notable differences appear in terms of spread and median for all conditions considered, leading us to conclude that combined tactile and visual feedback may have no beneficial impact on accuracy and that the individual forms alone may be sufficient.

#### Speed criteria

The analysis of SRF again showed no clear trend in improvement or degradation in SRF,

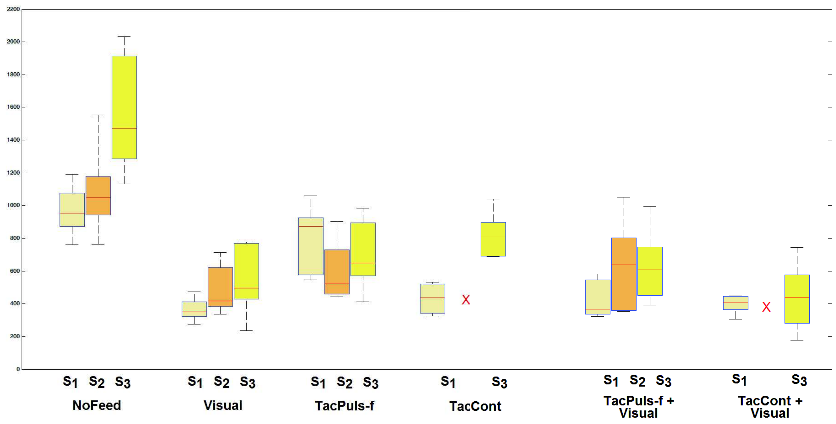


Figure 4.16: ***Feeding back the magnitude of force error :*** *Mean force hold error (FHE) in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

with similar interquartile ranges and medians for all conditions regardless of the type of feedback provided. This would once again indicate that subjects tended to slow down the task execution when using feedback to obtain greater accuracy, thus not significantly altering their efficiency in the task execution.

### Constancy criteria

Results in the reference condition were similar to those of previous experiments, with very large median Force Hold Error (FHE) and a relatively large spread of FHE (see fig.4.16). Providing any type of feedback once again reduced median FHE in varying degrees. The poorer performance observed in condition TacPuls-f when compared to Visual was the main driver behind the choice of once again introducing the continuous vibrotactile conditions (TacCont) in our experimental protocol. Despite our expectations, conditions TacCont and TacCont+Visual did not yield notably better results than the other feedback conditions. Visual feedback alone produced good improvements in force hold accuracy, and these improvements transferred to the combined pulsed vibrotactile feedback and visual feedback condition.

The conclusions drawn based on FHE are reflected in the analysis of the drift angles (see fig.4.17), with feedback generally improving performance in terms of drift, except for the pulsed vibrotactile feedback conditions (TacPuls-f and TacPuls-f+Visual). Best results were once again achieved in the visual, continuous vibrotactile and combined conditions, with D$\alpha$s consistently close to 0 and relatively low spread of performances.

### Conclusion

While providing feedback on the force error is a viable alternative to highlighting a target force in terms of obtaining improvements in accuracy and repeatability, it seems to change the factors influencing the feedback's efficiency. The pulsed vibrotactile scheme evaluated in this experiment partly lost its efficiency, probably because of the low speed of information delivery and possible

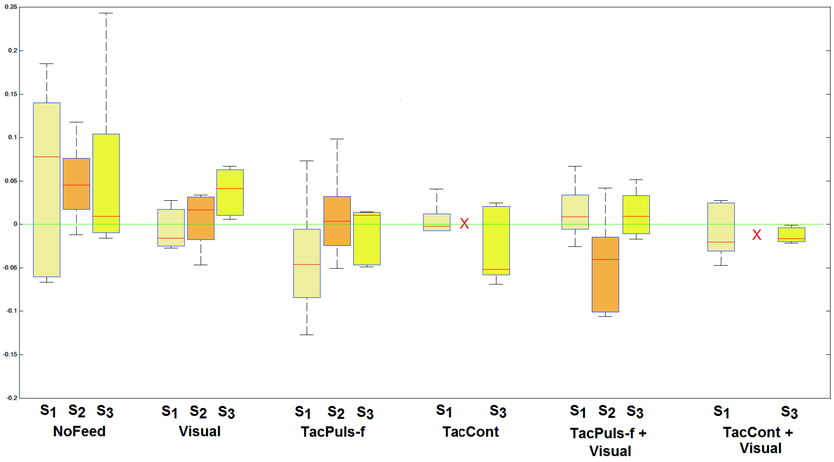


Figure 4.17: ***Feeding back the magnitude of force error :*** *Drift angles (Dα) in all four feedback conditions, with each subject's performance indicated by a colour. The horizontal green line represents the "ideal" drift value of 0. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

confusions between the absence of vibration when "on target" and the absence of vibration during the large inter-pulse intervals when close to the target force. In this situation, continuous vibrotactile feedback appears as a valid alternative, combining the advantages of visual feedback with lower distraction from the task at hand and thus resulting in performances similar to those obtained through visual feedback alone.

### 4.3.6 Third experiment - part 2 : Feeding back force error information - Amplitude and "direction"

The only difference between this second part of the third experiment and the first part is that this time a distinction is made between positive and negative force errors, and both magnitude and direction of the force errors are fed back to the surgeon. To do this, the vibrotactile feedback used a pair of ERM motors, one vibrating when the force error was positive, the other when the force error was negative. Similarly, the bargraph grew upward from the centre position (no force error) when the force error grew in the positive values and grew downward from the centre position when then force error grew in the negative values.

#### Results and discussion

Data for subject 3 in conditions TacCont and TacCont+Visual were corrupted for the force reach and hold (FRH) task and thus omitted from the discussion and figures 4.19 and 4.20. Also, as in the previous experiments, no new conclusions were drawn from the analysis of SRF, which was thus omitted from the following discussion.

##### Accuracy and repeatability criteria

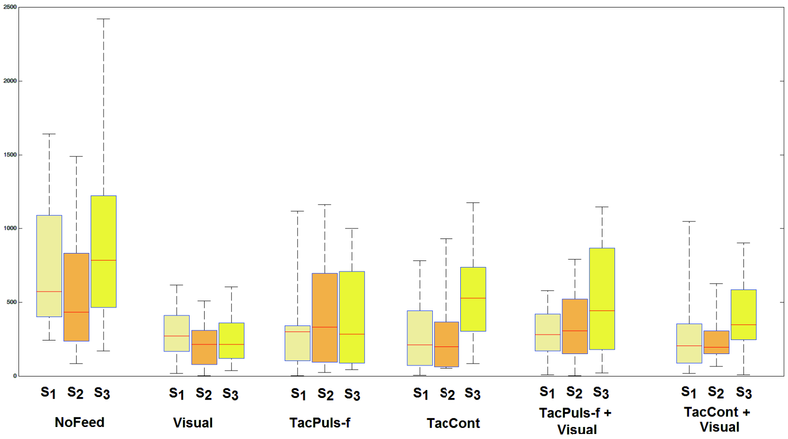


Figure 4.18: ***Feeding back magnitude and sign of the force error :*** *Absolute DTF in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

DTF median values and spreads are shown for each condition in fig.4.18. The pattern of performance improvements observed is almost identical to that of the experiment where only the error magnitude was fed back to the subjects, i.e. all feedback conditions yielded improvements in performance, with the most notable improvements both in median and spread occurring in the Visual condition. Vibrotactile feedback and its combination with visual feedback yielded comparable performances independently from the chosen vibrotactile encoding scheme. In their subjective assessment of the feedback schemes, users tended to note the information on the direction of the force error as very helpful in accomplishing the task. The quantitative performance data however do not back this statement up, either because the perceived help is an illusion or because the task is too complex given the subject's expertise in order to measure any beneficial effect on performance.

#### Constancy criteria

When both direction and magnitude information are provided about the force hold error, all studied forms of feedback yielded similar results (see fig.4.19), both in terms of median performance and of spread, with very marked improvements over the reference (NoFeed) condition. Subjects seemed to perform slightly better in conditions TacCont, TacCont+Visual and TacPuls+Visual, which may indicate that continuous vibrotactile feedback alone is an effective form of feedback for precisely holding a target force over longer periods of time. In terms of drift, only the visual and both combined tactile and visual conditions yielded notable improvements over the reference (see fig.4.20).

### Conclusion

Despite subjective evaluations on the parts of the subject indicating that the indication of the direction of the force error may be helpful in achieving the task, the results in this second part

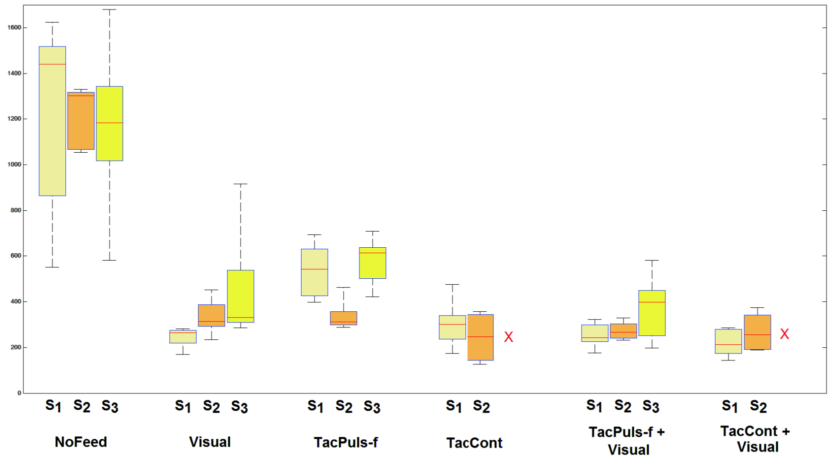


Figure 4.19: ***Feeding back magnitude and sign of the force error :*** *Mean force hold error (FHE) in all four feedback conditions, with each subject's performance indicated by a colour. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

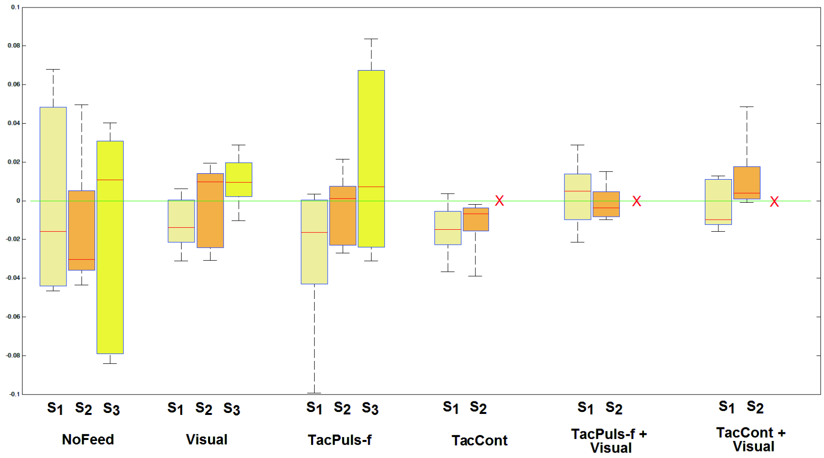


Figure 4.20: ***Feeding back magnitude and sign of the force error :*** *Drift angles ($D\alpha$) in all four feedback conditions, with each subject's performance indicated by a colour. The horizontal green line represents the "ideal" drift value of 0. Horizontal red lines indicate median performance, the rectangle indicates the interquartile range for performances and the whiskers the full range of performances.*

of our experiment on feeding back the force error are pretty much identical to those obtained when feeding back only the force error magnitude.

### 4.3.7 General conclusion on haptic and multimodal feedback of force information

In the present section, we detailed our work on using tactile and multi-modal feedback in assisting laparoscopic surgery gestures requiring fine control of interaction forces. Our experiments focussed on the manipulation of suture threads based on what would occur during conventional suture knot tying, whereby such interactions can easily be generalized to other manipulation tasks such as e.g. lifting tissue.

We presented a series of three experiments starting with the simple idea of feeding back quantitative information on the interaction force magnitude to the user in the hopes that such reliable information may help in better controlling interaction forces in terms of accuracy, repeatability and constancy over time. This initial experiment (*feeding back the magnitude of interaction forces* - see section 4.3.3) showed that **providing feedback on the interaction force magnitude to novices did indeed result in better performances for the given criteria. However, results for tactile feedback were quite disappointing when compared to performances obtained with visual feedback.** This led us to conclude that visual feedback of force information through an on-screen bar-graph provided references which were absent in tactile feedback and thus explained the significant difference in achieved performances.

This led us to our following experiments where we hypothesised that highlighting a previously known target force should bring the performances obtained with tactile feedback to a level comparable to the performances obtained using visual feedback (see section 4.3.4). Having noted the relative ineffectiveness of continuous vibrotactile feedback in providing information on force magnitudes, we focussed solely on using pulsed vibrotactile feedback and its combination with visual feedback. A second experiment was thus performed to validate this hypothesis, leading us to conclude that **when the target force is highlighted, tactile, visual and combined feedback are more or less equivalent in terms of performance, with more user comfort in the tactile feedback conditions.**

Since highlighting the target force supposes a prior knowledge and definition of the target force, we wished to explore an alternative feedback scheme which becomes possible in such a situation : feeding back the magnitude of the force error rather than the absolute interaction force magnitude to the user. A final experiment in two parts evaluated this last aspect, on the one hand providing only feedback on the force error magnitude (see section 4.3.5), and on the other providing information on the force error magnitude and direction (see section 4.3.6). **Pilot tests showed that feeding back information on the force error rather than on force magnitude significantly altered the way in which the feedback was used**, prompting us to once again investigate the effectiveness of continuous tactile feedback. **Results were similar to those obtained when highlighting a target force and did not differ depending on whether only magnitude or both magnitude and direction information were provided. As expected from the pilot tests, continuous vibrotactile feedback yielded better results than pulsed vibrotactile feedback in this modified scheme.**

**Overall, we have shown the potential of using tactile feedback in feeding back force information with the aim of improving accuracy, repeatability and constancy in fine force control tasks in laparoscopy.** These results however remain preliminary and would warrant further investigation as well as refining of the tactile feedback so as to unlock their full potential in terms of surgical gesture assistances.

## Prospects for future work

The work presented here has focussed on relatively simple interaction tasks, where knowledge of the force magnitude alone was usually sufficient for satisfactory performance. Certain surgical tasks however may require knowledge of force magnitude, direction of application and components of the force in various directions. Therefore it would be interesting to evaluate more complex feedback schemes for this additional information.

Also, the bi-manual tasks we evaluated here were limited to the assumption that applied forces were evenly distributed between both instruments, which is also often not the case in surgical practice. An evaluation of bi-manual feedback schemes would therefore also be of interest.

And last but not least, future work should ideally focus on surgeon populations with experience in laparoscopy so as to assess the benefit in task performance for the actual target population and in real clinical settings. This of course supposes the use of laparoscopic instruments fitted with adequate force sensors.

Chapter 5

# Refining the vibrotactile feedback design

## Contents

## 5.1 Introduction

Our experiments discussed previously showed avenues for improving performance in navigation and force control tasks by providing adequate feedback to users. In particular, vibrotactile feedback appeared as a novel alternative to conventional feedback methods, and could lead to performance improvements. However our initial experiments are far from an exhaustive analysis of design options for vibrotactile feedback systems. To lay the foundation for potential future tactile assistance systems for laparoscopic surgery application, it is necessary to systematically approach the design of tactile stimuli in the light of knowledge from ergonomics, human-machine interaction and the specificities of MAS. In the present chapter we wish to present an initial discussion on the avenues for vibrotactile feedback design, drawing parallels between literature findings and our own experience on the subject.

Several dimensions need to be taken into account in designing appropriate feedback for laparoscopic surgery applications if it is to function optimally with the widest possible acceptance. From a human factors point of view, critical information should be conveyed as efficiently as possible so as to maximize the recipient's comprehension while minimizing factors detrimental to task performance such as cognitive overload or distraction ( [306], [307]).

Wickens et al. introduce 13 principles for designing displays intended for information communication, grouped into four categories ( [308]):

- Perceptual principles
- Mental model principles
- Attention-based principles
- Memory principles

Following these principles is an effective method for designing displays which lead to reduced errors during use and training required, while increasing efficiency and user acceptance.

**Perceptual principles**
Regarding perceptual limitations, displays must first be legible, i.e. the different stimuli must be discernible by the user. Displays should also avoid absolute judgement limits, i.e. clear discrete changes in stimulus level should be preferred over gradual stimulus variations. A third point to take into account is "top-down processing", the fact that people perceive and interpret signals according to their expectations based on past experiences. A fourth principle is that of redundancy gain, that is that information is more clearly transmitted when displayed in a redundant manner - for example in a traffic light, the three possible states of information are coded both through position and colour of the lights. The fifth and final perceptual principle is that of discriminability, as similarity is a cause of confusion, discriminable elements should be used to convey information.

**Mental model principles**
There are two mental model principles, the principle of pictorial realism and the principle of the

moving part. The principle of pictorial realism states that one should aim for representations in displays which naturally reflect the information being conveyed, e.g. showing high and low speed on a vertical scale instead of horizontal scale since top and bottom more naturally associate with the concepts of high and low respectively. The principle of moving part states that moving elements should move in a pattern and direction compatible with a user's mental model of the actual movement in the represented system, e.g. the mobile element in an altimeter should move upward with increasing altitude.

#### Attention-based principles

The three attention based principles are the minimization of information access cost, the proximity compatibility principle and the principle of multiple resources. Information access cost should be minimized in that a user should not spend too much time searching for the correct source of information. Therefore, in complex displays, the most important source of information should also be the most salient, and information sources should be arranged in such a manner as to minimize searching between different information source locations. The proximity compatibility principle states that similarly functioning display elements are supposed to be closer together (either physically or within the user mental model) or at least display common elements (e.g. colour, shape in visual displays) so as to lower information access cost. The principle of multiple resources is based on Multiple Resource Theory developed by Wickens et al. ( [307]), stating that information is usually easier to process when well distributed over the user's various distinct attentional resources.

#### Memory principles

Finally, the three memory principles are the following: The replacement of memory with visual information, the principle of predictive aiding and the principle of consistency. The idea of replacing memory with visual information is that if information is displayed "ecologically" i.e. it directly resembles occurrences in the real world, the user can more easily decode the information and does not need to retain important information in working or long-term memory. The principle of predictive aiding states that pro-actively showing information about possible future happenings to users instead of only reactively responding to user's actions tends to improve performances. Finally, the principle of consistency relates to long-term memory in that previous user knowledge and experience of certain ways of displaying information should be reused for similar information and avoided for different information so as to capitalize on experience and avoid confusions.

When applied to information feedback displays in laparoscopic surgery, these imperatives dictate both the choice of sensory modality for communicating the information and the cue design, which in turn pose requirements towards the display technology to be used.

## 5.2 Modality

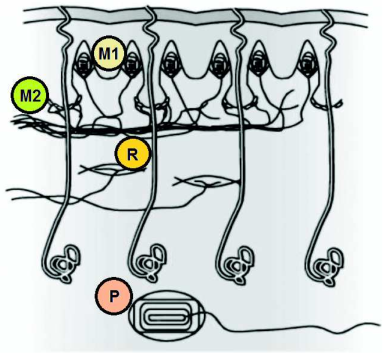
Our preliminary results have shown some potential of both vibrotactile and kinaesthetic cues for providing navigation information to the surgical tool user. Similar results were found for vibrotactile feedback in our experiments on feedback of interaction forces at the tool tip. However the complexity and specific challenges associated with kinaesthetic feedback through virtual fixtures led us to focus mainly on the development and evaluation of vibrotactile feedback cues for MAS applications.

In the present chapter, we will attempt to list recommendations for the design of tactile feedback stimuli providing information on task performance in a laparoscopic setting. A stimulus is generally defined through four attributes: modality, location, intensity, and temporal characteristics ( [94], [167]).

**The rest of this chapter is structured as follows :**
We begin by briefly presenting the biological aspects underlying the perception of vibrotactile stimuli. We then present an overview of the insights gained from our experiments regarding requirements for presenting force and position information in laparoscopy. Following this, we decompose vibrotactile stimuli into their various dimensions, briefly discussing literature and our own findings on each. Following the structure of the thirteen principles of display design discussed above, this allows us to draw up certain recommendations on the various dimensions of vibrotactile stimuli. Since not all 13 principles are directly relevant at this level of the discussion, we discuss the recommendations principle by principle for a selection of those directly applicable. Each time, we draw parallels between literature findings and our own findings. The principle of redundancy gain is discussed separately in brief concluding remarks on information transmission through simultaneous variation of multiple stimulus dimensions and multi-modality. Finally, we offer perspectives on future development of tactile assistance systems for MAS.

## 5.3 The biology behind the perception of vibrotactile stimuli

This section presents the biological aspects underlying the sense of touch, and in particular those pertaining to the perception of vibrotactile stimuli, in order to lay a foundation for the understanding of the following discussion on the usable stimuli parameters. More detailed information on the sense of touch in general, haptic perception and its applications can be found in works by Hayward [124], Lederman et al. [164] and McGlone and Reilly [186].



| receptor type | RAI<br>(Meissner) | SAI<br>(Merkel) | RAII<br>(Pacinian) | SAII<br>(Ruffini) |
|---|---|---|---|---|
| field diameter | 3–4 mm | 3–4 mm | > 20 mm | > 10 mm |
| mean receptive area | 12.6 mm$^2$ | 11 mm$^2$ | 101 mm$^2$ | 59 mm$^2$ |
| spatial resolution | fair | good | very poor | poor |
| frequency range | 8–200 Hz | DC–200 Hz | 50–1000 Hz | DC–200 Hz |
| most easily excited frequency range | 8–64 Hz | 2–32 Hz | > 64 Hz | < 8 Hz |
| relative amount | 43% | 25% | 13% | 19% |
| postulated sensed parameter | skin stretch | compressive stress (curvature) | vibration | directional skin stretch |
| density | 70–140 /cm$^2$ | 70–140 /cm$^2$ | 20 /cm$^2$ | 50 /cm$^2$ |

Figure 5.1: *Mechanoceptors in the skin : Merkel cells (M2), Meissner corpuscles (M1), Pacinian corpuscles (P) and Ruffini endings (R). The table on the right lists of few properties of each mechanoceptor in glabrous skin* [1].

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[1] Adapted from Kajimoto et al., "SmartTouch: electric skin to touch the untouchable" [144]

Among other organs for sensing e.g. temperature and pain, various cutaneous mechanoreceptors convert mechanical deformations caused by indentation, vibration or slip of the skin into electrical nerve impulses. The four main types of mechanoceptors (see fig. 5.1) in glabrous skin are categorized as per the size of their receptive fields and frequency responses. Mechanoceptors in the skin are either slow adapting (SA) or rapid adapting (RA) depending on their frequency response, and have either small receptive areas with clear boundaries (Type I units) or large receptive areas with poorly defined boundaries (Type II units). The receptor's behaviour displays large hysteresis, with strong reactions to pressure increases and minimal responses to pressure drops. Both SA and RA type I receptors are located in close proximity to the skin surface where skin deformation and stresses are more pronounced, these are the Merkel cells (SA) and Meissner corpuscles (RA). Type II receptors are usually located deeper within the skin and comprise the Ruffini endings (SA) and Pacinian corpuscles (RA). Merkel disks and Ruffini corpuscles are mainly sensitive to static pressure while Meissner and Pacinian corpuscles respond respectively to the low and high frequency components of skin indentation. The maximum frequency of perceptible vibrations is close to 1kHz ( [264]) with a peak in sensitivity between 250Hz - 300Hz ( [143]), corresponding to peak sensitivity of the Pacinian corpuscles. The relevant physiological details regarding perceptual thresholds for vibrotactile stimulus attributes are discussed below.

In their review on the design of tactile displays, Jones et al. ( [142]) conclude that among the information encoding parameters available through vibrotactile stimuli, the most promising for encoding a wide range of information efficiently would be in the variation of location and duration characteristics of the stimulus. Variations of frequency and intensity on the other hand appear more limited in their applications.

## 5.4 A brief overview of requirements for tactile assistance systems to MAS arising from our findings

### Assisting navigation of a laparoscopic instrument

Regarding presenting information for assisting navigation of a laparoscopic instrument towards a target using tactile feedback, our experiments led us to conclude that:

- Feedback highlighting a target yields better navigation accuracy when there is greater contrast between the near-target feedback and the on-target feedback (e.g. continuous vibration near the target and no vibration on target as opposed to vibration pulses with long inter-pulse intervals near the target and no vibration on target). This is consistent with findings by Oron-Gillad et al. [203].
- Quantitative information on the distance to a target (i.e. position error amplitude) is not an absolute necessity for improving accuracy, however indication of the direction of variation of the position error is.
- The intensity of presented vibrations should be limited as too much vibration tends to cause discomfort to the user and disturb corrective action.
- The refresh rate of tactile information and quick understandability of the feedback is critical. This is especially true during corrective movements close to the target.

### Assisting control of tool-tip interaction forces

With regards to presenting force information through tactile feedback, our experiments led us to conclude that:

- Presenting force magnitude information by itself is not helpful to users in force control tasks. To effectively use the feedback for correction of errors, users require some form of reference, which can be provided e.g. by highlighting a target force or target force range. There then seems to be little difference in effective performance between providing information on absolute force magnitude with a highlight of the target and presenting information on the force error magnitude with respect to the same target force.
- Rhythmical coding of force magnitude alone is more effectively understood than joint amplitude and frequency coding of the same information. This may either be due to increased resolution of the feedback or intuitiveness of such coding.
  Highlighting a target force by changing the location of the delivered tactile stimuli is effective.
- Similarly to navigation tasks, highlighting a target force through absence of feedback (as was the case when feeding back force error information) is more effective when the contrast with the near-target feedback is greater (in this case when using continuous tactile feedback instead of pulsed feedback). This again is consistent with findings by Oron-Gillad et al. [203].
  Providing a direction of variation of the force with respect to the target (i.e. closer/farther cues) helps users in their corrective movements, however an indication of absolute force variation direction (i.e. higher/lower absolute force) does not necessarily improve performance though it improves user comfort.
- Again, as for navigation information, the intensity of vibration should be limited, in particular close to the target force as too much vibration disturbs motor action. The refresh rate of tactile information must also be high and the information quickly understandable by the subject.
- These are initial recommendations drawn from our own experimentation, and the detailed analysis of vibrotactile stimulus dimensions and implications for feedback design in the following aims to expand on them and explain them in the light of literature findings.

## 5.5 Location

Stimulus location can be a powerful tool for encoding vibrotactile information. Coding information through vibrotactile location has been evaluated for various scenarios, including general purpose tactile displays ( [172], [287], [241], [315]), vision-substitution systems [20], gesture guidance ( [24], [25]), pedestrian and vehicle navigation ( [288], [284], [173], [130], [75]).

### 5.5.1 Physiological aspects

#### Spatial resolution - Detection and discrimination thresholds

Spatial resolution appears as a relatively tricky problem in tactile perception. A traditional measure of spatial resolution having lead to recommendations on the upper limit for the number of usable vibrotactile actuators in a given area is the 2-point threshold. Two-point discrimination is the ability to discern that two nearby stimuli presented to the skin are truly two distinct stimuli, not one (see fig. 5.2). The two-point threshold for a given area of the skin thus represents the limit value (in mm) below which two neighbouring vibrotactile stimuli are confused, appearing as a single point vibration.

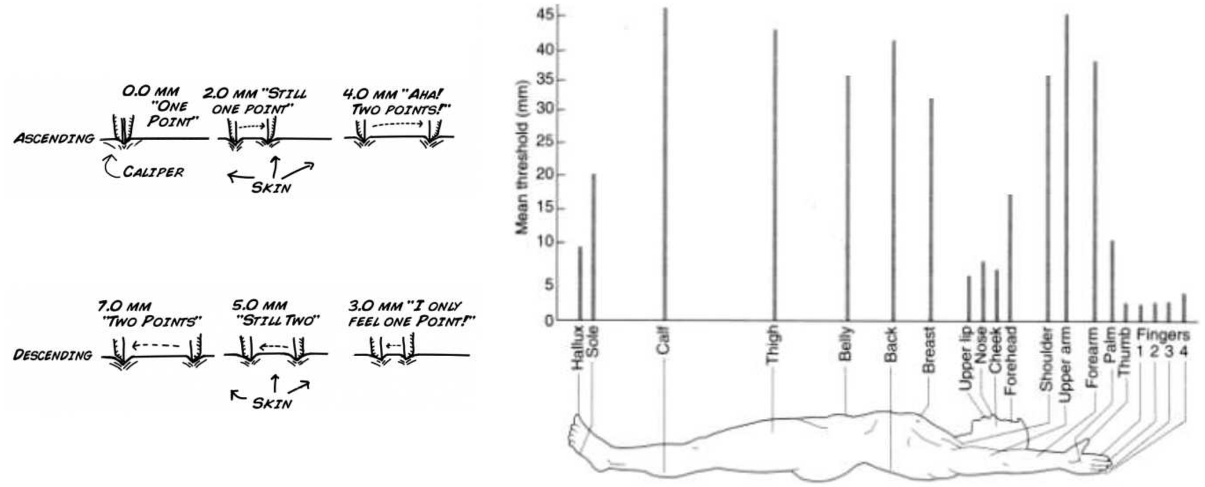

Figure 5.2: *Left : Traditional test to determine two-point threshold for skin indentation at a given location* [2] *; Right: Two-point pressure limen on various parts of the male body* [3]

The 2-point threshold varies greatly depending on the body site (see fig. 5.2), with excellent acuity displayed for pressure stimuli at the hand [217], and probably the worst at the back and lower limbs. However, it is to be expected that the large and poorly delimited receptive fields of the Pacinian corpuscles will lead to much lower spatial acuity for vibrotactile stimuli than for pressure stimuli ( [94]).

The two-point threshold on a given skin area is not constant, it is affected by the amplitudes, frequencies, vibration pulse durations and temporal synchronisation of the stimuli.

Concerning the impact of vibration pulse duration and temporal asynchrony on spatial resolution, Van Erp et al. ( [285]) for example studied the effects of varying these parameters when presenting pairs of vibrotactile stimuli to the torso, concluding that increases in both pulse duration and stimulus onset asynchrony had a positive impact on correct identification of the stimuli, based on a uniform acuity of 20-30 mm, except at the body mid-line, where it descended to approx. 10 mm.

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[2] From $http : //wiki.backyardbrains.com/Skin_{a}nd_{T}actile_{A}cuity$

[3] From Goldstein et al. "Sensation and Perception"

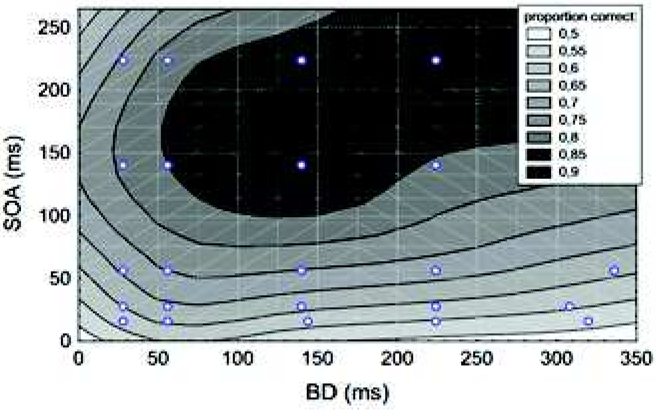

Figure 5.3: *Contour plot indicating correct identification rates of dual or unique pulses presented at the torso, as a function of burst (or pulse) duration (BD) and stimulus onset asynchrony (SOA). Darker colours indicate better performance (in % correct identification)* [4].

Vibrations tend to propagate throughout the skin, thus another measure of spatial resolution is the measurement of the maximum number of discrete points of vibrotactile simultaneous that can be correctly resolved as a function of location, amplitude and frequency.

As previously mentioned, the relative temporal onset of vibrotactile stimuli at different locations seems to play a significant role in whether they are resolved as a single stimulus or confused.

Concerning simultaneous stimulation, Geldard [94] suggested that no more than 13 simultaneous stimulation points throughout the body could be used to encode information through vibrotactile location. This values would seem to indicate that encoding of information through vibrotactile location alone would be appropriate for simple information and rapidly reach its limits when complex spatial information is to be presented.

However, according to Bach-y-Rita et al. [21] this limit value is somewhat restrictive. Having developed a 400pt vibrotactile actuator matrix with 10 mm resolution, they obtained excellent pattern recognition ability on the back. Their hypothesis is that similarly to vision, although there is a visual 2-point threshold, visual Vernier acuity [5] is approx. 10 times better than said threshold, and the number would be similar for vibrotactile sensation.

Concerning temporally discrete stimulation, similar studies have evaluated the presentation of vibrotactile patterns progressing along arrays of vibrotactile actuators [141] with encouraging results. Finally, it should be noted that there is a certain quantity of literature on the use of tactile illusions such as the funnelling illusion (see fig. 5.4) or cutaneous rabbit to produce the illusion of variations in location of the tactile stimulus with a limited number of actuators [125]

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[4] From Van Erp et al. "Vibrotactile spatial acuity on the torso: effects of location and timing parameters" [286]

[5] Vernier acuity is a type of visual acuity that measures the ability to discern a misalignment among two line segments or gratings. A subject's Vernier acuity is the smallest visible offset between the stimuli that can be detected. Because the misalignments are often smaller than the diameter and spacing of retinal receptors, this phenomenon is also known as hyperacuity.

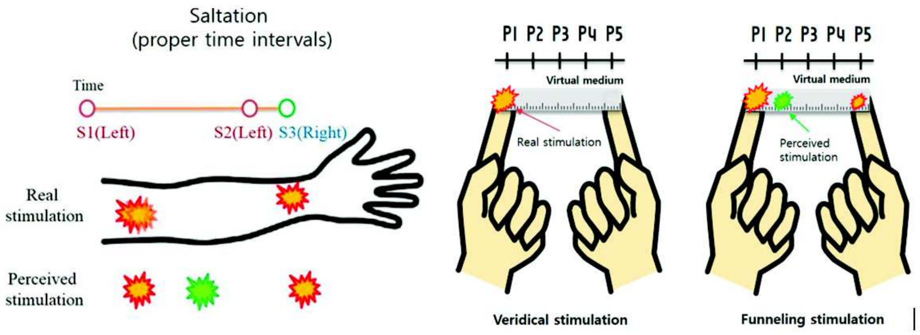

Figure 5.4: *Funnelling illusion* [6]*. With this illusion, an individual perceives simultaneous vibrations to multiple locations on an area of skin as a single vibration somewhere in between.*

Such illusions may be an avenue towards presenting more complex spatial vibrotactile stimuli ( [53], [29], [12], [226], [125]), but this should be approached cautiously as these illusions are not necessarily robust, and are heavily influenced by environmental conditions, subject expectations and mental workload.

#### Impact of location on perceived intensity of vibrotactile stimuli

We mentioned that location discrimination of vibrotactile stimuli is significantly affected by frequency, amplitude and temporal parameters of the stimuli groups. Inversely, it should be taken into account that tactile actuator placement has a significant impact on the perceived intensity of vibrotactile stimuli, given the differences between skin regions in terms of density of mechanoceptors and innervation. As such, distributed tactile feedback to present information based on location may require adjustment to the stimuli presented to different skin to compensate for physiological differences and create a unified perception.

### 5.5.2 Implications for coding information through location

As can be seen in the applications reviewed above, coding information through tactile stimulus location is a particularly popular approach for navigation and guidance applications ( [288], [284]). Indeed, the association between tactile location and desired direction of movement comes quite intuitively. Concerning feedback of force information, we found no literature expressly addressing this situation using coding through tactile stimulus location. However some parallels can be drawn between 1D navigation with indication of positional error and feedback of force error information as we have seen in our experiments in chapter IV. The above state of the art allows us to draw a certain number of conclusions regarding effective ways of feeding back information in navigation scenarios.

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[6] From Lee et al. "Brain Process for Perception of the “Out of the Body” Tactile Illusion for Virtual Object Interaction" ( [165])

### Principle of display legibility and of discriminability of elements

When coding information through vibrotactile stimulus location, display legibility and discriminability of elements are closely related. To ensure legibility, the vibrotactile actuators must be placed on skin locations where the stimuli they deliver are clearly perceptible. This is usually not much of a challenge unless operating close to the vibrotactile sensation threshold, as this can significantly differ from one body site to another. The main issue when placing the vibrotactile actuators lies in not hindering subject movement or causing discomfort while ensuring constant contact of the actuator with the skin. This last point is particularly problematic at joints and on body parts whose volume is subject to change (e.g. parts of the arm through muscular contraction, the hand through various movements, or the torso through breathing). Applications delivering stimuli to these locations have however successfully used workarounds to this issue by attaching the vibrotactile actuators using elastic straps.

In terms of disciminability of elements, the placement and spacing of the tactile actuators must take into account the physiological limits imposed by the vibrotactile two point threshold. That is the various vibrotactile stimulation points must be clearly discernible in order for the display to be efficient. Reviewed systems that used tactile actuator locations to encode information usually used up to 8 tactile actuators (seldom simultaneously) to indicate directional information and yielded satisfying results. To our knowledge there is little work on using larger number of tactile actuators to convey more abstract or complex directional information. In their work on vibrotactile feedback for surgical instrument navigation in open surgery, Brell et al. ( [41]) suggest that user comfort can be improved when coding information through vibrotactile stimulus location when the vibration is pulsed rather than continuous.

### Avoidance of absolute judgement limits

When applied to displays using vibrotactile stimulus location, avoidance of absolute judgement limits requires the stimulus locations to change in a discrete and clearly discernible fashion. This is usually inherently the case as to the best of our knowledge, there have yet not been any applications using tactile actuators whose position on the body changed over time. However, this point must be taken into account when taking advantage of hyperacuity [21] or using illusions of movement such as the funnelling illusion (see fig. 5.4) or vibrotactile saltation. In such cases, the clarity of changes in information content may be negatively affected by the lack or indistinct transitions between apparent vibrotactile stimulus locations.

### Top-down processing

When coding information in vibrotactile stimulus locations, the layout and activation pattern of vibrotactile actuators should correspond to user's expectations based on past experience. Though common applications using vibrotactile feedback which could be source of such experience are limited, it would seem sensible to have the vibrotactile feedback coming from the manipulated device (e.g. surgical tool) itself or at the very least to be presented in close proximity to the tool. This would take advantage of user expectations from manipulation of mobile devices with vibrotactile feedback. When coding directional information, aligning the stimulus locations with the task direction either physically or at least in a manner that is compatible with the user's mental model as well as the use of coherent mapping between stimulus direction and task is required. Finally, said mapping should stay constant throughout the different encountered situations so as to ensure a coherent user mental model of the feedback.

### Principle of pictorial realism and principle of the moving part

Pictorial realism requires the display to naturally reflect the information being conveyed, which is in this case also covered by the principle of the moving part.

Common sense would dictate that for when coding directional information only through vibrotactile stimulus position, a pair of motors is required for every direction component to be fed back, one for forward motion and one for backward motion. Indeed this is a principle followed in many of the considered applications. Bark et al [24] performed an experiment to assess if there were differences between "attractive" (the change of stimulus location takes place in the direction of the required movement) and "repulsive" (the change of stimulus location takes place in the opposite direction to that of the required movement) coding schemes for direction when using pairs of vibrotactile actuators to indicate a direction of corrective movement in a posture tracking task and found no significant differences overall, indicating that both schemes may be compatible with user mental models.

If coding information on the magnitude of a variable (e.g. interaction force or deviation distance), a natural association comes between a physically rising signal (i.e. location of stimulation travelling upward) and a rising value of said variable.

### Minimization of information access cost

Information access cost should be minimized in that a user should not spend too much time searching for the correct source of information. Similar to top-down processing, there is some evidence to suggest that performances are improved when feedback is presented as spatially co-located with motor action [90]. Thus it would be of interest to have the vibrotactile stimuli locations at the level of the hand manipulating the laparoscopic instrument or on the instrument handle itself.

From a purely practical point of view, our initial thoughts as to vibrotactile actuator placement led us to consider integration of vibrotactile actuators within the surgical tool handles. This would have the obvious benefit of not interfering with the surgical workflow while raising issues of instrument sterilizability and design.

Figure 5.5: *Varying grasps depending on surgeon, operating room configuration or stage of the surgery.* [7]

However, our observations during conventional laparoscopy procedures showed that depending on the surgeon, procedure and context, there is in most cases a wide variety of ways of holding a single tool, arguing against integration of tactile actuators to the tool handle in such situation. Nonetheless, it may probably still be sensible to have tactile actuators present on easily accessible portions of the instrument so as to present information to the surgeon should he or she desire it.

For guidance, integration in surgical gloves seems more sensible, but requires tracking of the surgeon's hand. Two scenarios arise in which control of tool-tip interaction forces may be necessary, grasping and handling tissue, sutures or other sensitive structures, and palpation or coming into contact with tissue. In the case of grasping, integration of vibrotactile actuators on the grasping surfaces or inside of the instrument (resting against the palm) is sensible as the act of grasping requires contact between the hand and these surfaces. Also, in the case of dexterous instruments, the control of the actuated degrees of freedom imposes contact between the hand and given parts of the instrument handle, which would also lead to a similar situation.

#### Proximity compatibility principle

The proximity compatibility principle states that similarly functioning display elements are supposed to be closer together, either physically or within the user mental model, and use similarly functioning elements. This is of particular importance when designing a vibrotactile display for several information components (e.g. simultaneous navigation and force information) in that grouping of vibrotactile actuator locations can serve as a distinguishing feature between information components.

## 5.6 Intensity

Intensity of a vibrotactile stimulus designates the magnitude of vibration. Among other things, it has been used as a parameter for encoding information in general purpose human-computer interaction ( [283]) feeding back deviation amplitudes in guidance tasks ( [24], [25]), and feeding back force magnitude information in force control tasks ( [7])

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[7] Photo credits: Thomas Howard 2015

Increases in vibration amplitude correlate with a direct perceived increase in intensity (or « loudness »), such that the terms intensity and amplitude are often used interchangeably when discussing vibrotactile stimuli [35]. Similar to audio signals, vibrotactile intensity is expressed in decibels above the detection threshold - or Sensation Level [dB SL]. This detection threshold is thus defined as the lowest amplitude of periodic displacement that can be detected as a tactile sensation.

### 5.6.1 Physiological aspects

#### Detection threshold and range

The vibrotactile detection threshold is highly dependent on several variable, such as the subject experiencing the vibration ( [101]), the size ( [296]) and properties of the vibrotactile actuator ( [290], [101], [98]) and location of presentation of the stimulus (see fig. 5.6). In particular, the sensation of vibrotactile intensity is highly frequency dependent, except in the lower range between 20-40Hz. Between 40 and 700Hz, peak sensitivity is generally observed between 250Hz and 300Hz ( [159]). An example of the perceived vibrotactile intensities depending on frequency and stimulus location is shown as examples in fig.5.6.

There is also an interplay between stimulus duration and spacing and perceived intensity, i.e. amplitude variations in long continuous vibrations are better resolved than differences in amplitude between short successive bursts [96]. Further complexity arises in the perception of vibrotactile intensity when multiple stimuli are involved, as the interplay between them modifies their perceived intensity. Zhang et al. ( [323]) performed an evaluation of the vibrotactile two-point threshold and noted that discrimination of amplitude differences between two vibrotactile stimulations severely degraded as they came closer to each other, nearing the two-point threshold. Marks ( [182]) also shows that when superimposed vibrotactile stimuli are delivered to the skin via a single tactile actuator, the overall perceived intensity also depends on the frequency difference between both stimuli. With small frequency differences, the tactile sense acted by summing energy and with large frequency differences, the tactile sense acted by summing loudness.

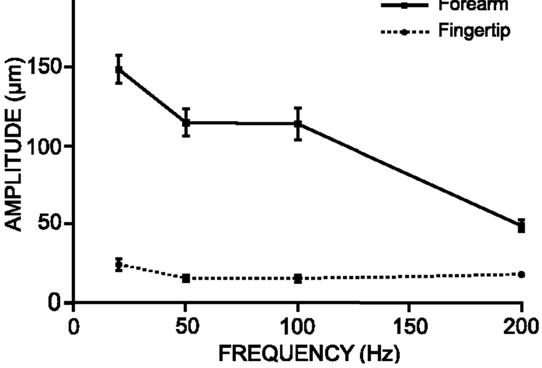

Figure 5.6: *Vibrotactile intensity detection threshold on the forearm and fingertip as a function of vibration frequency, from Mahns et al. [180]*

### Discrimination of vibrotactile intensities

Discriminability of vibrotactile intensities is measured through the so-called difference limen, i.e. the amount of variation required in the stimulus to achieve a change in perceived intensity. The difference limen is usually expressed either through the relative amount of change required in the stimulus (in [dB]) or through a ratio called the Weber fraction, obtained by dividing the required intensity increase to notice a change by the base intensity of the vibration ( [251]). The Weber fraction for vibrotactile intensity has been the subject of many studies, with values ranging between 0.07 and 0.4 ( [290]), as these are also dependent on stimulus frequencies, body site to which the vibration is presented and actuator properties.

Ahmaniemi et al ( [7]) investigated amplitude modulation for feedback of pressing force using one finger, concluding that dynamic feedback seems to help in accuracy of repetition, less so in holding. Overall, amplitude and frequency modulations yielded worse performances than rhythmical coding of force information through vibrotactile pulse trains (see fig. 5.7).

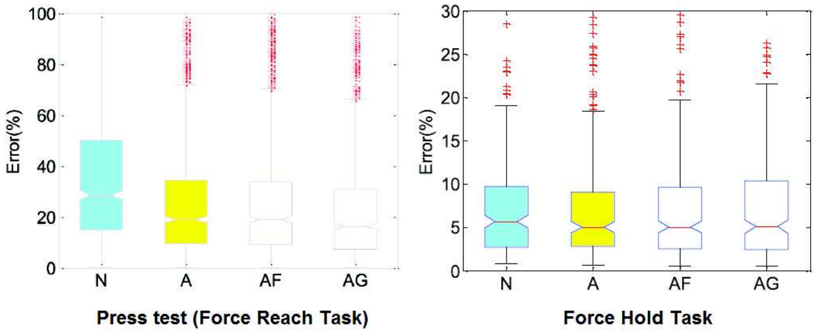

Figure 5.7: *Evaluation of amplitude modulation (A) in force control of fingertip pressing force, compared to absence of feedback (N), joint amplitude and frequency modulation (AF) and pulse rate modulation (AG) [7]*

### Absolute identification of vibrotactile intensities

The difference limen for vibrotactile intensities can indicate intensity steps so as to provide a user with the sensation of a change in intensity, however it cannot directly be used to calculate the number of absolutely identifiable vibrotactile intensities. Some psychophysical studies have been conducted on absolute identification of vibrotactile intensities with rather disappointing results ( [54], [94]).

## 5.6.2 Implications for coding information through vibrotactile intensity

### Principle of display legibility

To ensure legibility of vibrotactile signals with regards to intensity, the stimuli must be above the detection threshold (see fig.5.6 and [290], [289]) for the given user. This detection threshold can either be deduced from existing psychophysical studies combined with a given safety margin or assessed individually for the given user thanks to psychophysical study methods such as the Method of Constant Stimuli [8] ( [95]).

General guidelines relating to the physiological limits of intensity ranges allowing for perceptible communication of vibrotactile intensity are the following : Peak sensitivity is generally observed for vibration frequencies between 250Hz and 300Hz ( [159]). A rigid element around the vibrating actuator ("surround") lowers the detection threshold in the lower frequency ranges ( [98]). Vibrotactile intensities should not exceed approx. 55dB SL, as above this threshold, vibration tends to cause discomfort and even pain ( [290]). Finally, Bark et al. ( [24]) recommend using graded feedback (i.e. with more than an on/off state, with indication of direction of variation) when encoding deviation information through vibrotactile intensity, ideally using adaptive dead-bands that adjust to the tracking system performances.

### Avoidance of absolute judgement limits and Discriminability of elements

The principle of avoidance of absolute judgement limits implies that rather than continuously varying vibrotactile intensity to encode information, it is more sensible to encode information through a series of distinguishable fixed vibrotactile intensities.

This could partly explain the relatively poor performance of continuous vibrotactile feedback in presenting force magnitude information in our experiments on controlling tool-tip interaction forces.

As mentioned above, the usable vibrotactile intensity range lies between 0dB SL and 55dB SL. The Weber fraction for vibrotactile intensity discrimination being largely dependent on actuator properties, an evaluation on the set-up at hand would be required to make best use of the vibrotactile intensity range for encoding information. However, Brown ( [46]) suggest that a safe intensity step to ensure vibrotactile intensity discrimination would be above 2.3dB. This would therefore lead to a maximum number of 22 vibrotactile intensity steps available for encoding discriminable information in the best case scenario, and when absolute identification is not necessary.

When absolute identification is necessary, much more conservative estimates are provided in work by Goble et al. ( [101]), suggesting that independently of other factors, four levels of vibration amplitude are always easily identifiable. Studies by Geldard et al. ( [94]) and Cholewiak et al. ( [54]) support this claim, suggesting that no more than three levels of vibrotactile intensity be used over a large range of frequencies when absolute identification is required without training, a value which may rise as high as 15 different vibrotactile intensities in the event of prior training with the display.

Oron-Gillad et al. [203] studied navigation towards a target in 2D space under provision of feedback on deviation amplitude thanks to joint vibrotactile amplitude and frequency modulation. They showed that a decisive factor in accuracy and efficiency during such a task was a high

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[8] The method of constant stimuli is a psychophysical method for studying sensory absolute and differential thresholds developed by Gustav Fechner. The absolute threshold of a modality is examined by repeatedly presenting a series of fixed stimuli in random order and asking the subject to report if they detect it or not. The threshold is determined as the value that was detected 50% of the time.

contrast between the near-target vibration amplitude and the on-target vibration amplitude.

#### Top-down processing and Principle of pictorial realism

Pictorial realism states that one should aim for representations in displays which naturally reflect the information being conveyed. Higher vibration intensities can tend to be associated with higher levels of a variable as well as with a sense of urgency [44]. Thus coding variable such as force magnitude or deviation amplitude in a manner that low values are associated to low vibration intensities and high values are associated to high vibration intensities would seem sensible, and has been a widely used encoding both in works from the literature discussed previously and our own work with satisfying results in terms of understandability.

Along the same lines, in the study by Oron-Gillad et al. [203], subjects indicated a preference for absence of feedback on target though this did not correlate with any significant measured improvement in performance. This preference was confirmed in pilot tests we conducted while deciding the vibrotactile feedback scheme for our navigation experiments though we did not conduct any quantitative evaluation of differences in resulting performance.

The use of higher vibration intensities to indicate the need for urgent user reaction also has potential and may have positively contributed to reaction times during corrective movements in our series of experiments on laparoscopic instrument navigation.

#### Principle of the moving part

As higher intensities are associated with higher levels of a given variable, the principle of the moving part would indicate that increases in a displayed variable should be communicated through increases in vibration intensity.

This is somewhat disputed by Oron-Gillad et al. [203] in their analysis of a 2D aiming task with feedback of deviation direction through vibrotactile stimulus location and deviation amplitude through joint vibration amplitude and frequency modulation. They analysed several deviation encoding schemes and noted no difference in achieved performance when feedback frequency and intensity jointly increased or decreased as the subject moved closer to the target.

Relative intensity of pairs of vibrotactile actuators placed along a given direction can also indicate direction information for e.g. a desired movement [241].

## 5.7 Frequency

Frequency of vibrotactile stimulation refers to the rate of vibration presented to the skin (measured in [Hz]). As noted by Birnbaum et al. ( [35]), vibrotactile pitch – i.e. the perceptual variable mainly modulated by stimulus frequency content - is not directly comparable to auditory pitch as several factors interact to complicate it. Perceived pitch is highly dependent on amplitude of skin displacement (i.e. it is closely related to intensity) ( [201]), stimulus duration ( [112]) and stimulus location ( [139]). In the present section we will only cover frequency in the sense of frequency of sinusoidal vibrations, not frequency of vibrotactile pulses, which will be covered in the following section on temporal characteristics of vibrotactile stimuli. Frequency has been used as a parameter for vibrotactile information transmission with applications to tactile speech encoding ( [236]), coding deviation amplitudes in guidance tasks ( [24], [25]) and coding force magnitude information in force control tasks ( [7])

### 5.7.1 Physiological aspects

#### Detection threshold and range

Though frequency detection thresholds, ranges and difference limen for the human skin vary depending on the person and body site, the frequency range of the human skin is considered as lying between approx. 10Hz and 1kHz ( [251]). However, Cholewiak et al. ( [55]) suggest that the usable range is much more limited and lies between approx. 10Hz and 400Hz. This is also largely dependent on the site of vibrotactile stimulation, e.g. Mahns et al. ( [180]) conducted a series of experiments concluding that vibrotactile frequency detection thresholds on hairy skin are markedly higher than on glabrous skin.

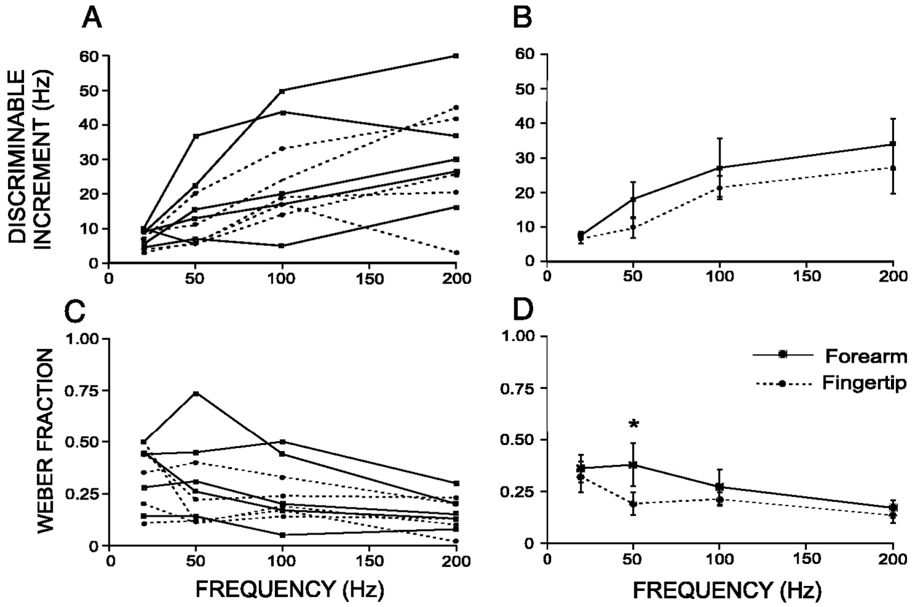

Figure 5.8: *Vibrotactile Frequency Discrimination in Human Hairy Skin, from Mahns et al. [180]. Discriminable frequency increments ($\Delta f$) and Weber Fractions ($\Delta f/f$) for vibration on the forearm hairy skin and fingertip skin as a function of four frequencies, 20, 50, 100, and 200 Hz.*

#### Difference thresholds

Due to the close interaction between frequency and intensity on the perception of vibrotactile stimuli, it can be difficult to measure difference limen for vibrotactile frequency. Quite a few attempts to do so have however been performed, resulting in Weber fractions between 0.2 at 50Hz to 0.55 at 200Hz at the fingertip ( [103]) or between 0.2 and 0.3 in the 10Hz to 300Hz range on the forearm ( [236]). These findings suggest that difference limen for frequency are larger in the lower frequency ranges. Both these studies also confirm that similarly to perceived intensity, there is peak sensitivity to frequency changes around 250Hz.

#### Absolute identification

Experiments by Sherrick et al. ( [250]) concluded very poor absolute identification capabilities for vibrotactile frequencies, with subjects only correctly identifying three to five different levels of frequency. This range was however found to increase to eight absolutely identifiable levels by jointly varying intensity alongside frequency.

### 5.7.2 Implications for coding information through vibrotactile frequency

Similarly to amplitude modulation, frequency modulation is a popular solution for conveying continuously varying dimensions (e.g. applied force level, distance to a target). For both perceptual and practical hardware reasons, frequency modulation is often used in combined frequency and amplitude modulation to encode information.

#### Principle of display legibility, avoidance of absolute judgement limits and discriminability of elements

As with vibrotactile intensity, the three concepts of display legibility, avoidance of absolute judgement limits and discriminability are closely related when encoding information through vibrotactile frequency. Delivered stimuli should focus on the usable range of detectable frequencies between 10Hz and 400Hz suggested by Cholewiak et al. (Cholewiak1992a). For improved discriminability, it is sensible to try and focus presented intensities around the peak sensitivity which occurs between 250Hz and 300Hz as lower difference limen are observed in this range.

The principle of avoidance of absolute judgement limits could partly explain the relatively poor performance of continuous vibrotactile feedback in presenting force magnitude information in our experiments on controlling tool-tip interaction forces.

When encoding information through different frequencies alone, no more than the five absolutely identifiable steps determined by Sherrick et al. ( [250]) should be used, whereby this limit may be pushed a little when jointly varying frequency and intensity to encode the same information as would be the case when using Eccentric Rotating Mass (ERM) motors.

#### Top-down processing and Principle of pictorial realism

There is some literature on cross-modal effects in the auditory domain suggesting that higher frequencies are naturally associated with higher up spatial locations while lower frequencies are associated with the opposite [238]. This may transfer to the tactile domain also and could serve as a guide for creating intuitive mappings of variable to vibrotactile frequency. The points previously mentioned when discussing top-down processing, the principle of pictorial realism and the principle of the moving part also apply similarly to communication of information through vibrotactile frequency.

## 5.8 Temporal characteristics (duration and rhythm)

Rhythmical encoding of information has been used in navigation applications ( [171]), force control in object manipulation ( [257]), general purpose man-machine interaction ( [43], [271], [44])

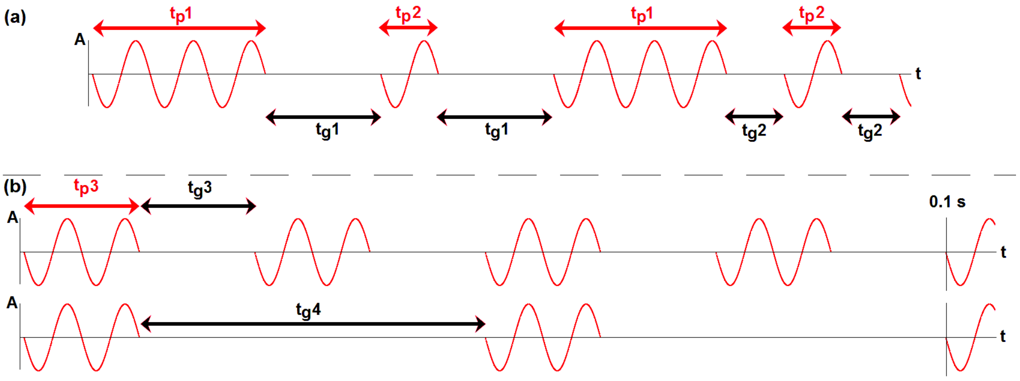

Figure 5.9: *Temporal characteristics of vibrotactile stimuli : (a) Duration (of pulses and inter-stimulus pauses) and rhythm ; (b) Pulse rate*

### Duration

Duration of vibrotactile stimuli (i.e. burst or pulse duration) refers to the length of time during which a given stimulus is presented, i.e. the time between onset and termination of the stimulus. Common orders of magnitude of vibrotactile stimuli durations are between 1ms and 1s. Fig.5.9 (a) shows an example of long pulses (A, of duration $t_p1$) and short pulses (B, of duration $t_p2$).

### Pulse rate

Vibrotactile pulse rate is the frequency at which single vibrotactile pulses are presented to the skin when burst-type stimuli are used to convey information. Fig.5.9 (b) shows an example of different pulse rates for a fixed pulse length, a high pulse rate is shown at on top (40Hz) and low pulse rate is shown at the bottom (20Hz). The variable pulse rate is obtained by modulating the inter-stimulus gap length.

#### Rhythm

Vibrotactile rhythm is a natural extension of vibrotactile stimulus duration and pulse rate, in that information can be coded into the variation of combined vibration bursts and gaps of different durations that form temporal patterns. In fig.5.9 (a), the long and short pulses (A and B) combine with long gaps (C, of duration $t_g1$) and short gaps (D, of duration $t_g2$) to form a complex vibrotactile rhythm (A,C,B,C,A,D,B,D).

Modulating temporal characteristics such as duration and rhythm of the provided vibrotactile stimuli provides great freedom in the encoding of information. However, unlike attributes such as frequency, intensity and location, the speed of delivery of the information is directly linked to the complexity of the provided stimulus patterns. Indeed, the greater the number of steps in length of a stimulus, the longer it will take to unambiguously identify a given stimulus as such - especially when the duration increases. Similarly, the greater the number of rhythms used, the more chance there is for ambiguous perception of a given rhythm as long as it has not completed at least one cycle.

### 5.8.1 Physiological aspects

#### Detection threshold and range

Concerning duration, stimuli must be long enough to be felt by the user, but short enough to ensure fast and understandable information transfer. According to Geldard et al. ( [94]), the usable range for vibrotactile stimulus durations lies between 0.1s and 2s.

Concerning rhythm, an important factor is the duration of gaps between vibration bursts. Verrillo et al. ( [290]) evaluated gap detection for click stimuli, evaluating the gap detection threshold to somewhere around 10ms, with variation depending on the length and intensity of the surrounding vibrations. Increasing said length and intensity usually lowered gap detection thresholds. Van Doren et al. ( [282]) confirmed this result on the thumb, concluding that 10ms gaps between vibrations are detectable at approx. 25dB SL, with 100ms gaps becoming detectable between vibrations as low as 8dB SL. The perception of rhythm however requires more than the adequate perception of stimulus lengths and gap lengths, some counting is necessary.

#### Difference thresholds

Concerning duration, Geldard et al. ( [94]) evaluated Just Noticeable Differences (JNDs) for vibrations presented to the chest, with results ranging between 0.05s and 0.15s for stimuli durations ranging between 0.1s and 2s. The general conclusion of these experiments was that users were able to make approximately 25 distinctions over said range of durations.

Contrary to frequency of sinusoidal vibrotactile stimulation, sensitivity to changes vibrotactile pulse rate is much more robust to variations of other factors such as e.g. the stimulus intensity.

Rothenberg et al. ( [236]) investigated short vibrotactile pulse trains at varying rates, concluding in Weber fractions as low as 0.09 in the 10Hz-20Hz range, and between 0.15 and 0.3 in the 100Hz-300Hz range. Vibrotactile pulse rates are thus best discriminated when below 100Hz.

To our knowledge there has been no work on assessing the difference thresholds for vibrotactile rhythms, which seems reasonable given the complexity and scope of such an undertaking and the relative novelty of the use of vibrotactile displays for information transmission.

#### Absolute identification

Despite the 25 distinct durations identifiable in the range of durations between 0.1s and 2000ms found by Geldard et al., subjects were only capable of absolutely identifying four to five different levels of duration, and this only after extensive training ( [94]).

According to experiments by Sherrick et al. ( [250]), subjects are capable of absolutely identifying five distinct levels of vibration pulse rate in the 2Hz-300Hz range. However, they note that joint variation of frequency and intensity improves absolute identification performances, with up to eight distinct levels being reliably identified.

Kosonen et al. ( [155]) compared memorization of audio, visual and tactile rhythms composed of combinations of short and long stimuli and pauses, concluding that audio rhythms are more easily remembered than tactile rhythms, which in turn are better remembered than visual rhythms.

### 5.8.2 Implications for coding information through vibrotactile cue temporal characteristics

#### Principle of display legibility

In terms of display legibility, vibration pulses and spacing need to be long enough to be detectable and clearly discernible, i.e. longer than 10ms in the best intensity, frequency and position conditions. They also need to be short enough to keep information transfer at a reasonable speed and not put too much load on subject memory. In their study on vibrotactile feedback to guide fast arm motions, Bark et al. ( [24]) note that keeping tactile feedback response time and information delivery time low is critical. Concerning rhythms, Sherrick et al. ( [251]) report that vibrotactile stimuli to the skin are inaccurately counted if more than five pulses are presented within a 700ms period, which can serve as a good starting point for design.

#### Avoidance of absolute judgement limits and discriminability of elements

Clear discrete changes in the stimulus level should be preferred over gradual stimulus variations. Concerning stimulus duration and if applicable the resulting pulse rate, though Geldard et al. ( [94]) evaluated JNDs for vibration durations to somewhere between 0.05s and 0.15s over the usable range of stimulus durations, with approximately 25 distinguishable steps, it is safe to assume that a lower number of duration steps should be used to ensure information clarity. When encoding a variable such as deviation from a target, it may thus be sensible to follow the idea put forward by Bark et al. [26] suggesting that coarse graded feedback (i.e. feedback proportional to the deviation amplitude) be only used close to the target, with limited resolution beyond that range (e.g. one "near" and one "far" level) so as to limit the number of distinct feedback levels.

#### Top-down processing

A third point to take into account is "top-down processing", the fact that people perceive and interpret signals according to their expectations based on past experiences. There is some evidence suggesting high pulse rates convey a sense of urgency, this could therefore be taken into account when designing feedback schemes ( [222], [22]), associating levels of a variable which require urgent corrective action (e.g. high deviations from a target force or position, proximity to a sensitive anatomical structure).

#### Principle of pictorial realism and principle of the moving part

Both these principles dictate that variations in the information displayed should correspond to real-world variations and the way the information is expected to vary by the user according to his mental model. As high pulse rate can be associated with urgency, it would be sensible to associate increases in errors with increases in pulse rate and improvements with gradually slowing pulse rates.

## 5.9 Waveform

Waveform refers to the shape of the vibration wave, the most common used waveform for vibrotactile displays being approximate sine waves. Vibrotactile waveform has probably the subject of the smallest body of work among the various possible vibration parameters. Most of the academic study on waveforms has focussed on the effect of waveform on perception of parameters such as intensity or frequency and comparatively little has focussed on waveform discrimination, let alone the use of waveforms to encode tactile information.

Modulating waveforms requires appropriate hardware as ERM and LRA can only produce single frequency sinusoids, in combination they may be used to create complex waveforms but this rapidly creates hardware intensity. Thus literature on applications using waveform modulation is more limited than for the vibrotactile stimulus dimensions discussed previously. The two main hardware options for creating complex waveforms at affordable hardware complexity are voice coils and piezoelectric (PZT) actuators. Voice coils are linear DC motors consisting of a magnetic housing and a coil. Applying an alternating voltage across the terminals of the motor causes the motor to alternately move in a direction and subsequently in the opposite direction. This causes a vibration at the frequency of the applied alternating current, with an amplitude proportional to the current flowing through the coil. PZT actuators are devices based on the counter-piezoelectric effect, whereby applying a voltage to the device causes a displacement. Thus application of an alternating voltage causes vibration at the voltage frequency. The excellent performance of PZT actuators give them tremendous potential in the area of tactile feedback. However, the voltages required to drive them are usually very high, which can be problematic from the point of view of the driving electronics complexity and from the point of view of safety and electromagnetic interference. Fig. 5.10 shows example schematics of each of these haptic actuator technologies.

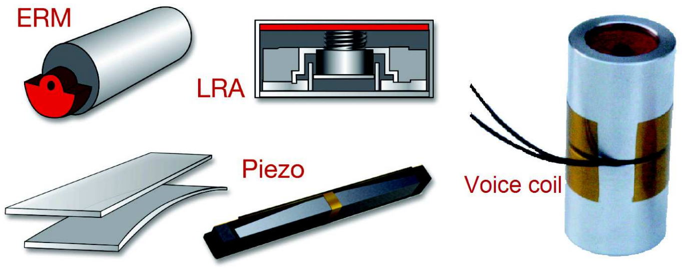

Figure 5.10: *Haptic actuators : Eccentric rotating mass motors (ERM) use an eccentric mass mounted on the shaft of a DC electrical motor to induce vibration with jointly varying frequency and amplitude depending on the drive current and mechanical properties of the actuator; Linear resonant actuators (LRA) use a voice coil attached to a spring and mass system, allowing generation of vibration at a fixed resonant frequency with short reaction times and compact hardware; Piezo actuators use the counter-piezoelectric effect to transform applied alternating voltage to oscillating displacement; Voice coils function identically to audio speakers, oscillating a mobile coil within a magnetic housing through application of alternating voltage to the coil.*

## Physiology and perception of vibrotactile waveform modulation

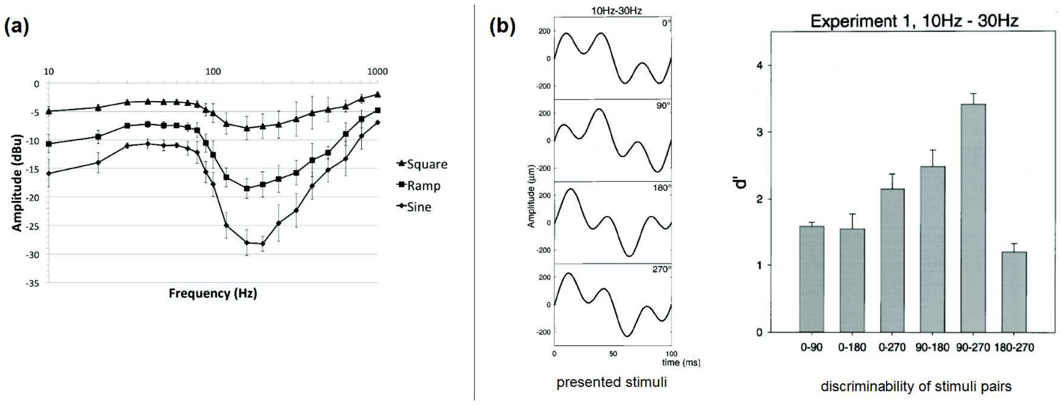

Figure 5.11: *(a) Detection thresholds for four vibrotactile waveforms as determined by Young et al. [319] ; (b) Measure of discriminability of four complex vibrotactile waveforms by Bensmaïa et al [30], d' values close to one indicate confusion whereas higher values indicate good discriminability*

The ability of the somatosensory system to differentiate waveforms is markedly inferior to that of the auditory system [19]. Summers et al. ( [260]) for example show that sinusoidal vibrotactile stimulation is not readily distinguishable from monophasic or tetraphasic pulse stimulation. Gunther at al. ( [112]) suggests that subjects are unable to differentiate between pure sine waves and sawtooth waves at a given frequency, but that sine waves are usually perceived as "smoother" than sawtooth waves. This relationship between amplitude modulation and perceived roughness is somewhat backed up by work by Krueger et al. ( [156]), Van Doren et al. ( [282]) and Weisenberger et al. ( [300]).

Waveform is thus not completely without merit as an option for information transmission. Young et al. ( [319]) for example conducted an experiment to assess human ability to distinguish between pure sinusoidal and complex waveforms with non-sinusoidal periodic shape containing different harmonic content at a given fundamental frequency, with rather good results (see fig.5.11 - a). Bensmaïa et al. ( [30]) studied the discrimination of complex vibrotactile waveforms consisting of superimposed pairs of sinusoids at varying phases on the fingertip at varying frequencies (see fig.5.11 - b). They found that low-frequency waveforms were discriminable from one another while high-frequency vibration discrimination was comparatively poor. Finally, Russo et al. ( [239]) present a series of five experiments investigating the ability to discriminate between musical timbres with same fundamental frequency based on vibrotactile stimulation presented to the back. Subjects successfully discriminated between dull and bright timbres varying only with regard to spectral centroid.

#### The limited scope of applications using waveform for tactile information coding

As previously explained, the complexity of study of the effects of vibrotactile waveform combined with the stringent hardware requirements for adequately rendering complex waveforms somewhat limit the literature available on the subject. To our knowledge, most of the work on applications of vibrotactile waveforms to information displays has focussed on mobile devices and touch-screen interaction, with the objective of rendering complex abstract messages [46] or textures [201]. Both these applications are not directly applicable to our present work on vibrotactile feedback for MAS applications but are worth mentioning because of the great potential for complex information displays.

Concerning communication of abstract messages, there is substantial body of work on the design, discriminability and application domains of tactons ( [42], [46]), which are complex vibrotactile messages obtained through a combination of waveform modulation and rhythmical patterns.

In the domain of mobile human-computer interaction, a few application seek to understand the potential of waveform modulation for intuitively communicating complex information. For example Shoogle ( [310]) is an experimental hardware platform designed for feeding back information in a mobile device through display of complex waveforms in reaction to the user shaking the mobile device, which serves as a form of active exploration. Another example comes from Oakley et al. [200] who explore the use of complex vibrotactile waveforms for feedback during virtual scrolling tasks.

One particularly notable application of waveform modulation which may be of use in applications such as those that we explored is the use of asymmetric sinusoidal vibrations with varying skew ( [13] - see fig. 5.12). These vibration patterns have been successfully used for communicating directional information and may even generate the illusion of an attractive force in a given direction. Thus applications both to instrument navigation and force control may be envisaged. However this must be approached with caution as it relies on a tactile illusion, and tactile illusion effectiveness is highly dependent on user specificities, expectations and mental workload.

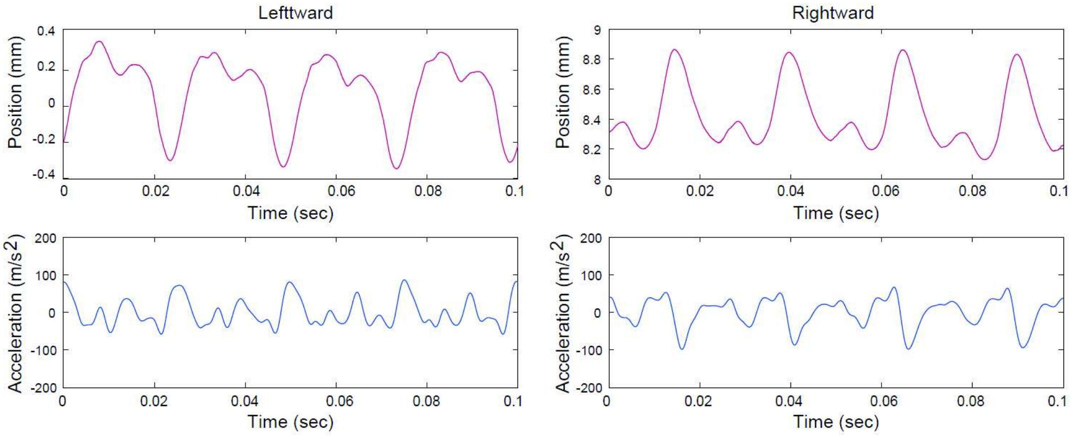

Figure 5.12: *Asymmetric vibrations used to generate an illusion of attractive or repulsive force in a given direction using a single vibrotactile actuator. [13]*

## 5.10 Modulating multiple stimulus dimensions and the impact of multimodality

### Within the tactile feedback : Modulating multiple stimulus dimensions

Within a tactile feedback display, it may be interesting to modulate several stimulus dimensions simultaneously. Stimulus dimensions may be combined redundantly, with two or more dimensions jointly manipulated to encode the same information, or orthogonally, with each dimension manipulated independently to encode a different information component.

Garner et al. ( [93]) suggest that stimuli dimensions can be classified as either integral or separable. Integral dimensions easily combine according to a Euclidian metric to form unitary stimuli and are thus difficult to analyze as separate components. Separable dimensions however can be individually analysed and perceptually processed. To gain insight into which dimensions of stimuli are integral or separable, discrimination and classification tests can be performed. In such tests, changing integral dimensions in a correlated fashion should result in improved performance, while correlated changes of separable dimensions should have little effect on final performance.

For vibrotactile stimuli, studies have demonstrated that frequency and amplitude are integral dimensions ( [268], [261]). On the other hand, there is no evidence that duration and frequency are integral dimensions of vibrotactile stimuli ( [138]). These findings are partly mirrored in the work of Zhou et al. [324] on laparoscopic palpation, where the authors show that the effectiveness of vibrotactile feedback for force feedback is positively correlated with the number of simultaneously modulated stimulus dimensions, which in this case were amplitude, frequency and burst rate.

When comparing redundant and orthogonal coding of information in vibrotactile feedback, Rabinowitz et al. ( [225]) conclude that both lead to increased transmitted information but that orthogonal coding leads to greater gains.

### Beyond purely tactile feedback: the influence of multi-modality

Multisensory integration phenomena resulting from certain forms of congruence between stimuli delivered to different modalities can be exploited in multi-modal feedback systems so as to create stronger perceptions of the transmitted information by the recipient. It is commonly understood that the visual modality usually dominates perceptions, biasing both audio perception [249] and haptic perception in many tasks although certain examples to the contrary exist ( [105], [106]).

Welch and Warren ( [301]) hypothesised that the influence of perception in a given modality depends on the modality's appropriateness for the given task. Thus, vision has a greater influence on localization estimates than hearing, and hearing and touch have a greater bearing on timing estimates than vision [163]. The dynamic re-weighting of cues to form percepts is somewhat explained by the theory of Bayesian integration, which attempts to explain how the brain deals with different inputs of varying reliability ( [72]).

Presenting cues in a multi-modal fashion may lead to decreased reaction times thanks to processes of intersensory facilitation ( [128]). In a study by Forster et al., observers responded faster to simultaneous visual and tactile stimuli than to single visual or tactile stimuli. Reaction times to simultaneous visual and tactile stimuli was also faster than reaction times to simultaneous dual visual or tactile stimuli. The advantage of combined visual-tactile stimuli over the other types of stimulation in terms of reaction times could be accounted for by intersensory neural facilitation rather than by probability summation, and can be ascribed to the convergence of tactile and visual inputs onto neural centres which contain flexible multisensory representations of body parts ( [85]).

A second advantage of multi-modal presentation of information may be redundant target effects, i.e. the fact that subjects typically respond faster to two targets presented simultaneously than to either of the targets presented alone. This difference in latency is termed the redundancy gain ( [231]).

Burke et al. ( [47]) performed a meta-analysis of 43 studies looking at the effects of visual-tactile and visual-auditory feedback on user performances. Results show that adding an additional modality to visual feedback improves performance overall. In particular, visual-tactile feedback provides advantages in reducing reaction times and improving performance scores, but has not shown effectiveness in reducing error rates. The greatest gain in effectiveness from visual-tactile feedback is found when multiple tasks are being performed and workload is high.

The performance gains from multi-modal information displays are coherent with predictions as made in Wickens' Multiple Resource Theory ( [306], [307]), which hypothesises the following:

- people have multiple semi-dependent cognitive resources;
- some of these resources can be used simultaneously without negatively affecting performances, others cannot;
- tasks requiring the use of the prior can often effectively be performed together;
- competition of tasks for the same resource can produce interference effects;
- dissimilar cognitive resources exist to process information from different sensory modalities.

Multiple resource theory both defines these cognitive resources and predicts to what extent information from a given sensory channel can be effectively offloaded onto another. This offloading is more or less effective depending on several factors:

- workload - i.e. higher likely efficiency in high workload conditions;
- visual attention requirements - i.e. higher likely efficiency when there are high requirements for both focal and ambient vision;
- cue overlap between modalities on common task components;
- degree of attention required by the separate tasks.

## 5.11 Concluding remarks and perspectives

In the present chapter, we reviewed the literature to compile recommendations for future designs of vibrotactile interfaces for applications in laparoscopic surgery in the light of our own initial experimental findings on the subject. These recommendations can therefore serve as a basis for further investigation into the efficacy of tactile information systems in minimal access surgery and for the development and optimisation of display hardware.

Human factors and interface design theory provides general principles for designing information displays such a way as to ensure they are understandable, usable and comfortable for the user. We reviewed these principles and their implications when encoding information through the various vibrotactile stimulus dimensions, i.e. stimulus location, vibration intensity, vibration frequency, temporal characteristics of the vibration (duration, pulse rates and rhythm) and vibrotactile waveform. This results in recommendations for cue design, choice of presented information and choice of hardware that are confirmed through a review of various studies and applications of vibrotactile displays as well as our own previous findings. We hope that this analysis may serve as a foundation for future development of vibrotactile feedback systems to MAS.

It is important to always bear in mind that beyond the factors involved in the design of vibrotactile stimuli discussed here, a number of more complex phenomena may positively or negatively affect perceptions of such stimuli in a display. We briefly discussed interplay between stimulus dimensions and multi-modality, but several more effects can be expected in complex vibrotactile displays. These include adaptation phenomena, where sensitivity to vibrotactile stimuli decreases after extended exposure to stimuli, both spatial and temporal masking effects, where vibrotactile stimuli presented in too close proximity tend to "hide" each other, and the various effects of differences between users.

As with any human factors work, such development will have to follow an iterative process, putting users in the loop early on and confronting the systems to use cases similar to their end use environment. Once functional systems are developed, it should be possible to refine them through extensive user testing combined with subjective acceptance measurement and measures of task workload (e.g. NASA TLX [120], [121]).

Chapter 6

# Conclusion and prospects for future work

Looking at the current state of laparoscopic surgery, it appears that despite its growing use, it is still plagued with many drawbacks in dexterity, perception and learning that limit its applicability and performance where it is used. Limitations in perception of relative positions of instruments to target organs and other sensitive structures as well as of interaction forces lead to surgeon errors with potentially grave consequences. To reduce risks and improve both surgeon comfort and performance without disrupting surgical work-flow it would be interesting to feed back reliable information which would allow the surgeon to avoid or effectively correct errors

Conventional approaches in feeding back information have been largely based on visual feedback, which has been shown to be effective but also faces a certain number of challenges.

- First of all, it raises potential safety concerns in the case of immersive displays, augmented and virtual reality, as these can eliminate surgeon's situational awareness and potentially hide critical information on the surgical scene.
- Secondly, it increases the load on the already saturated visual modality, potentially increasing surgeon fatigue, degrading performance and distracting from other information components.

The stated objectives of this thesis were to evaluate the respective contributions of added information via various forms of haptic feedback to the performance of different conventional laparoscopic surgery gestures. We hypothesized that on the one hand, feeding back information on tool-tip positions with respect to surgical targets or sensitive anatomical structures could benefit navigation in laparoscopic surgery, and on the other, feeding back information about the tool-tip interaction forces could allow for safer and more efficient control of these forces by the surgeon.

While the idea of using haptic feedback to provide information in surgery is not completely new, with a few works on platforms and evaluation of their contributions in open surgery and a few works on hardware without evaluation of performance improvement in laparoscopy, the originality in our work was to take a different approach:

- First of all, we attempted to isolate components of the information missing for the surgeon along with ways to present them in a manner that could improves final performance;
- Secondly, we developed evaluation methods and set-ups allowing for comparison of final performances on specific surgical tasks with and without the evaluated forms of feedback.

The main contributions of the present work lie in testing the impact of tactile feedback on task performance for applications in conventional laparoscopic surgery. This evaluation of the impact on task performance was performed both between different haptic feedback prototypes and comparatively to other conventional options for information feedback, i.e. visual and kinaesthetic.

Concerning the first application, laparoscopic instrument navigation, we evaluated the potential for tactile and combined visual and tactile feedback of deviation information with respect to known surgical targets in improving gesture accuracy and efficiency. In initial experiments on assistance to instrument navigation towards a planar target in free space, we demonstrated the potential of various forms of feedback (visual, haptic and combined) in improving overall gesture quality, mainly in terms of precision criteria. We then performed a second simplified guidance experiment designed to better understand the role of the various information components (indication of deviation direction, distance or both) in assisting parts of the gesture (initial reaction to a deviation, correction and final stabilisation around the target). Continuous vibrotactile feedback yielded the best reaction times in the event of a deviation, probably because of the immediate nature of the signal and the fact that tactile feedback forces attention to the presence of a deviation. However, both these experiments used set-ups which remained quite removed from actual laparoscopic clinical practice, leaving a certain number of crucial open questions as to the applicability to laparoscopic surgery. The effectiveness of feedback while the user is engaged in complex visual-motor tasks such as precise cutting or suturing remained to be verified. Thus, we developed a final experiment on a navigation task closer to clinical training reality, based on the Fundamentals of Laparoscopic Surgery (FLS) cutting task. This yielded mixed preliminary results as slight improvements were observed when tactile feedback was provided, however these were far less pronounced than in the previous experiments in free space. This would seem to indicate either limitations in the applicability of such feedback to complex trajectories and tasks requiring interaction with the environment or point to the fact that non-experts are not an adequate sample population to test the effectiveness of tactile and multi-modal feedback in more complex laparoscopic tasks. The drop in observed improvements in performances obtained through feedback when navigation tasks were complicated would suggest that an evaluation of the effectiveness of feedback on non-novice populations would be of interest.

Concerning the second application, control of tool-tip interaction forces, we set up a series of experiments focussed on the manipulation of suture threads. Our series of three experiments started with the simple idea of feeding back quantitative information on the interaction force magnitude to the user in the hopes that such reliable information may help in better controlling interaction forces in terms of accuracy, repeatability and constancy over time. This initial experiment showed that providing feedback on the interaction force magnitude to novices did indeed result in better performances for the given criteria. However, results for tactile feedback were quite disappointing when compared to performances obtained with visual feedback. This led us to our following experiments where we hypothesised that highlighting a previously known target force should bring the performances obtained with tactile feedback to a level comparable to the performances obtained using visual feedback. A second experiment was thus performed, concluding that when the target force is highlighted, tactile, visual and combined feedback are more or less equivalent in terms of achieved performances, with greater user comfort in the tactile feedback conditions. Since highlighting the target force supposes a prior knowledge and definition of the target force, we wished to explore an alternative feedback scheme which becomes possible in such a situation: feeding back the magnitude of the force error rather than the absolute interaction force magnitude to the user. A final experiment in two parts investigated this last aspect, on the one hand providing only feedback on the force error magnitude, and on the other providing information on the force error magnitude and direction. Results were similar to those obtained when highlighting a target force and did not significantly differ depending on whether only magnitude or both magnitude and direction information were provided. Overall, we demonstrated the potential for using tactile feedback in feeding back force information with the aim of improving accuracy, repeatability and constancy in fine force control tasks in laparoscopy.

The experiments discussed above allowed us to develop effective set-ups and evaluation metrics highlighting benefits and limitations of the studied forms of feedback for both applications. This guided us towards avenues for designing effective feedback schemes and eliminated certain non-viable options, allowing us to look at the very rich and general bibliography on haptic feedback for information communication with the aim of:

- Cataloguing the possibilities for encoding information in tactile cues,
- drawing parallels with the types of information encountered in our applications,
- and thus listing recommendations for future designs of tactile cues for these applications.

Based on the thirteen principles of interface design introduced by Wickens et al. and the extensive literature on the perception of vibrotactile stimulus dimensions, we listed a number of ideas and recommendations to take into account when designing vibrotactile feedback systems for assistance to laparoscopic surgery gestures. Following our state of the art and recommendations, and applying and expanding on the evaluation methods developed here in studies involving surgeons of varying degrees of expertise should provide conclusive insights into whether this technology is actually viable as an effective method for communicating information to surgeons without disrupting work-flow. Future work should therefore focus on refining the haptic cues based on our recommendations in order to increase their information content, intuitiveness and comfort of use.

Should all this result in the development of application-specific tactile or multi-modal cue sets that are proven effective in improving surgeon gestures, it will still be necessary to develop and evaluate various hardware platforms for delivering the feedback to the surgeon. This means developing sensorized instruments with tactile feedback capability or connected to systems with separate tactile feedback components, such as e.g. surgical gloves incorporating tactile feedback.

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