Touch Magnifying Instrument Applied to Minimally Invasive Surgery

Hsin-Yun Yao

Department of Electrical & Computer Engineering
McGill University
Montreal, Canada

September 2004

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Engineering.

2004/09/14

Your file Votre référence
ISBN: 0-494-06595-8
Our file Notre référence
ISBN: 0-494-06595-8

Abstract

The MicroTactus is an instrument designed to detect signals arising from the interaction of a tip with soft or hard objects and to magnify them for haptic and auditory reproduction. An enhanced arthroscopic surgical probe was developed using an accelerometer and a custom-designed actuator for haptic feedback. Measurements were made to characterize the device and the results showed that numerous factors such as gripping method and gripping force influenced the system response in a complicated manner. The device was tested with the task of detecting surface defects of a cartilage-like material. Subjects were asked to detect the cuts of different depths under four conditions: no amplification, with haptic feedback, with sound feedback, and with passive touch. Both haptic and auditory feedback was found to significantly improve detection performance, which demonstrated that an enhanced arthroscopic probe provided useful information for the detection of small cuts in tissue-like materials.

Résumé

Le MicroTactus est un instrument conçu pour détecter les signaux provenant de l'interaction de l'extrémité de l'instrument avec des surfaces et les amplifier de façon haptique et auditive. Une sonde d'arthroscopie a été modifiée pour effectuer un retour de vibration en utilisant un accéléromètre et un actuateur spécialement conçu à cet effet. Pour caractériser l'instrument, des mesures ont été effectuées et les résultats ont démontré que de nombreux facteurs pouvaient influencer la réponse du système de manière complexe. Des expériences avec MicroTactus ont été effectuées avec des sujet humains. Les sujets devaient détecter la présence de défauts de surfaces avec la sonde sous quatre conditions: sans amplification, avec retour haptique, avec retour auditif, et par exploration passive. Les deux tests: retour haptique et auditif eurent une influence positive et significative sur la performance des sujets. Ceci démontre l'utilité de l'information haptique et auditive traduite par la sonde MicroTactus durant la détection de petites coupures sur une surface souple.

Acknowledgments

First, I would like to thank Prof. Vincent Hayward for his guidance through the past two years, as well as Prof. Randy Ellis for giving me the opportunity to work on such an exciting topic. Without the support and guidance, this work would be impossible. I would also like to acknowledge helps from all my colleagues in the Haptics Laboratory for providing valuable ideas and a stimulating research environment. Many thanks to my parents and my sisters for supporting my research activities like they always do. Finally, I would like acknowledge my husband, Jean-Samuel Chenard, for his unconditional support in every aspect of this project.

This project is partly sponsored by IRIS and NSERC.

Claim of Originality

To the author's knowledge, the following constitute original contributions of this thesis:

- A tactile amplifying probe for minimally invasive surgery;
- An actuator design to reproduce the signal sensed from an accelerometer;
- A method of mounting the actuator inside a probe handle;
- A practical implementation of the above.

Contents

List of Figures

Chapter 1

Introduction

1.1 Motivation

Minimally invasive surgery benefits patients over traditional surgical methods by the small size of incisions, less pain, less trauma and shorter healing periods. The surgeon, however, must cope with loss of direct tactile and visual information. It has been demonstrated that even partial restoration of the sense of touch improves performance in teleoperation and virtual environments [3]. However, as pointed out in [4], systems with "augmented reality" often have features in the graphics domain but provide little in haptic feedback. The motivation for this thesis was to build and test a new tool for improving the sense of touch during procedures in minimally invasive surgery.

1.2 Overview

We have developed an integrated system designed to improve the sense of touch of a surgeon holding an instrument during tissue examination. The device has the appearance and function of an arthroscopic instrument, but it actively enhances the tactile experience of interacting with objects by amplifying the mechanical interaction signal. The same signal can also be transformed into sound to further heighten sensitivity to small details.

We have fabricated an arthroscopy hook, integrated an accelerometer near the tip, and custom-designed an actuator that was embedded in the handle. The complete system is simple and easy to manufacture. Basic measurements made on the device showed complex and multiple relationships between the measure acceleration and many factors such as hardness of the surface and gripping methods. We conducted preliminary experiments in which an acceleration signal was amplified and processed with simple filtering to test our device in a tear-detection task. The results indicated that with even rudimentary signal processing in the haptic and auditory domains, tear-detection performance was significantly improved.

1.3 Thesis Outline

The main goal of this thesis is to introduce a novel tactile amplification device which is named MicroTactus. The organization of this thesis as follows: Chapter 2 provides a brief literature review in minimally invasive surgery, texture perception and vibratory haptic devices. Chapter 3 explains the principle of operation and designs strategy of the MicroTactus. Results and discussions of quantitative measurements are shown in Chapter 4, and Chapter 5 presents the results and analysis of user experiments. Finally, in conclusion, we briefly describe our findings and possible future work.

Chapter 2

Literature Review

Because this thesis is dedicated to a surgical device with haptic feedback, the literature review will cover the following topics: minimally invasive surgery and its instrumentation, perception of surface texture and vibratory haptic devices. An overview of techniques of minimally invasive surgery is first presented, followed by a summary of recent developments in smart surgical tools and computer assisted surgery. The last section is a brief overview in texture perception with rigid probes and haptic devices displaying vibration.

2.1 Minimally Invasive Surgery

Minimally Invasive Surgery (MIS), also called *Minimal Access Surgery*, is one of the most important surgical techniques developed in the late 20th century. Compared to traditional open surgery where large incisions are made to "open" up the operation area, minimally invasive surgery is performed either through natural openings in the body, where no incision is required, or through small incisions no bigger than 5cm. Instead of directly seeing and touching the tissues and organs, surgeons rely on the images provided by miniaturized imaging systems inserted inside the patient, and use prolonged surgical instrumentation to perform the operations [5].

Endoscopic surgery, which is a broad term for operations performed using an endoscope and laparoscopic surgery, which is surgery that is performed in the abdominal cavity through small incisions, are both examples of minimally invasive surgery [6, 7]. Today, this technique has applications in almost every traditional discipline in surgery. It is now considered "... not a discipline unto itself but more a philosophy of surgery, a way of thinking" [5].

The biggest benefit of minimally invasive surgery is reduced trauma for patients. The operation typically occurs through a "keyhole" which therefore results in a smaller wound and less pain for the patient since the organ suffers from less train. The result is a remarkably faster healing time compared to traditional open surgery [8]. Due to the small access point, however, the main disadvantages are restricted vision and mobility for instrument handling. The long and thin tools fail to transmit most of the tactile feedback to the surgeons' hands.

2.1.1 Arthroscopy

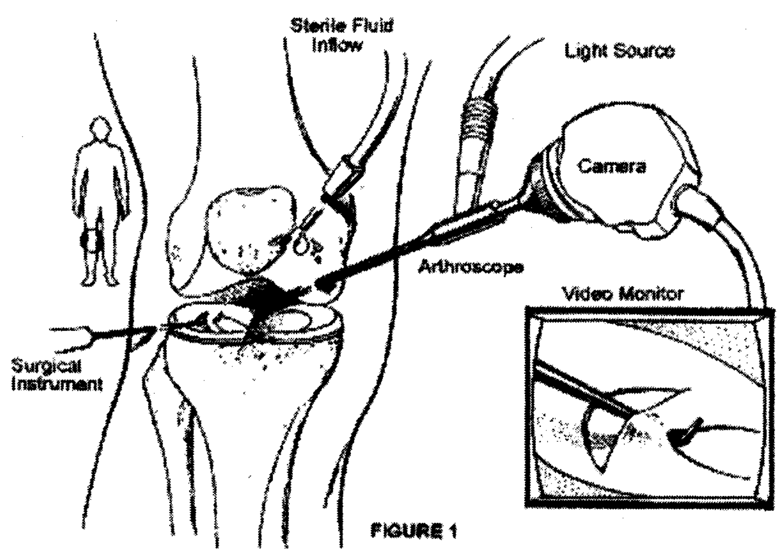


Fig. 2.1 Arthroscopy [1]

Arthroscopy is a type of minimally invasive orthopedic surgery [9]. During arthroscopy, the surgeon holds a compact size camera inserted into the target area with one hand and the surgical instrument with the other. He or she performs the operation by looking at the video images transmitted by the camera, while probing the tissues with surgical tools. The camera replaces the surgeons' eyes, and the surgical tools extend the surgeon's hand. When it is necessary to examine places where the camera cannot reach, the surgeon must rely completely on the haptic feedback transmitted from a surgical instrument.

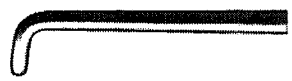


Fig. 2.2 Arthroscopy Hook (adapted from [2])

Some arthroscopy operations are diagnostic while others are operative. One commonly used instrument used during diagnostic arthroscopy is a simple metal probe. The tips may have many different shapes, but the "arthroscopic hook" with a tip bent to a 90-degree angle is commonly used. With this instrument, a surgeon probes the surface of tissues, including ligaments, menisci and cartilage, to find anomalies.

2.2 Computer-Assisted Minimally Invasive Surgery

Recent developments in computer technologies have entered the operating room, bringing countless opportunities for new advancements and improvements. Surgical operations are now assisted by intelligent systems in many aspects such as pre-operative planning, image guidance, autonomous or teleoperated surgical robots, surgical assistants and smart or augmented devices. Dario, Taylor et al. presented a broad overview of computer-assisted surgical systems in the survey papers [4] and [10].

Among different categories in surgery, minimally invasive surgery is a field which may specially benefit from enhancements of intelligent systems. Because mechanical instruments (for example surgical tools) and electrical instruments (for example cameras) define how the the tactile and the visual feedback reach surgeons, these tools provide a natural place to attach micro-electromechanical (MEMS) sensors or actuators for enhancements. Tendick et al. surveyed applications of micromechatronic systems applied for minimally invasive surgery before 1998 in [11], and in 2004, Rebello presented an up-to-date overview of MEMS devices used in all surgical fields [12]. Although much effort has been dedicated to better haptic displays, all the above papers noted that in existing systems, tactile feedback is still the weakest aspect and compared to visual displays, much remains to be done to reach an equal level of realism.

2.2.1 Devices Collecting Haptic Data

Many augmented devices have been developed to measure the properties of live tissues. Examples of work can be found in [13, 14, 15, 16, 17, 18, 19, 20, 21]. Scilingo, Bicchi et al. described in [13, 14] a tool equipped with sensors to detect the elastic property of tissues. Force and position sensors are mounted on laparoscopic pliers for the data collection. Similarity, Ottensmeyer et al. presented in [15] a minimally invasive instrumentation to measure mechanical properties of solid organs such as kidney, spleen and liver *in vivo* by using force and position sensors during laparoscopic procedures. Rosen et al. described in [16] a system to measure the kinematics and the dynamics of minimally invasive surgical *in vivo* using torque, position and force sensors as well. In [17], a method is described to decompose MIS operations into sequences of basic tasks such as "closing-pushing" or "pushing-rotation" automatically. Greenish et al. investigated haptic signals during surgical cutting in [18]. A mechatronic device described by Dario, D'Attanasio et al. provides the functionalities of tracking, collision detection and tool tip steering for arthroscopy and endoscopy [19, 20]. The hand-held micro-surgical instrument with inertia sensors and actuated tool tip by Ang et al. could perform error cancellation and tremor reduction [21].

2.2.2 Devices Providing Haptic Feedback

The data collected by measuring devices can be used in the creation of more realistic visual and haptic displays in surgical simulation tools. Haptic rendering can be based on two different models: reality-based and simulation based. Reality-based models take the data acquired by the measuring device, and simulation-based haptic displays obtain them from formula describing the mechanical behaviour of the force interaction. Surgical devices augmented with haptic feedback often perform the rendering using the reality-based method because of the complex and the highly non-linear nature of living tissue. However, as explained in [22, 18], the disadvantage of reality-based models is the lack of flexibility. These devices can only display data collected during data acquisition, and are very limited if the simulation is to be extended to different tools under different conditions.

An example of work for tactile and force feedback devices can be found in [23], where Howe et al. described a sensor-actuator system to perform remote palpation. The tactile display is composed of arrays of pins which raise and fall to display approximated shapes. In [3], Rosen et al. describe a teleoperated endoscopic grasper that gives the user force feedback. Performance is evaluated in the task of differentiating the compliance of several objects, and the results show a significant improvement in the performance when force feedback is turned on. As indicated in several survey papers, much work has been done for haptic sensing, but not many devices can give realistic haptic feedback, because of the lack of suitable haptic transducers [4, 24, 12].

2.3 Texture Perception and Display

The most natural way to explore the texture of a surface is to use our bare fingers. We apply our fingers to the surface and usually move laterally along the surface. A widely accepted model states that the perception of texture is directly related to instantaneous skin deformation when the skin comes in contact with the surface [25]. This deformation generates static and vibratory signals which provide information for spatial and temporal coding of the surface [26, 27, 28]. These studies showed that in the perception of fine texture, vibration has been proven to play an important role.

2.3.1 Perceiving Texture through a Probe

Besides using bare fingers, surface textures can also be perceived through a rigid link. For example, when we write with a pen, we easily notice the differences among several kinds of paper. Long ago, Katz observed that subjects could discriminate different types of paper surfaces with a wooden rod, and argued that the vibration signal transmitted through the grip plays an important role [29]. With training, surface texture probing with a rigid probe can be performed very accurately. For example, during an arthroscopy, surgeons use probes instead of bare fingers. Their diagnostics are largely based on how they "feel" with their probe.

The probing of surface texture using a rigid probe can be influenced by numerous factors. Lederman and Klatzky have studied this subject in a series of psychological experiments. An overview of their published work on this topic before 1998 is provided in [30]. They have studied many factors that influence the texture perception:

using a bare finger versus a rigid probe [31], the exploration speed [32, 33], exploration mode: active versus passive [32], the applied force [33, 34], and the probe geometry with respect to the exploring surface [35]. These studies showed that first, for the same set of textures, the perception of roughness using a rigid probe has a different relationship compared to bare fingers. In addition, the perception of roughness estimation is shown to be influenced by the speed of exploration, the geometry of probe and the application force in a complex manner. These factors should be taken in to consideration while designing haptic devices.

2.3.2 Haptic Rendering and Vibro-Tactile Display

From research laboratory to commercial market, the development of haptic devices has enjoyed an ever-increasing popularity during the past decade. A recent and thorough survey can be found in [36], by Hayward et al. Although the importance of vibratory signal in texture perception has been shown in many past studies, most haptic devices still do not give it the attention it deserves. One of the first haptic texture displays is Minsky's *Sandpaper* system described in [37]. They used a mass-spring-damper system to model texture perception. Successive work suggested a solution to the problem of haptic texture by "Force Shading" [38, 39, 40] : modulating forces parallel to the surface. Different methods of implementation were demonstrated to be successful in [41, 40, 42]. However, there were few attempts to address the haptic texture directly with vibratory signals.

Previously, vibration display has been used in teleoperation applications. To provide vibro-tactile feedback to the master operator, Kontarinis and Howe mounted accelerometers on the slave operator to capture the vibratory signal and displayed it with a loud speaker attached to the master operator [43]. They conducted experiments to prove a significant performance improvement in some particular tasks. Along the same idea, Pai et al. developed a wireless texture sensing pen with accelerometers and force sensors. They used an embedded micro-controller to sample the signal at 400Hz [44]. Debus et al. also showed the importance of vibration signal in a teleoperation setting [45]. The vibro-tactile display embedded in the handle of the master operator conveyed forces into amplitude-modulated vibrations at 300Hz. With user experiments, they showed that the vibration helped the subjects to improve performance. Okamura raised the question of how most haptic devices failed to display proper vibration feedback [22]. Using accelerometers, the authors demonstrated that much is lost in the haptic display of collisions between objects of different materials. Recently, Hwang, Williams and Niemeyer proposed an open-loop and event-based approach to simulate a mass hitting a stiff virtual surface [46]. To display high-frequency signals occurred during the collision, they suggest sending short pulses of force in an open-loop fashion to bring the mass to stop.

Chapter 3

MicroTactus: The Touch Amplifying Probe

Fig. 3.1 The Touch Amplifying Probe

This chapter presents the principle of operation and implementation of the touch amplifying probe "MicroTactus". Dario et al. grouped robotic surgical devices into three different categories: hand-held tools enhancing the capabilities of surgeons, teleoperated surgical tools and autonomous surgical robots [4]. The MicroTactus-type devices belong to the group of hand-held devices that collect signals related to tissue properties and provide haptic feedback to enhance surgeons' tactile capabilities.

3.1 Principle of Operation

3.1.1 Principle

Consider a user holding a pen-like probe and dragging it over a surface. With such an instrument, it is possible to assess surface roughness/smoothness, softness and texture based on the tactile information collected at the handle. This idea has been discussed in related literature, most notably by Katz [29] and more recently by Klatzky [31]. From a system's point of view, the inputs are 1) the pressure of the tool exerted against the surface and 2) the dragging speed of the tool. The output is the resulting vibration movements produced at the handle. The tactile experience results from the deformation of the skin in contact with the moving probe handle and the movement of the handle is related to the movement of the probe tip.

The above analysis suggests that using an actuator capable of altering the vibrations of the handle could also alter the user's perception of the surface. Moreover, the user's sensitivity could be heightened by placing a sensor at the tool tip to measure the movement of the probe tip and by reproducing this signal with the actuator.

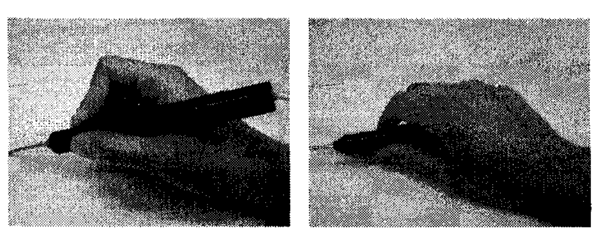
3.1.2 Acceleration versus Force

Acceleration sensors, or accelerometers, are used to measure the movement of the tool tip. With appropriate integration constants, acceleration signals entirely describe the movement of any object. The only aspect of the interaction not described by the acceleration signal is the steady state and the low frequency components of the tool displacements. To a certain extent, when one drags a tool over a surface, the harder one presses on the surface the better the tool tracks the valleys and bumps and the the movements and vibrations become more pronounced. However, clearly for each surface and each tool there is a preferred pressing force and a preferred speed. Finding and regulating these quantities depends on the skills of the user. This can be related to the work by Lederman et al., who found that the stronger the application force, the rougher a surface was perceived [33]. For the same pressing force, amplifying the vibration movements will have the effect of enlarging and reshaping the bumps and valleys. Smaller undulations will appear to be larger and will be easier to detect. We can conclude that the information to be amplified for tactile enhancement purposes is embodied in the acceleration of the tip of the probe and that sensing force or strain is unnecessary.

3.1.3 Additional Consideration

The structural dynamics of the tool also influences the behaviour of the system. This includes the stiffness, the weight distribution of the handle and the metal tool tip. The more rigid the system and the lower its mass, the more it can transfer the force or acceleration with high fidelity. In addition, since the tool "samples" the exploring surface with its tip, the size and the shape of the tip also play and important role in the system behavior. Klatzky discussed the relationship between the probe tip and toughness perception in [35]. The tool tip should be compatible with the target surface features. The finer we wish to sample the surface, the smaller the tool tip should be. But a fine tip could damage or be damaged by the surface. Arthroscopic and dentistry instruments provide many examples of these tradeoffs.

Because the vibration signal is transmitted to the user through the hand, the manner by which the user grips the probe plays an important role as well. First, the more tightly the tool is gripped, the less the tool is allowed to move, so the smaller the resulting acceleration is. Because the tactile sensation is produced by skin movement [25] a tight grip also reduces the resulting tactile sensation. The gripping method also changes the system response. Two examples of gripping methods are shown in Figure 3.2. In Figure 3.2a, the probe is held as a pen; in Figure 3.2b, the probe is held in the manner of a surgical knife. As shown in more detail in the next chapter, these two holding methods yield very different responses.



(a) Holding as a pen (b) Holding as a knife

Fig. 3.2 Examples of the two holding methods

3.2 Implementation

MicroTactus has four different components: the sensor, the actuator, the handle and the signal processing unit. In this section, the components will be presented in the mentioned order.

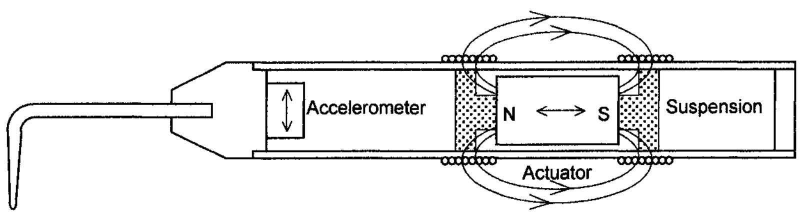


Fig. 3.3 Probe Sketch

3.2.1 The Sensor

The accelerometer was mounted at the base of the probe's metal tip. The approximate range of acceleration produced during a probing activity was found by looking at the output of the accelerometer with an oscilloscope. These preliminary trails indicated that scratching a soft surface produced accelerations of about ±2 g; for harder surfaces, such as wood or plastic, the scratching acceleration was about ±5 g. Knocking on a wooden surface or scratching it at high speed could yield up to ±10 g. A 2 g dual-axis accelerometer (Analog Devices, ADXL311) was selected for a tear-detection task, as described in Chapter 5.

3.2.2 The Actuator

The tactile transducer demanded special attention. After numerous design iterations, we converged on a structure comprising a cylindrical rare earth magnet (NdFeB) elastically suspended inside the handle with two sets of coils wrapped around the handle. Descriptions of previous versions of the actuator can be found in Appendix A.

Figure 3.3 shows that, to a good approximation, the field lines escaping the magnet crossed the two coils at right angles. When electrical current flows, a Lorentz force is developed between the magnet and the handle.

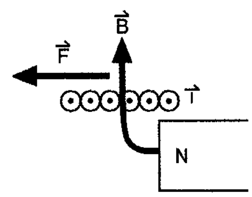


Fig. 3.4 Lorentz Force produced by the Actuator

$$\vec{F} = \vec{i} \times \vec{B}, \ |i| \propto V \Rightarrow |F| \propto V$$

$$F = m * a \Rightarrow a \propto V$$

The above equations express the fact that the relative acceleration between the magnet and the handle is proportional to the voltage across the coils if its impedance is assumed to be scalar and constant. By controlling the voltages, one can control the acceleration sensed by the user. The Lorentz's force moving the suspended magnet and the handle is transformed into tactile signals by deforming the skin of the holding hand. In the simplest configuration, the accelerometer's voltage output can, with some amplification, be directly used as input to the actuator. Experiments showed that a mere 10 W of electrical power caused vibrations large enough to numb the fingers in wide range of frequencies. This low power consumption and the modest bandwidth requirements enabled us to use an ordinary audio amplifier to drive the device.

Although there may be numerous alternative designs (e.g., using variable reluctance actuators) or optimized designs (e.g., using a tubular soft-iron magnetic return), this simple "open magnetic circuit" design was appropriate and gave excellent results.

3.2.3 The Handle

To create an "augmented" arthroscopy probe, we machined a tip similar to a real probe made of the same bio-compatible metal. The metal tip was fixed to a holder made of Delrin plastic, which was inserted and attached in the handle. The handle was made of carbon fiber tube of 15 mm diameter and 180 mm long. Carbon fiber material was chosen instead of aluminum or plastic because of its stiffness and its light weight. The dual-axis accelerometer was attached at the base of the tool tip, and the tactile actuator was placed inside the handle.

The basic idea of enhancing tactile sensations is to amplify the signals from the sensors and play them back to the actuator. However, because the sensor and the actuator are connected physically through the probe's structure, the system could easily become unstable. To address this problem, the accelerometer was oriented to measure acceleration in the directions radial to the axis of the handle, while the movement created by the actuator was axial to the handle. This had the effect of dynamically decoupling the input from the output. Although coupling is inevitable when the probe touched a surface, this design greatly improved the stability.

The actuator can only produce alternating forces, or vibrations. During a surface-exploring task, the tool tip moves, tracking the surface. When its acceleration is captured and sent to the actuator, the magnet inside the handle moves the similarly to the variations of the surface, hence producing a vibratory sensation similar to what one feels when doing the task directly. The system can also amplify or modify the tactile sensations, hence the signal processing can be application-specific.

3.2.4 Signal Processing Unit

Although the system could operate quite well with just analog signals, a digital signal processor evaluation board (Analog Devices Blackfin533) was used. It gave us more flexibility in filtering and signal shaping and made recording and playing tactile signals more convenient.The 16-bit fixed-point processor clocked at 270 Mhz has computing headroom for high-order filters and other real-time processing algorithms.

Accelerations were sampled with 16-bit resolution at the rate of 48 kHz by a coder-decoder (codec) designed for audio signals. Clearly, the capacity of this audio codec surpassed what was needed for touch. Although audio codec does not provide the information on voltage offset (DC component), it does not represent a limitation because the actuator can display alternating signals (AC component).

The signal was first anti-aliased by digital filters. The anti-aliasing filter was a low-pass finite impulse response filter of order 64. It had a 3 dB cut-off frequency at around 500 Hz, and its stopband attenuation was around 50 dB. This was needed to

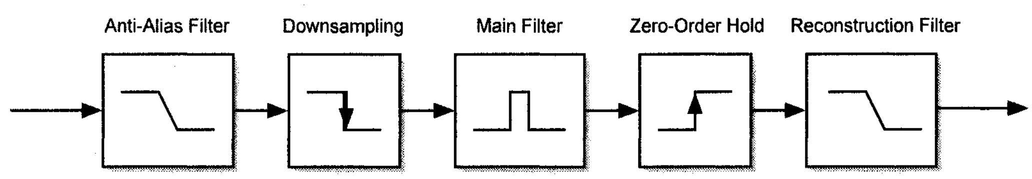


Fig. 3.5 Diagram of operations in DSP

filter out high frequency components which had little chance to be relevant to touch while keeping the bandpass as flat as possible. After anti-aliasing, the signal was down-sampled to 2400 Hz. This sampling rate is high enough to represent signals below 1200 Hz, which are sufficient for haptic signals. By limiting the bandwidth of the output, downsampling increased the stability of the system and eased the design of filters by targeting only the frequency range of tactile sensations. Referring to Figure 3.5, the main filter is used for additional processing. Before the output signal can be sent to the codec, its sampling rate must be converted back to 48 kHz. This is done with a zero-order hold filter.

3.2.5 General Design Consideration

The probe was easily manufactured and it still has room for additional functionalities. First, it has a very simple physical structure, so all electrical, mechanical and electro-mechanical parts are easy to procure or manufacture. Some components, such as the accelerometer and the DSP board can be purchased for a relatively low cost. The accelerometers are widely used in the automobile industry and they come in many different ranges and resolutions. The DSP processor is designed for multi-media applications, which typically require a lot more computing power than haptic applications. By using audio equipment for haptics, wide bandwidth, large memory space and high operating speed are readily available for adding new functionalities.

3.2.6 Configurations

The design of MicroTactus allows for several different configurations. Besides the original purpose for touch amplification, it is also possible to use it for remote sensing, surface recording and audio feedback.

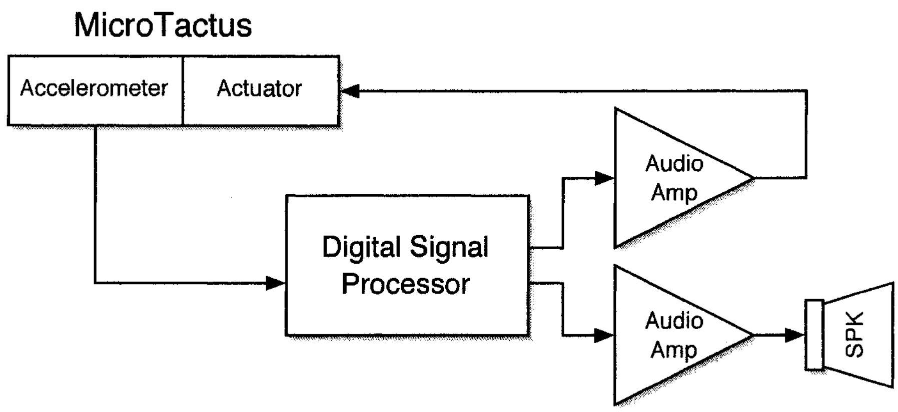


Fig. 3.6 MicroTactus System Diagram

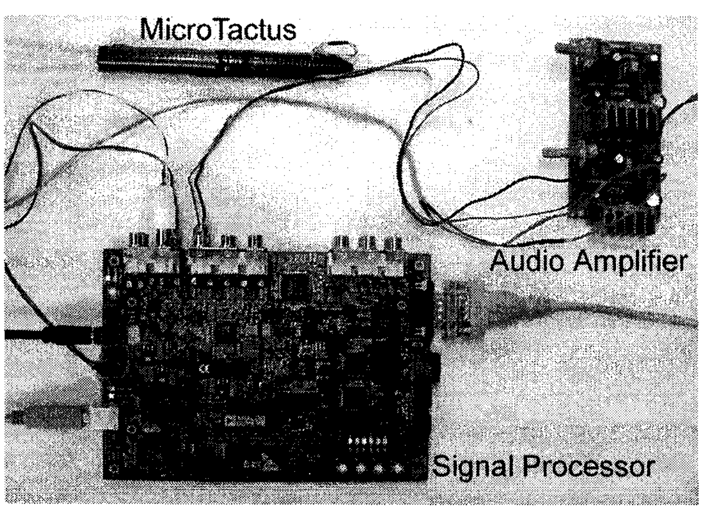


Fig. 3.7 MicroTactus and all its components

Since the actuator was driven by a signal that is to some degree independent of (and orthogonal to) the sensed signal, the probe could be used as a stimulator *independent of actual contact of the probe tip with a surface.* Thus, the probe could be used as a "tactile display" device that could fit in an "augmented reality paradigm". With a second identical probe of the same design, it is also possible to sense surfaces remotely. For example, we could use one hand to manipulate the probe and the other to experience the surface. Alternatively, it is possible to have an assistant scratch and tap a surface while a user experiences this physical interaction remotely. The device could also be used as a surface-recording tool so that, for example, we could record what a surgeon experiences during arthroscopy and play back the experience to one or several trainees for instruction. Finally, because of its spectral characteristics, the signal can also be recorded, played back, or monitored with an ordinary audio system.

3.3 Subjective User Feedback

Once the device was put together, a short and informal survey was conducted with several people. Here is a summary of what the users feel about the device under different operating modes.

3.3.1 With Actuator On

In this mode, the gain of the system was tuned to the maximum stable gain. Users found that when the probe was dragged over a sharp edge, the sensation was enhanced. It was as if the edge were much higher than it actually was. If the surface had regular textural features, this regularity was also enhanced. Interestingly, users sometimes only noticed the effect of the actuator at the instant it was turned on or off. This may be because the enhanced tactile signal is so natural that it is hard to distinguish it from the nominal signal. It could also be that the gain of the system was not high enough. To increase the gain, more sophisticated feedback control should be designed and implemented in the signal processor.

3.3.2 With Sound Feedback

Past studies showed that with bare finger, the sound produced while exploring surface texture does not play a significant role in texture perception [47]. However, while feeling texture with a probe, haptic and audio cue both contribute to the perception of surface roughness [48]. With our device, this mode with sound feedback works remarkably well. Because the recorded signal is sent to a speaker, there is no stability issue and the gain is as high as the user desires. The details on the surfaces are very accurately heard from the speaker and the effect is similar to when a microphone is dragged over the surface, yet the sound is clean and highly detailed.

3.3.3 Remote Sensing

In this mode, the sensor and the actuator are detached. One user drags the probe tip over a surface while the second user holds the actuator. The effect is surprisingly accurate on surfaces with fine tactile texture and patterns. Because most users are not familiar with tactile displays, they find it very interesting that one can feel a tactile signal remotely. Similar to the mode of sound feedback, stability is not an issue, and so the gain can be increased to suit user's needs.

Chapter 4

Device Analysis

This chapter presents the results of the response analysis of the MicroTactus device. Measurements of the frequency response of under different conditions were made and are discussed. Recordings when the probe is dragged over different surfaces were collected.

4.1 Conditions of Analysis

The device dynamics can be represented as a system with inputs and outputs, as described in the previous chapter. When the device operates normally, the input is the acceleration when the user drags the probe over a surface, and the output is the skin movement generated by the actuator's acceleration. The analysis was performed in two steps. In the first step, the system response was analyzed in the frequency domain while the probe was held in free space. Then, sequences of signals were recorded and studied when the probe tip was dragged over various surfaces.

The holding hand plays an important role in the complete system dynamics. The modeling of the system without the holding hand was not investigated nor was it necessary, since this was not a useful operating condition. Thus, it is important to recall that all measurements were made while holding the device, and hence suffer from some variability. The gripping method, the gripping forces, the normal force applied to the surface and the dragging speed all influenced the response. These factors were kept as constant as possible by the experimenter.

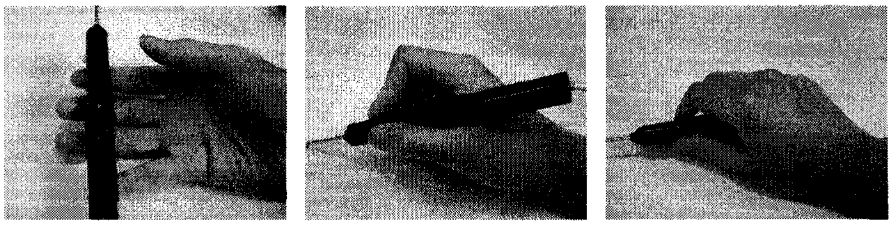
4.2 Measuring Hand-Loaded Response

The System Identification toolbox of SigLab™ was used to measure how input voltage was translated into output acceleration. This involved sending swept-frequency waveforms from 0 to 400 Hz as input, and measuring the resulting output acceleration in the radial and axial axes. The response was obtained by estimating the transfer function from the input to output. Here is a summary of the different conditions under which measurements were made:

- Acceleration in Different Axis:
  1. axial acceleration;
  2. vertical acceleration;
  3. horizontal acceleration.
- Holding Method:
  1. placed on four extended fingers;
  2. as a surgical knife;
  3. as a pen.
- Surface touched by probe tip:
  1. free, not touching anything;
  2. touching a soft surface;
  3. touching a hard surface.

4.2.1 Axis and Holding Method

The definition of the three axes is shown in Figure 4.2. Recall that the actuator was designed to generate acceleration only on the axial direction. The three holding methods are defined in Figure 4.1. When the probe is placed on four extended fingers, the hand minimally restricts the probe movement. In contrast, when the probe is held like a pen or like a surgical knife, the fingers impose significant constraints to the probe's movement.



(a) Placed on extended fingers (b) Holding as a pen (c) Holding as a knife

Fig. 4.1 Definition of the 3 holding methods

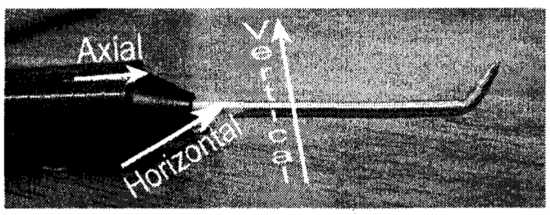


Fig. 4.2 Definition of the 3 axis

Measurements were made for the three axes under three holding conditions. Figure 4.3 presents the results grouped for each axis. A peak around 43Hz is present in all conditions, which corresponds to the resonance frequency of the actuator moving mass.

To prevent distortion of tactile signals, the frequency response should be as flat as possible within the range of interest: between 50Hz to 400Hz. In order to flatten the response, this resonance frequency should be filtered out. Although not implemented, to achieve this, a simple high-pass filter should be sufficient.

As shown in Figure 4.3, the axial acceleration was relatively regular with little amplitude variation for all the three holding methods. As expected, this shows that the actuator has a relatively linear response and a sufficiently large bandwidth. On the other hand, the vertical and the horizontal accelerations are not as regular. If the actuator were ideal, it would only move in the axial direction and the radial directions would show signals of low amplitude. However, as shown, the horizontal and vertical directions seem to couple with the axial direction for frequencies below 100 Hz (Figure 4.3).

For later implementation, if the acceleration produced by the actuator must be decoupled with the radial axis to ensure stability, a filter must be applied at the input to reduce the frequency components in this range.

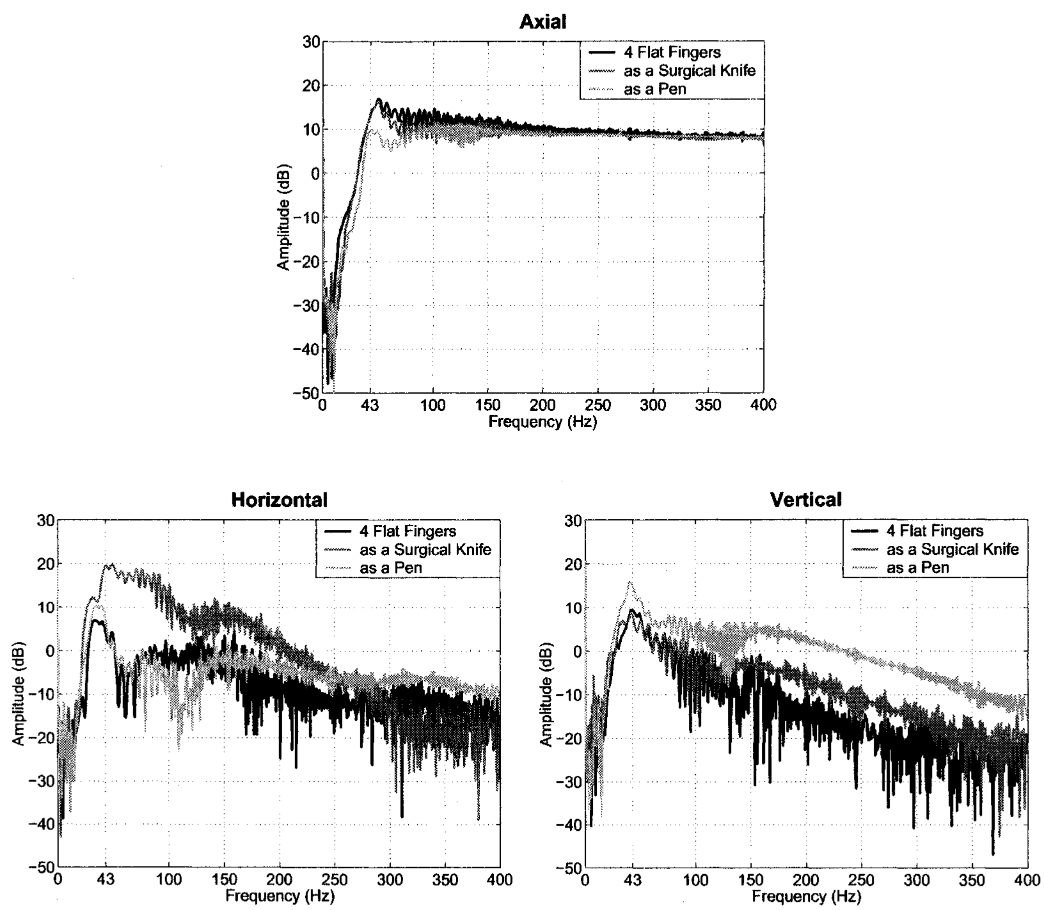


Fig. 4.3 Responses grouped in holding method

Figure 4.4 presents the same data grouped by holding method. When the probe was held by four extended fingers, the axial acceleration was decoupled from the other two axes. Except for the peak around the resonance frequency, the axial acceleration was almost uniform, and the horizontal and vertical acceleration responses were lowered approximately by 10 dB. When the probe was in contact with the skin, its movement had almost no constraint and the acceleration measured was close to the free response of the actuator. The 10 dB amplitude difference between axial and radial directions showed that the actuator's movement was well aligned.

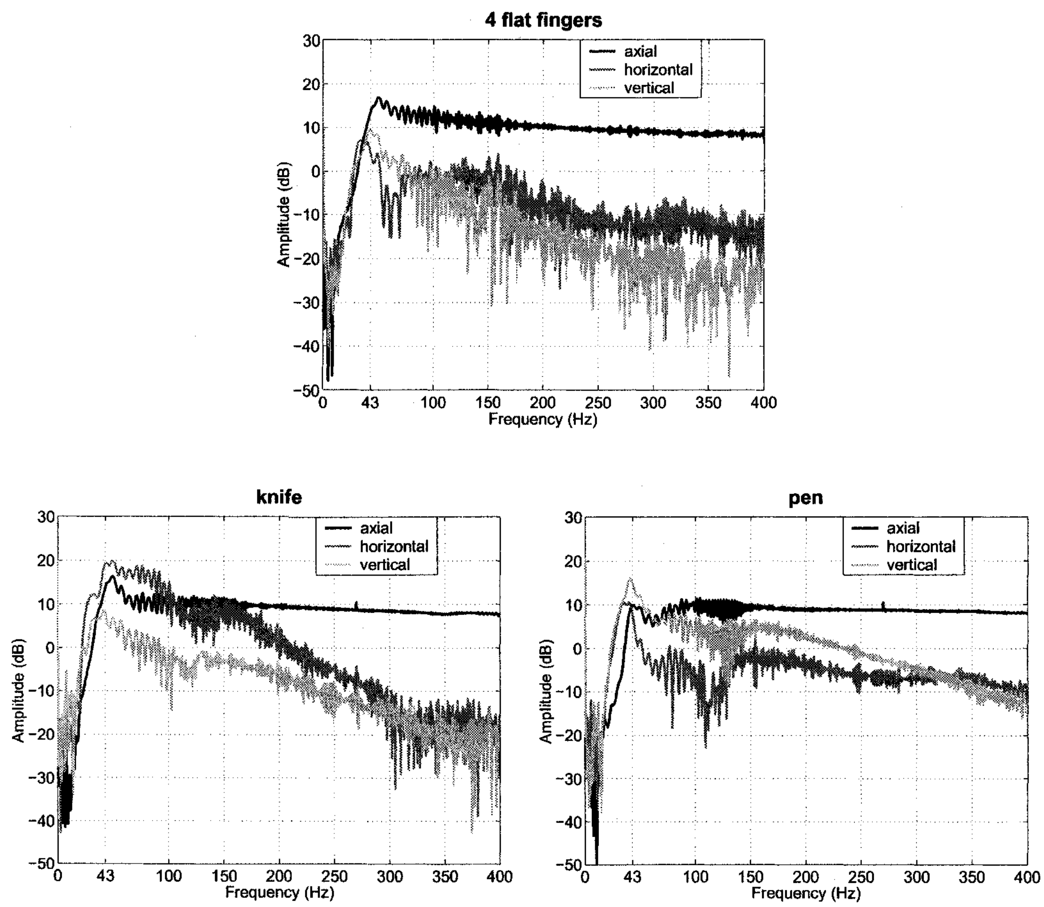


Fig. 4.4 Responses grouped in axis

When the probe was held as a knife or as a pen, the responses for the radial acceleration are the same order of magnitude as the axial acceleration within the coupling range, below 100 Hz. We can conclude that the coupling of the three axes happens when the probe is constrained by the hand. While holding the probe, the grip of the fingers restricted the movement of the probe in certain direction and allowed freedom of movement in others.

When held as a pen, as shown in Figure 4.1, the probe was restricted in its axial movement and had more freedom in the radial direction. There were three points of contact around the actuator, and one above the actuator further from the tip. The later touches the skin tangentially, and this may explain why the acceleration was lower horizontally than vertically.

When the probe was held as a knife, the axial acceleration was also restricted. Since the probe was held from the side, and the four fingers are on one side and the thumb on the other, there was more room for horizontal movements than vertical movements. This could explain the high amplitude of the horizontal acceleration.

The coupling of the three axes occurs only in low frequencies in each of the cases shown here. The amplitude of the radial frequency response above 200 Hz is much lower than the axial direction. For input signals above this frequency, the axial and the radial acceleration can be considered decoupled. One may conclude that the gripping effect of the hand does not induce coupling for higher frequencies.

4.2.2 Gripping Force

Responses were also measured for two different gripping forces and showed in Figure 4.5. The results did not show large differences when the device was held lightly or tightly. One could reason that the acceleration should be attenuated when the gripping force is larger, but such was not the case. Notice that when the probe was held tighter, the tissues of the fingers are more compressed, but this did not seem to affect the response.

In the range of frequency below 150 Hz where the acceleration is coupled in the three axes, a tighter grip reduced the axial acceleration amplitude by a few dB, and increased the horizontal and vertical response by approximately the same amount. This may indicate that the tighter the grip, the larger the coupling effect. It also agrees with the fact that the axial acceleration was well decoupled when the probe was held by four extended fingers. Here, the greater the grip force is, the greater the coupling effect.

For the frequency range above 150 Hz, the horizontal and vertical accelerations have greater amplitude when the probe is gripped tighter, while the axial acceleration remains constant. One possible explanation is that the finger tissues act like a low pass filter when they are relaxed. When the gripping force is greater and the tissue is

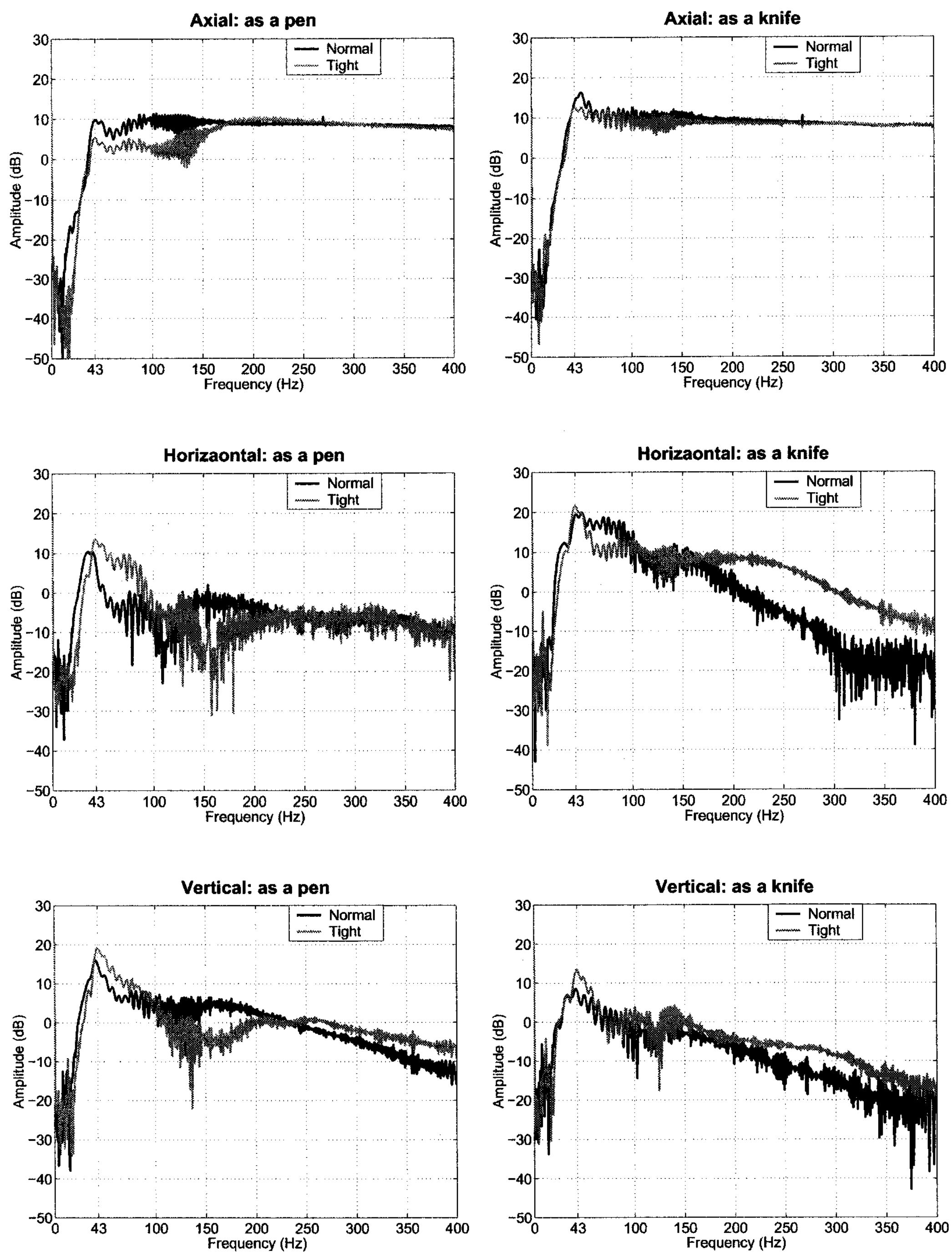


Fig. 4.5 Responses when held with different forces

compressed, the high frequency vibrations are no longer filtered out and are passed to the bones.

4.2.3 Surfaces

The response of the probe when it touches two different surfaces is discussed for two cases: a soft, skin-like surface and a hard, wooden surface. The soft surface is made of very compliant silicon gel, and the hard surface is made of compressed wood.

For the axial acceleration, the harder the surface, the smaller the amplitude, by a difference of a few dB. For radial accelerations, the changes were more significant. Moreover, the responses were similar when the probe tip was free and when it touched soft surfaces, but naturally the amplitudes were greater when the probe was free. This similarity was expected, because a compliant soft surface does not impede the probe movements.

When the probe touches hard surfaces, the response is reduced in amplitude for low frequencies, and a peak appeared around 280 Hz. This is probably a resonant frequency introduced by the metallic tip. According to the figures, for hard surfaces, it is easier to decouple the acceleration by filtering out lower frequency components because they are less significant. This is not true for soft tissues with responses very close to the free response. It is not possible to decouple the different directions by simple filtering techniques that could apply to all cases.

Additional observations can be made for the different directions. According to the analysis in the previous sections, when the device is held as a pen, the acceleration coupling is in the vertical direction. When it is held as a knife, it is in the horizontal direction. For the pen-like grip, the coupled direction, which is the vertical direction, has similar responses for frequencies under 150 Hz in the three cases. The decoupled direction, the horizontal direction, has rather irregular responses. Similarly, the knife-like grip gave more regular results in its coupled direction, the horizontal direction, than the decoupled vertical direction.

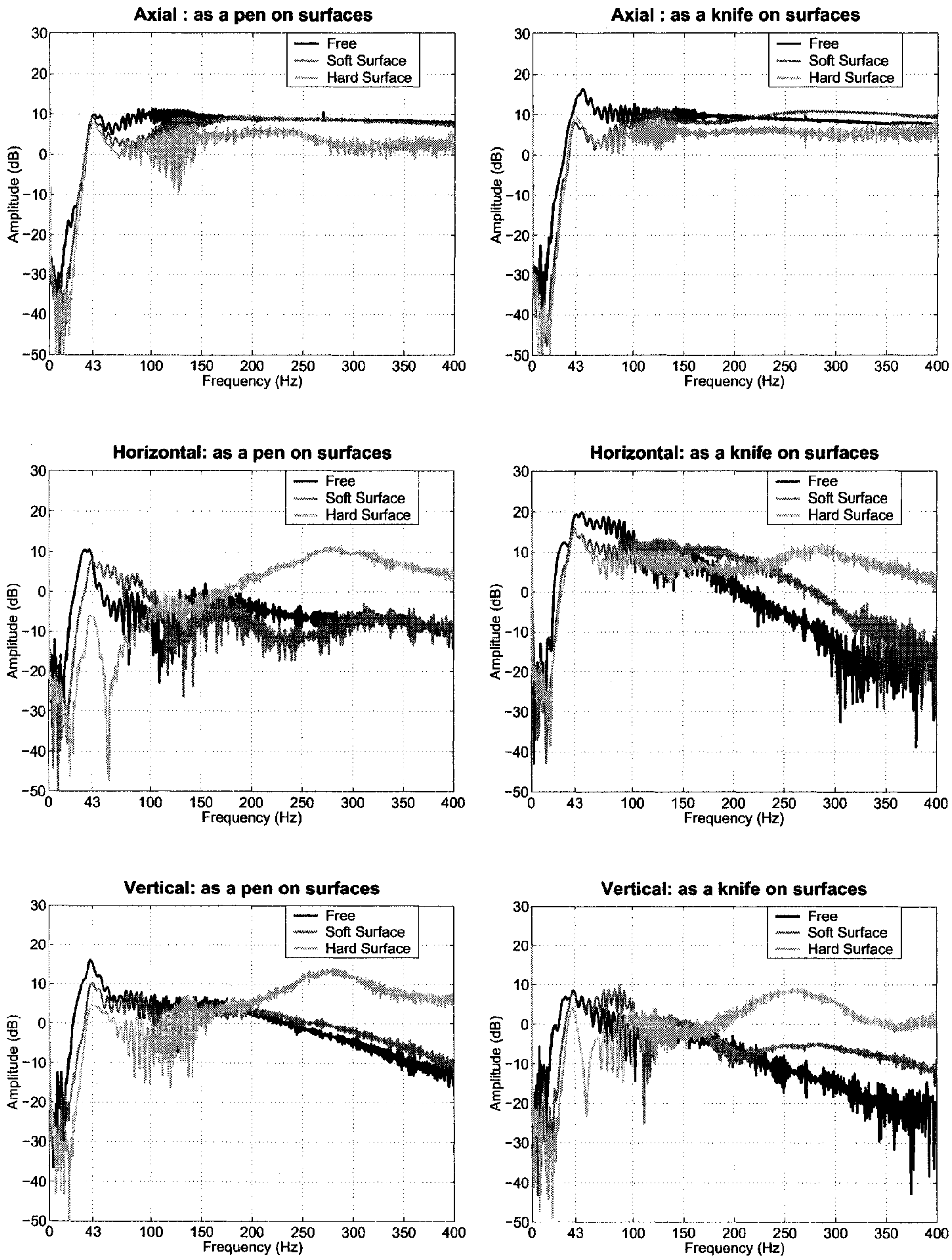


Fig. 4.6 Responses dragged over different surfaces

4.2.4 Summary of Hand-Loaded Response

In itself, the actuator has an acceptably linear response in the frequency domain. However, when it is mounted inside the handle, different factors influence its performance. Particularly, the coupling of the three axes varies under different conditions. The degree of coupling changes with the griping method, gripping force and probed surface, therefore, it is very difficult to obtain a response which can represent all cases. Besides what was tested in this section, there are many other factors which can influence the results. Just to mention a few: the application angle of the tool tip, the force at which the probe is pressed against the surface, different hand size, etc. Because the probe is manipulated by people, the numerous interconnected factors make a complete analysis very complex. Semere et. al. recently did interesting studies in sensor actuator asymmetry [49] which could be related to the findings of this chapter.

4.3 Dragging over Surfaces

The objective of this section is to report on the device response "in action". Signals were recorded when the probe was dragged over different surfaces. The measurements were made when the probe was gripped like a knife, and both vertical and axial acceleration signals were recorded. The knife-like gripping method was investigated since it is the way surgeons hold a diagnostic probe.

The vertical and the axial acceleration was recorded because when probing a surface, the acceleration in these axes is stronger. The axial acceleration was also recorded also because it directly measures the contribution of the actuator.

The following list summaries the measurements reported in this section:

- Surface Measured
  1. soft silicon gel;
  2. soft silicon gel with a cut at the surface;
  3. computer mouse pad;
  4. computer mouse pad with a cut at the surface;
- Axis Measured:
  1. vertical acceleration;
  2. axial acceleration.
- Operating Mode:
  1. actuator off;
  2. actuator on;

4.3.1 Silicon Gel

The result for a soft silicon gel surface is shown in Figure 4.7. First, when the actuator is turned off, the acceleration is much greater vertically than it is axially. This was expected because the probe tip was perpendicular to the probing surface, and the axial axe was, to some degree, decoupled from the radial axes. When the actuator was turned on, the amplitude of the axial acceleration was visibly magnified. This difference contributes to the enhancement of the tactile information, which is the goal of a MicroTactus device. Notice that the vertical acceleration is not changed by much because of the good decoupling.

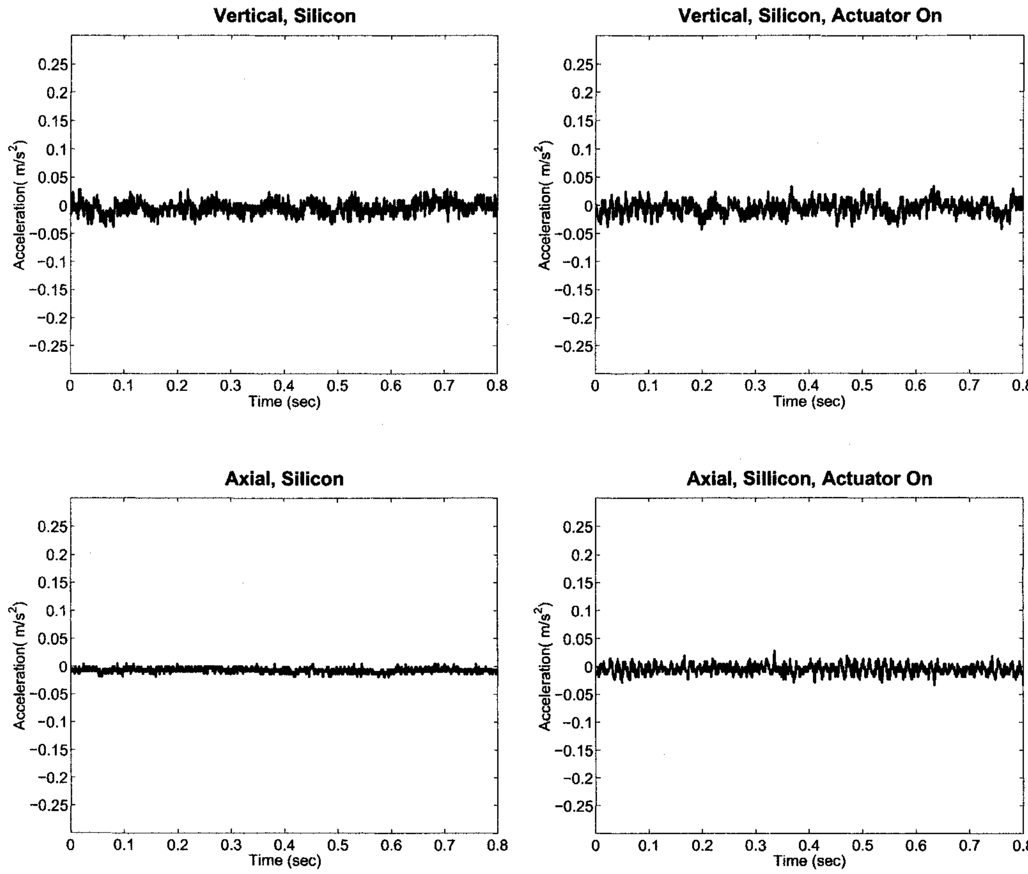


Fig. 4.7 Recordings when dragged over soft silicon gel

It is worth noting that the gain was manually tuned to the maximum value within the stability range. Because the recorded acceleration had a very low amplitude, if the gain were set too high, the output signal became noisy. Hence in this condition the device performance is essentially limited by the sensor's performance.

In Figure 4.8, one can see recordings when the probe was dragged over a deep cut on the same surface. The "spike" caused by the cut is visible in all the subfigures, and this demonstrated that the two axes are not entirely decoupled. Similar to what is seen in the previous figures, the "spike" had a lower axial acceleration compared to the vertical acceleration. Compared to Figure 4.7, the actuator not only amplified the signal, but also caused ringing. This may be because of the resonance of the actuator or to the surface.

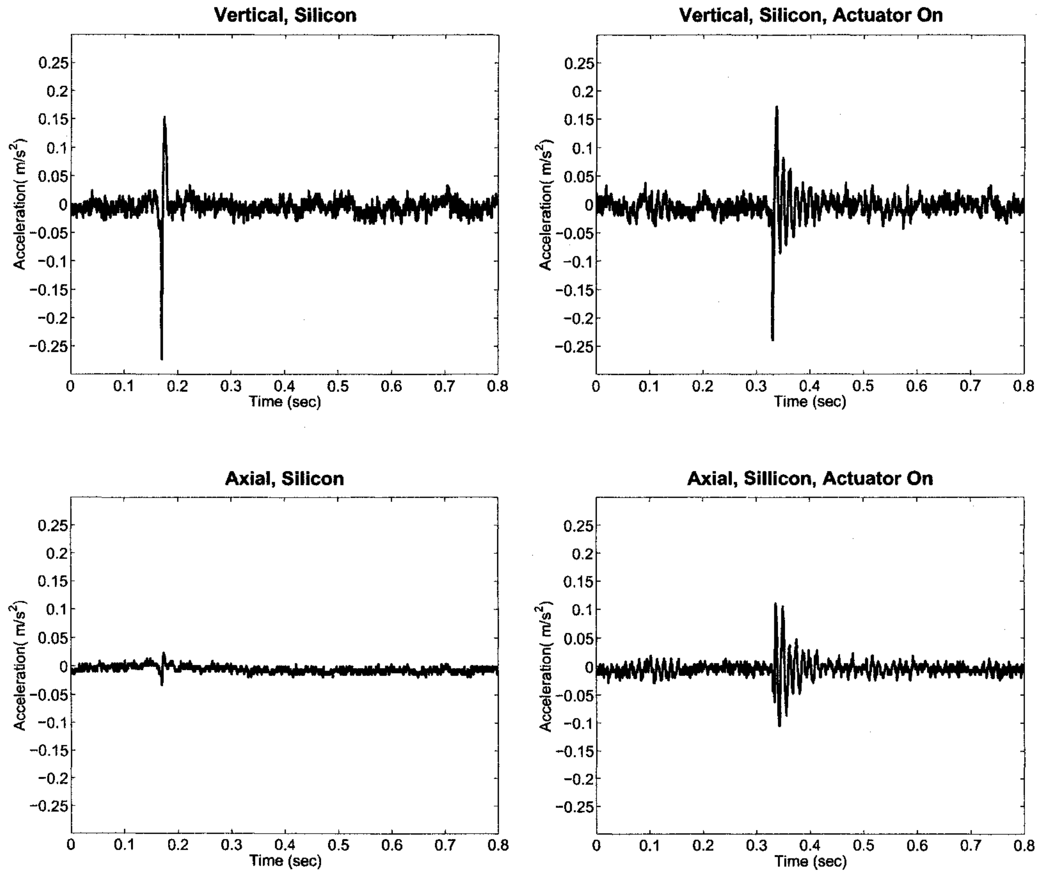


Fig. 4.8 Recordings when dragged over a cut on soft silicon gel

The frequency spectrum of the above recordings in Figure 4.9 showed a non-uniformed amplification of the signal when the actuator is turned on. The low frequency ringing caused by the actuator can be seen: one peak appears around 75 Hz, and another weaker one at around 60 Hz. The ringing was caused by the sensor-actuator feedback loop and by the natural resonance of the actuator.

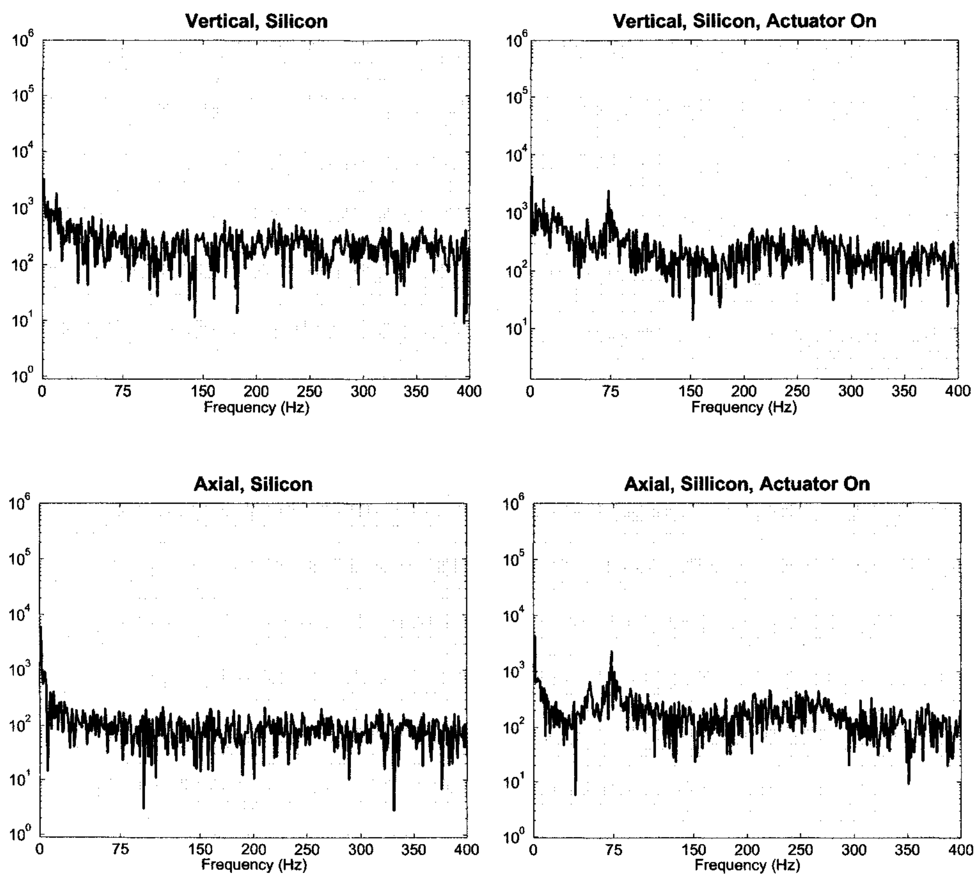


Fig. 4.9 Frequency plots of the recordings when dragged over soft silicon gel

4.3.2 Computer Mouse Pad

The mouse pad had a hard plastic upper layer, and a soft foam backing layer. The top plastic sheet had regular surface texture. The regular texture of the top hard plastic was an excellent surface to test the texture enhancement capacity of Micro-Tactus. The soft bottom layer increased the stability margin because of the low-pass characteristic of the rubber.

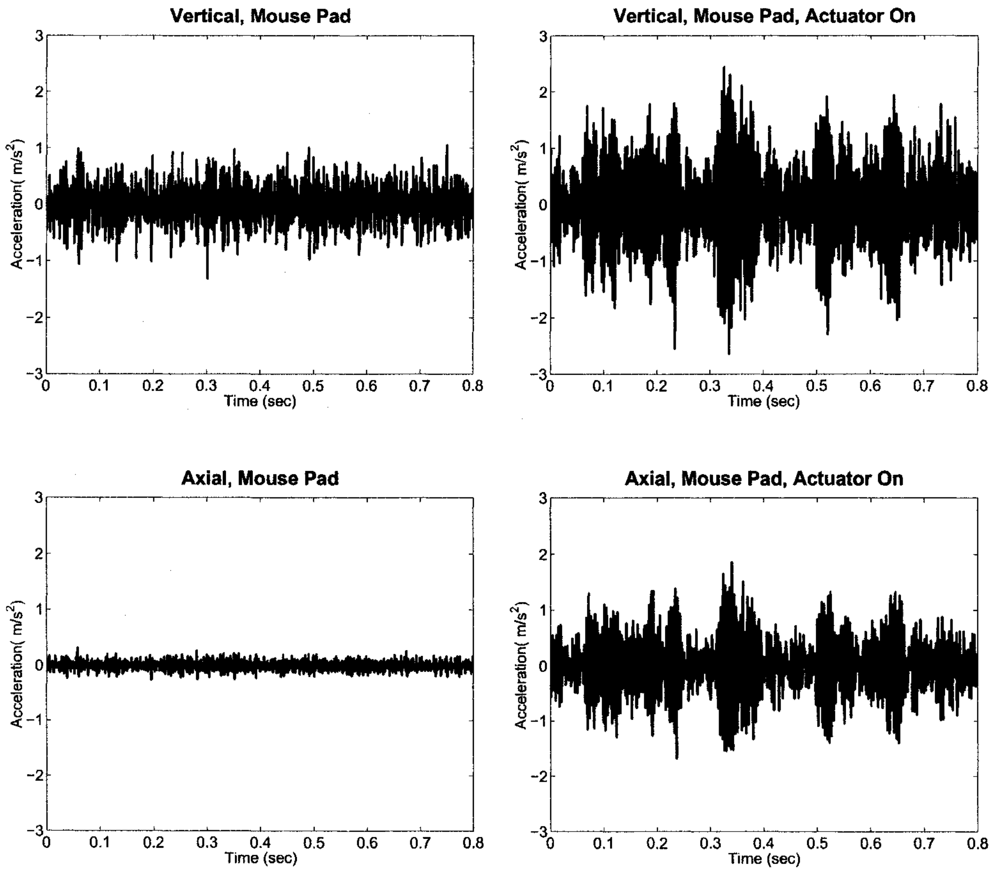


Fig. 4.10 Recordings when dragged over the computer mouse pad

Recordings obtained when the probe was dragged over the mouse pad can be found in Figure 4.10. Note that the scale of the vertical axis is different from that of the figures for the silicon gel. The amplitude of the acceleration is more than ten times greater here. Similarly to the silicon gel surface case, the actuator amplified largely the axial acceleration. However, it is also easy to notice the appearance of a low frequency component. This indicates that some frequency components are amplified more than others.

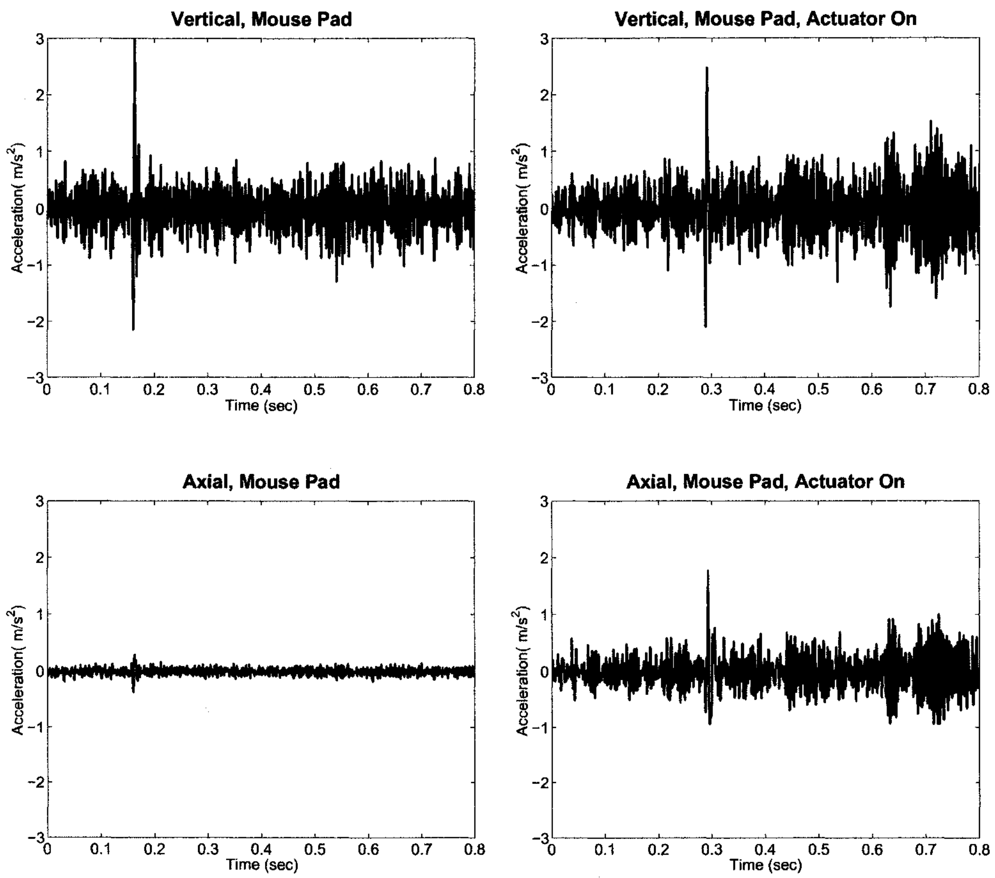


Fig. 4.11 Recordings when dragged over a cut on the computer mouse pad

Figure 4.11 shows the recordings when the probe was dragged over a cut surface. One can notice the amplitude peak in all the sequences. Compared to Figure 4.10, the increase in the amplitude when the actuator is turned on is not as pronounced, possibly because of the dragging speed or the force at which the probe is pressed against the surface. No ringing caused by the actuator is visible in these graphs.

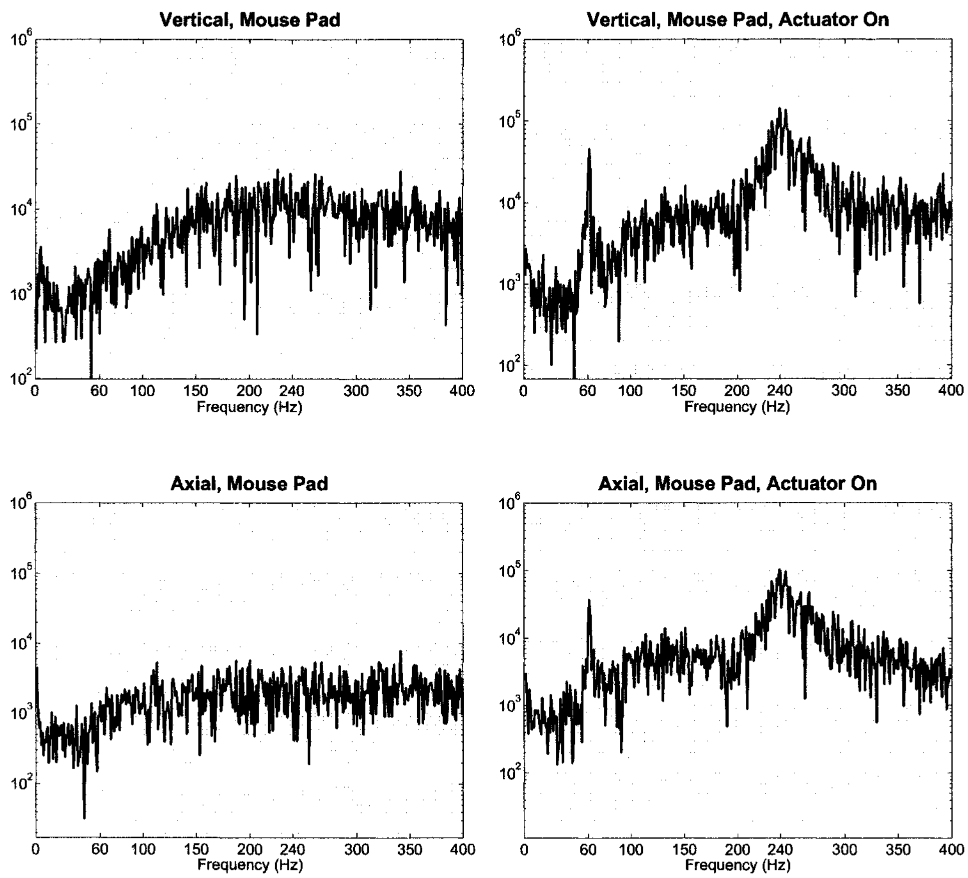


Fig. 4.12 Frequency plots of the recordings when dragged over the computer mouse pad

The frequency plot 4.12 shows that the actuator amplification is not uniform in the frequency domain. The low frequency component caused by the actuator, as indicated in Figure 4.10, is the peak around 60 Hz. This coincides with the resonance frequency of the actuator. A more important peak is around 240 Hz. A peak at around the same frequency was also observed in Figure 4.6. It seems that the resonance frequency for all hard surfaces is around this value. This non-linear amplification effect may even be sometimes desirable since it enhances certain characteristics of the surface.

4.3.3 Summary of Surface Recording

When the actuator was turned off, the sampled vertical acceleration was greater than the axial acceleration. The actuator takes the vertical acceleration and reproduces it in the axial acceleration, and therefore both axial and vertical accelerations are present in the axial direction. In general, hard surfaces produced greater acceleration than soft surfaces. In the frequency domain, the amplification did introduce distortion for the texture signal because signals were not amplified equally in the frequency domain. However, because part of this is caused by the surface itself, amplifying specific frequency range may enhance aspects of perception and improve the performance in texture discrimination. In addition, when the probe is dragged over surface cuts, the amplitude of the spike is increased, this amplifies the perceived effect for the cut.

Chapter 5

User Experiments

This chapter describes user studies which were performed with the MicroTactus device. The experimental method is presented in the first section, followed by a report of the results and a discussion.

5.1 Experiment Method

The experiments designed in this chapter aim at demonstrating the utility of the probe. We tested it during the difficult task of superficial tear detection. In this task, the probe tip was dragged gently on the surface of a cartilage-like material. If there was a crack in the surface the tip would dip slightly in the crack, producing a transient signal that could be detected by touch. If the crack were sufficiently deep relative to the radius of the probe tip, and/or if the normal force were sufficiently high, the tip would catch the lip of the crack and produce a large transient. These, and perhaps other cues, could be used by surgeons to detect and characterize surface anomalies.

5.1.1 Surface Preparation

To approximate the conditions of tear detection during arthroscopy, we prepared 3 mm-thick-pads made of Viton, a high-performance fluoroelastomer that resembles cartilage. Four 10×30 mm pads were glue-mounted on small boxes for easy handling. Cuts were made on the surface of the pads with a sharp blade protruding by a set distance out of a block of hard rubber. The first pad had no cut, the second had a 1.5 mm-deep-crack, the third had two 1.5 mm-deep-cracks, and the forth was completely cut 3 mm-deep. The four pads used in the experiment are described below:

- Pad 0: No cut
- Pad 1: With one cut
- Pad 2: With two cuts
- Pad 3: With one deep cut

The recorded acceleration while dragging the probe over the surface is shown in figures 5.1 and 5.2. The undulation in pad 0 is caused by of the surface texture. The single cut in pad 1 and 3 are very noticeable, as well as the double-cut in pad 2.

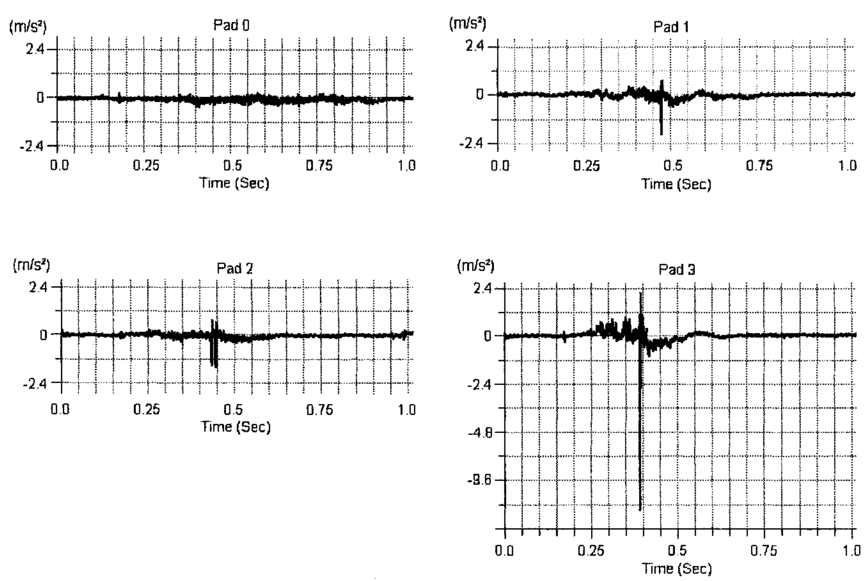


Fig. 5.1 Recordings when dragged over the pads used for the experiments

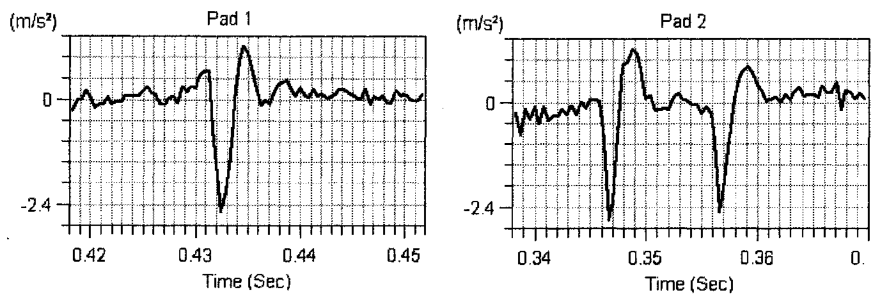


Fig. 5.2 Zoom-in for Recordings of Pad 1 and Pad 2

5.1.2 Subjects

We recruited eight healthy individuals of age 22 to 28. Two of them were physicians and six were students from the Electrical Engineering Department of McGill University. Four subjects were completely unfamiliar with our work, and the other four subjects had used the device before the experiments but did not know the details of its design. Subjects were paid for their participation. The procedures were approved by the McGill University Ethics Committee (see Appendix B).

5.1.3 Procedure

Two identical haptic enhancing probes were connected to the signal-processing system. Subjects sat at a table, held one probe with their dominant hand and explored the surface of the samples while using the other hand to hold the sample mounted on the boxes. The subjects were trained in the task under the guidance of the experimenter.

During the trials, the lights of the windowless room were dimmed so that it was no longer possible to see the cuts but the pads could be found on the table. A sequence of 24 pads was given to each subject in a randomized order, with each pad being presented 6 times. Subjects were asked to detect if there were a cut in the pad. They had to decide rapidly and answered by pressing keys labeled YES and NO. They were told that the experiment was timed. Trials were done under four conditions in the following order:

1. `Haptic`: subjects explored the pads with tactile feedback activated on the same

probe used for exploration.

2. `Audio`: subjects explored the surface with the probe, but instead of tactile feedback, audio feedback was relayed through a loudspeaker.

3. `Passive`: subjects held the second probe while the experimenter explored the pads with a first probe attempting to keep a constant speed. The tactile feedback from the first probe was sent to the second probe which was passively held by the subject.

4. `Off`: The subjects used a probe to explore the pads without tactile or audio feedback.

The duration of each testing session was less than one hour.

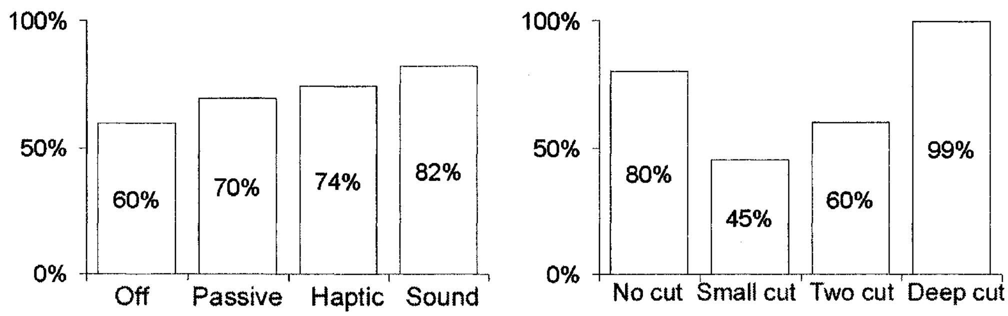
5.2 Analysis Method

The performance of the subjects is calculated as the percentage of good answers of the six trials. An *Analysis of Variance* (ANOVA) was carried out to test whether there is a significant difference between the two conditions. The results are first grouped by condition: `haptic`, `audio`, `passive` and `off`, and ANOVA is employed between `off` condition and `audio`, `passive`, and `haptic`, respectively. The results were also grouped by pad to test if each pad represented different levels of stimuli. Finally, a significance test was performed between novice and experienced subjects.

5.3 Results

Figure 5.3 summarizes the results (a) by condition and (b) by pad. Figure 5.3a shows that the performance of the subjects improved with haptic and sound feedback. A significance test confirmed that the haptic and sound feedback both influenced the performance. Sound feedback improved the performance by approximately 20%, and haptic feedback by 10%.

More detailed data is presented in Figure 5.4. Deep cuts were almost perfectly detected, and most subject also responded correctly for the surface with no cuts. For pads with small cuts, the performance in `Haptic`, `Sound`, and `Passive` was better than in the `Off` condition. When there was no feedback, the subjects failed to detect the presence of small cuts most of the time.



(a) By Condition

(b) By Pad

Fig. 5.3 Results summarized by condition and by pad

One-way analysis of variance (ANOVA) of the three conditions `Off`, `Haptic` and `Audio` confirmed the significance of the differences ($p = 0.015$, $p < 0.05$). The ANOVA test applied to pairs of conditions yielded $p = 0.015$ between the `Audio` and `Off`, and $p = 0.059$ between `Haptic` and `Off` conditions. There was no significant difference between `Haptic` and `Passive` conditions ($p = 0.15$, $p > 0.05$). The difference in performance between naive and non-naive subjects was not significant as indicated by a 2-way ANOVA test ($p = 0.53$, $p > 0.05$). There was no significant difference between the physicians and the other subjects ($p > 0.05$).

5.4 Discussion

5.4.1 Detection Task

The results for each pad are presented in Figure 5.3b and Figure 5.4. For the uncut and the deeply cut pads, the performance was well above chance. The deep cut was almost perfectly detected under all conditions. The haptic and audio feedback did not have a negative influence on detection of a deep cut, and the subjects performed at least as well with feedback as without. Furthermore, in passive detection, the haptic signal was adequate for the correct detection of a deep cut. Without haptic

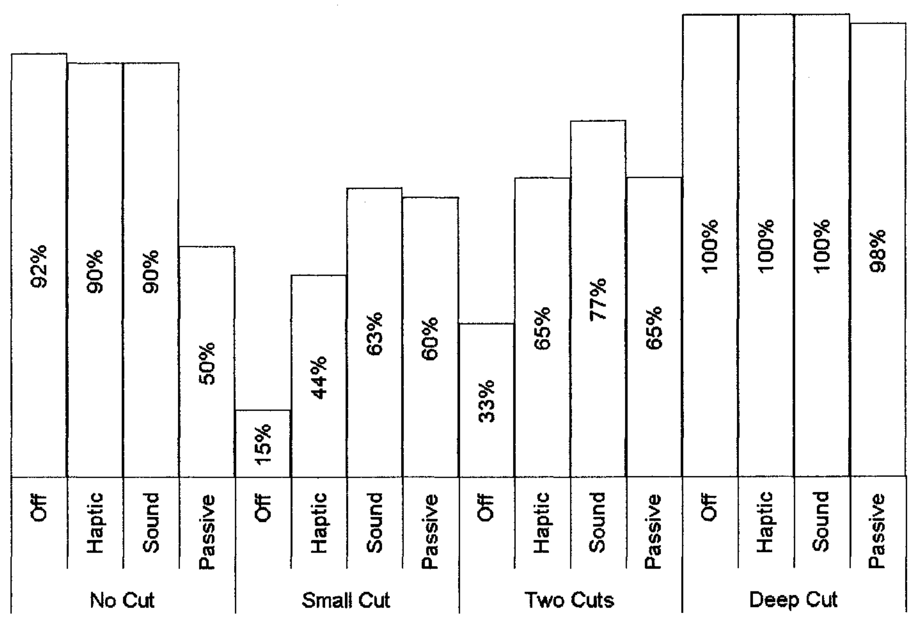


Fig. 5.4 Detailed results of user experiments

or audio feedback, passive detection was impossible. However, our results show that subjects performed remarkably well: the 2% miss rate for passive detection may well have been due to a single error made when the subject entered the data.

Figure 5.3b also showed that with one or two small cuts, performance without enhanced feedback was not far from the rate predicted by chance. This suggested that the dimensions of the cuts were close to the threshold of detection. From Figure 5.4, we concluded that without feedback, the cuts were hard to detect. With either auditory or haptic feedback, the detection rate increases. Thus, the device MicroTactus could improve the performance of subjects in detecting superficial cuts in a cartilage-like material.

5.4.2 Passive Detection

Figure 5.3a summarizes the performance for each condition. The test of significance indicated that haptic and auditory feedback had positive influences on the performance. About passive cut-detection task, the performance is at least as good as with active exploration without augmentation. In the passive condition, subjects had no control of the probe and could not see how the experimenter explored the surface. When subjects used the probe themselves, they could vary the speed and the pressure applied by the probe. However, subjects were still able to detect the cuts well, as shown in Figure 5.4. For pads with small cuts, the performance in the `Passive` condition is similar to `Off` and `Haptic` conditions.

5.4.3 Audio Feedback

Performance with audio feedback was consistently better than with haptic feedback, and most subjects spontaneously contributed an opinion to this effect. The simplest explanation is that the auditory system is better able to detect small transients out of a noisy background than is the tactile system. It is also possible that, using the two combined modalities of touch and audition, sensitivity may increase. Another possible explanation is that some useful information was lost in the filtering process. The signals to the speakers were not processed, but for haptics the signals were filtered and downsampled in an attempt to eliminate sensor noise. Although the 400 Hz threshold was imposed during the filtering, there may be some useful information above this frequency. Signal enhancement techniques beyond plain magnification in a frequency band may be useful.

Chapter 6

Conclusion

This thesis presented the design, fabrication, characterization and validation of a novel tactile magnification device: the Microtactus. After a brief literature review in the fields of augmented minimally invasive surgery instrumentation, texture perception and vibratory haptic devices (Chapter 2), the principle of operation, the design and the implementation of the device were explained (Chapter 3). The probe was designed such that it can function in several different modes: tactile amplification, remote detection and audio feedback. Objective measurements were made (Chapter 4) and it was concluded that because the probe is held by human hand, many factors may influence its response, and that it is very hard to find a mathematical model which can well describe its behavior under all conditions. Despite these difficulties in measurements, we conducted the user experiments (Chapter 5) to show that the probe has a measurable effect on the performance of subjects when performing a tear-detection task.

Many issues remain to be addressed. The first and most important is stability. We need to be able to increase the maximum stable gain. Previous chapters showed that the system dynamics is very complex because of human interaction, therefore, a simple system model will not be sufficient. A complete model of the system including the effect of human interaction on the mechanical properties should be built. Such a model would be helpful in the design of adaptive and non-linear filters for more stabilization.

From the analysis and the results, we concluded that the probe behaves very differently for hard and soft surfaces. It is therefore, easier to solve the stability problem by considering operation during two distinct regimes: with hard surfaces and with soft surfaces. The probe should function in two distinct modes, and different filters should be implemented to suit the specification in each mode. There is still lot of room for additional processing in the signal processor.

In the validation of the device, additional experiments are necessary. To assess its usefulness in a clinical settings, some experiments can be done using artificial samples of joints representing different diseases. It would include the performance evaluation of experienced and inexperienced surgeons. Besides in arthroscopy, it is important to verify the possibility application in other fields of Minimally Invasive Surgery such as laparoscopy. In addition, this device can be used to study aspects of tactile perceptions such as texture discrimination and discontinuity detection. Because vibratory signals can be recorded and manipulated in high fidelity, it provides the possibility to establish relationship between the mathematical expression and perceived sensation. It could also be used to study the relationship between the enhanced tactile sensation and visual or audio sensation in, for example, texture perception.

In summary, we have designed and built a tool capable of enhancing tactile sensation for surface texture and irregularities. Because this work is the first attempt to fabricate such an instrument, much remains to be done before it can be used in the operating room. We found that it is, however, an encouraging start.

References

[1] Johns Hopkins Hospital, "Johns hopkins orthopaedic surgery: Patient guide to knee arthroscopy." http://www.hopkinsmedicine.org/orthopedicsurgery/sports/knee.

[2] Skelar, "Sklar surgical instruments - product id 45-6070." http://www.sklarcorp.com/.

[3] J. Rosen, B. Hannaford, M. P. MacFarlane, and M. N. Sinanan, "Force controlled and teleoperated endoscopic grasper for minimally invasive surgery-experimental performance evaluation," *IEEE Transactions on Biomedical Engineering*, vol. 46, pp. 1212–1221, 1999.

[4] P. Dario, B. Hannaford, and A. Menciassi, "Smart surgical tools and augmenting devices," *IEEE Transactions on Robotics and Automation*, vol. 19, pp. 782–792, 2003.

[5] S. I. Schwartz, ed., *Principles of Surgery - 7th Ed. (1999).* Orlando, Florida, USA: McGraw-Hill Health Professions Division Date Accessed:, 1999.

[6] C. E. Scott-Conner, A. Cuschieri, and F. J. Carter., *Minimal access surgical anatomy.* Philadelphia: Lippincott Williams Wilkins, 2000.

[7] J. G. Hunter and J. M. Sackier, *Minimal access surgical anatomy.* New York: McGraw Hill, Inc., Health Professions Division, 1993.

[8] J. B. McGinty, ed., *Operative arthroscopy.* Philadelphia: Lippincott Williams Wilkins, 2003.

[9] R. Treuting, "Minimally invasive orthopedic surgery: Arthroscopy," *The Ochsner Journal*, vol. 2, p. 158–163, 2000.

[10] R. H. Taylor and D. Stoianovici, "Medical robotics in computer-integrated surgery," *IEEE Transactions on Robotics and Automation*, vol. 19, pp. 765–781, 2003.

[11] F. Tendick, S. Sastry, R.S.Fearing, and M.Cohn, "Applications of micromechatronics in minimally invasive surgery," *IEEE/ASME Transactions on Mechatronics*, vol. 3, pp. 34–42, 1998.

[12] K. J. Robello, "Applications of mems in surgery," *Proceedings of the IEEE*, vol. 91, pp. 43–55, 2004.

[13] E. P. Scilingo, D. De Rossi, A. Bicchi, and P. Iacconi, "Sensors and devices to enhance the performances of a minimally invasive surgery tool for replicating surgeon's haptic perception of the manipulated tissues," in *Proceedings of IEEE International Conference on Engineering in Medicine and Biology society*, pp. 961–964, 1997.

[14] A. Bicchi, G. Canepa, D. De Rossi, P. Iacconi, and E.P.Scilingo, "A sensorized minimally invasive surgery tool for detecting tissutal elastic properties," in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 884–888, 1996.

[15] M. P. Ottensmeyer and J. K. Salisbury, "In vivo data acquisition instrument for solid organ mechanical property measurement," in *Proceedings of Medical Image Computing and Computer Assisted Intervention (MICCAI)*, pp. 975–982, 2001.

[16] J. Rosen, J. D. Brown, L. Chang, M. Barreca, M. Sinanan, and B. Hannaford, "The bluedragon - a system for measuring the kinematics and the dynamics of minimally invasive surgical tool in-vivo," in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1876–1881, 2002.

[17] J. Rosen, B. Hannaford, C. G. Richards, and M. N. Sinanan, "Markov modeling of minimally invasive surgery based on tool/tissue interaction and force/torque signatures for evaluating surgical skills," *IEEE Transactions on Biomedical Engineering*, vol. 48, pp. 579–591, 2001.

[18] S. Greenish, V. Hayward, V. Chial, A. Okamura, and T. Steffen, "Measurement, analysis and display of haptic signals during surgical cutting," *Presence: Teleoperators and Virtual Environments*, vol. 6, pp. 626–651, 2002.

[19] P. Dario, M. C. Carrozza, M. Marcacci, S. D'Attanasio, B. Magnani, O. Tonet, and G. Megali, "A novel mechatronic tool for computer-assisted arthroscopy," *IEEE Transactions on Information Technology in Biomedicine*, vol. 4, pp. 15–29, 2000.

[20] S. D'Attanasio, O. Tonet, G. Megali, M. C. Carrozza, and P. Dario, "A semi-automatic handheld mechatronic endoscope with collision-avoidance capabili-

ties," in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1586–1591, 2000.

[21] W. T. Ang, C. N. Riviere, and P. K. Khosla, "Design and implementation of active error cancelling in handheld microsurgical instrument," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1106–1111, 2001.

[22] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein, "Reality-based models for vibration feedback in virtual environments," *IEEE/ASME Transactions on Mechatronics*, vol. 6, pp. 245–252, 2001.

[23] R. D. Howe, W. J. Peine, D. A. Kantarinis, and J. S. Son, "Remote palpation technology," *IEEE Engineering in Medicine and Biology Magazine*, vol. 14, pp. 318–323, 1995.

[24] A. Liu, F. Tendick, K. Cleary, and C. Kaufmann, "A survey of surgical simulation: applications, technology, and education," *Presence: Teleoperators and Virtual Environments*, vol. 12, no. 6, pp. 599–614, 2003.

[25] M. M. Taylor and S. Lederman, "Tactile roughness of grooved surfaces: A model and the effect of friction," *Perception and Psychophysics*, vol. 17, pp. 23–36, 1975.

[26] A. M. Smith, C. E. Chapman, M. Deslandes, J.-S. Langlais, and M.-P. Thibodeau, "Role of friction and tangential force variation in the subjective scaling of tactile roughness," *Experimental Brain Research*, vol. 144, pp. 211–223, 2002.

[27] K. O. Johnson and S. S. Hsiao, "Evaluation of the relative role of slowly and rapidly adapting afferent fibers in roughness perception," *Canadian Journal of Physiology and Pharmacology*, vol. 72, pp. 488–497, 1994.

[28] M. Hollins and S. R. Risner, "Evidence for the duplex theory of tactile texture," *Perception and Psychophysics*, vol. 62, pp. 695–705, 2000.

[29] D. Katz, *The World of Touch.* Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1925/1989.

[30] S. J. Lederman and R. L. Klatzky, "Chapter 10: Perceiving texture through a probe," in *Touch in virtual environments* (M. L. McLaughlin, J. Hespanha, and G. Sukhatme, eds.), pp. 180–193, Upper Saddle River, NY: Prentice Hall PTR, 2002.

[31] R. L. Klatzky and S. Lederman, "Tactile roughness perception with a rigid link interposed between skin and surface.," *Perception and Psychophysics*, vol. 61, pp. 591–607, 1999.

[32] S. Lederman, R. Klatzky, C. Hamilton, and G. Ramsay, "Perceiving surface roughness via a rigid probe: Effects of exploration speed and mode of touch," *Haptics-E*, vol. 1, 1999.

[33] S. Lederman, R. L. Klatzky, C. Hamilton, and M. Grindley, "Perceiving surface roughness through a probe: effects of applied force and probe diameter," in *Proceedings of the American Society for Mechanical Engineers, Dynamic Systems and Control Division*, pp. 1065–1071, 2000.

[34] S. J. Lederman, R. D. Howe, R. L. Klatzky, and C. Hamilton, "Force variability during surface contact with bare finger or rigid probe," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 154–160, 2004.

[35] R. L. Klatzky, S. Lederman, M. Grindley, and R. H. Swendsen, "Feeling textures through a probe: Effects of probe and surface geometry and exploratory factors," *Perception and Psychophysics*, vol. 65, pp. 613–631, 2003.

[36] V. Hayward, O. R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre, "Haptic interfaces and devices," *Sensor Review*, vol. 24, pp. 16–29, 2004.

[37] M. Minsky, O. young Ming, O. Steele, F. P. Brooks, Jr., and M. Behensky, "Feeling and seeing: issues in force display," in *Proceedings of the Symposium on Interactive 3D graphics*, pp. 235–241, ACM Press, 1990.

[38] K. Salisbury, D. Brock, T. Massie, N. Swarup, and C. Zilles, "Haptic rendering: programming touch interaction with virtual objects," in *Proceedings of the 1995 symposium on Interactive 3D graphics*, pp. 123–130, ACM Press, 1995.

[39] D. C. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," in *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pp. 345–352, ACM Press/Addison-Wesley Publishing Co., 1997.

[40] C. Ho, C. Basdogan, and M. A. Srinivasan, "Efficient point-based rendering techniques for haptic display of virtual objects," *Presence*, vol. 8, pp. 477–491, 1999.

[41] J. Siira and D. K. Pai, "Haptic textures – a stochastic approach," in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 557–562, 1996.

[42] S. Choi and H. Z. Tan, "An analysis of perceptual instability during haptic texture rendering," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002.

[43] D. A. Kontarinis and R. D. Howe, "Tactile display of vibratory information in teleoperation and virtual environments," *Presence: Teleoperators and Virtual Environments*, vol. 4, pp. 387–402, 1995.

[44] K. Pai and P. R. Rizun, "The WHaT: A wireless haptic texture sensor," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003.

[45] T. Debus, T. Becker, P. Dupont, T.-J. Jang, and R. Howe, "Multichannel vibrotactile display for sensory substitution during teleoperation," in *SPIE International Symposium on Intelligent Systems and Advanced Manufacturing*, 2001.

[46] J. D. Hwang, M. D. Williams, and G. Niemeyer, "Toward event-based haptics: Rendering contact using open-loop force pulses," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2004.

[47] S. Lederman, "Auditory texture perception," *Perception*, vol. 8, pp. 93–103, 1979.

[48] S. J. Lederman, R. L. Klatzky, C. Hamilton, and T. Morgan, "Integrating multimodal information about surface texture via a probe: Relative contributions of haptic and touch produced sound sources," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 97–104, 2002.

[49] W. Semere, M. Kitagawa, and A. M. Okamura, "Teleoperation with sensor/actuator asymmetry: task performance with partial force feedback," in *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 121–127, 2004.

Appendix A

Probe Evolution

The design of MictoTactus went through different design iterations before it reached the present state. The first proof-of-concept version has the actuator separated from the sensor. An accelerometer was mounted on the top of a metal rod as sensor. The sensed signal is connected to an audio amplifier, which is connect to an actuator. The design of the actuator was originated by Prof. Vincent Hayward. A very strong, rare-earth magnet of cubic form was suspended on two elastic leaves between two sets of coils. The magnet and the coils were mounted on a L-shape aluminum bracket. This actuator is extremely precise and has a bandwidth larger than what can be perceived as tactile and audio signals.

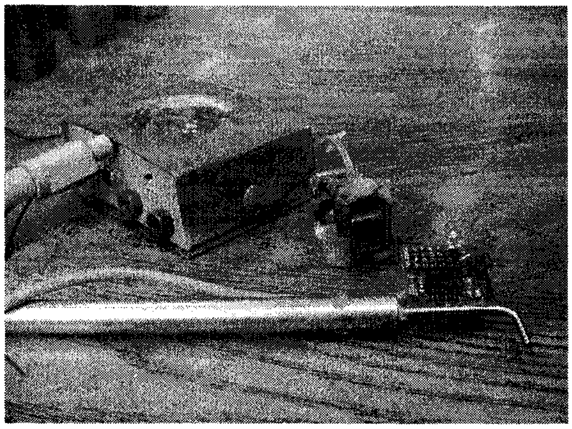
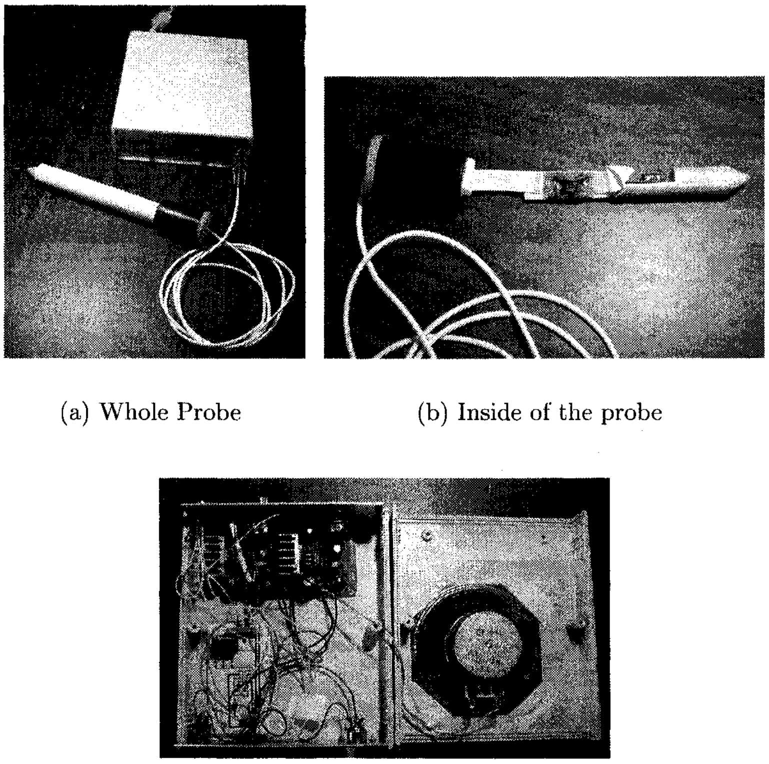


Fig. A.1 MicroTactus Version 1

A second attempt was to mount the actuator on the handle. Because the actuator was too big to fit inside the handle, it has to be attached at the far end of the probe. This makes the weight distribution not balanced with respect to the center, hence not ideal for manipulation. Also, the accelerometer had to be mounted inside the handle. The one used originally ADXL250 had a dimension of 10mm x 10mm x 2mm, which forced the handle to have an inner diameter of at least 13mm. A plastic handle of this size was heavier than the moving magnet, resulting in very week acceleration. There were many improvements that could be made to this version.



(a) Whole Probe (b) Inside of the probe

(c) Inside of the interface unit

Fig. A.2 MicroTactus Version 2

The changes in MicroTactus version 3, the most recent one, are mainly in the actuator design. Instead of having the magnet mounted on a separated bracket, the actuator is suspended inside the handle between two pieces of rubber membrane glued to the handle. The coils are wrapped directly on the handle. With this new design, the force applies directly on the handle, so no energy is lost in additional intermediate parts. In addition, the handle is now made of carbon fiber, which reduces the weight and makes the resulting acceleration stronger. The model of the accelerometer is also changed: the ADXL311 model has a dimension of 5mm x 5mm x 2mm, which can be fit into the 12mm-handle without any problem.

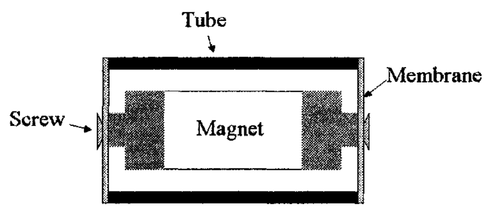


Fig. A.3 Actuator in MicroTactus Version 3

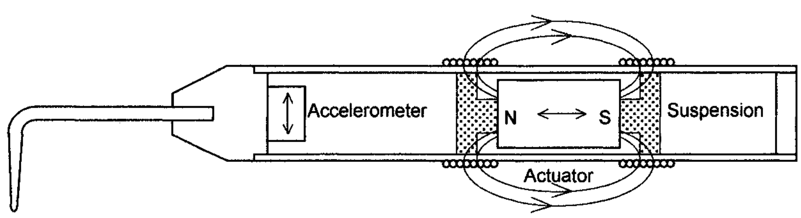


Fig. A.4 Probe Sketch of MicroTactus Version 3

Table A.1 Design Iterations

Part	Design Option	Why not Successful
Actuator	angular actuator (version 1)	cannot be mounted efficiently
Actuator	cylindrical actuator with synthetic sponge-like foam as vibrating membrane	The actuator moved out of its position with load signal.
Actuator	cylindrical actuator with carved brass sheet cut as vibrating membrane	The brass sheets were very fragile. They broke when receiving loud, low frequency signals.
Actuator	cylindrical actuator placed near the tool tip	It interfered with the accelerometer.
Actuator	cylindrical actuator with rubber as vibrating membrane placed midway on the handle	current design
Sensor	ADXL 250	too big to be mounted perpendicular to the handle
Sensor	ADXL 311	current design
Handle	Delerin Plastic	Too heavy
Handle	carbon fiber	current design
Amplifier	Class-D Audio Amplifier	Class-D power switching circuit introduced too much noise

Appendix B

Ethical Approval Form

MCGILL UNIVERSITY FACULTY OF EDUCATION

STATEMENT OF ETHICS OF PROPOSED RESEARCH

It is assumed that the responses to the questions below reflect the author's (or authors') familiarity with the ethical guidelines for funded and non funded research with human subjects that have been adopted by the Faculty of Education and that responses conform to and respect the Tri-council Policy Statement: Ethical Conduct for Research Involving Humans (1998).

Note: It is important to answer every question.

1. Informed Consent of Subjects

Explain how you propose to seek informed consent from each of your subjects (or should they be minors, from their parents or guardian). Informed consent includes comprehension of the nature, procedures, purposes, risks, and benefits of the research in which subjects are participating. Please append to this statement a copy of the consent form that you intend to use.

Subjects will be asked to sign the attached consent form and will be debriefed as to the purpose of the study.

2. Subject Population and Subject Recruitment

2.1 Describe the subject population and how and from where they will be recruited and encouraged to participate. If applicable, attach a copy of any advertisement, letter, flier, brochure or oral script used to solicit potential subjects (including information sent to third parties). Describe the setting in which the research will take place. Describe any compensation or inducement subjects may receive for participating.

Subjects will be recruited by means of fliers and word of mouth.

2.2 Indicate if the subjects are a captive population (e.g. prisoners, residents in a centre, students in a class) or are in any kind of conflict of interest relationship with the researcher such as being students, clients, patients or family members.

N/A.

2.3 Explain how you will ensure pressure to participate or perceived pressure will not penalize students for choosing not to participate. (Please take note that it is important to inform subjects, especially In Teacher Action Research or Participatory Action Research, that no grading or evaluation is involved).

Subjects will be asked for free and informed consent.

2.4 What is the nature of any inducement you intend to present to prospective subjects to persuade them to participate in your study?

Participants will be given a small monetray compensation.

2.5 How will you help prospective participants understand that they may freely withdraw from the study at their own discretion and for any reason?

This is indicated in the consent form.

2.6 Comment on any other potential ethical concerns that may arise during the course of the research.

None.

3. Subject Risk and Well-being

What assurance can you provide this committee (as well as the subjects) that the risks, physical and/or

HAPTIC PERCEPTION IN HUMANS AND ITS APPLICATION TO THE DESIGN OF HUMAN-MACHINE INTERFACES
Supported by IRIS Project
Intelligent tools for medical diagnosis and interventions
Project acronym: IT-MED

Vincent Hayward and Hsin-Yun Yao
Center for Intelligent Machines
McGill University

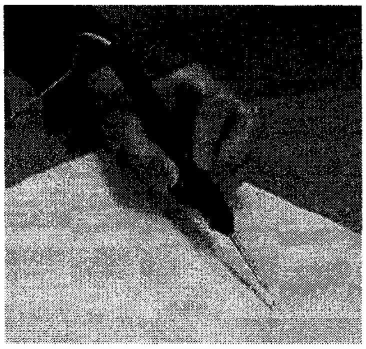
GOAL OF THE RESEARCH PROGRAM

The purpose of this research program is to evaluate human performance enhancement while using a hand-held, touch-enhancing instrument. The overall development project is supported by a grant from the Network of Centers of Excellence (IRIS) and NSERC.

BRIEF DESCRIPTION OF THE RESEARCH PROJECT

Human subjects will use a pen-like probe designed to amplify touch sensations while exploring a surface. It works on the principle of picking-up the tiny acceleration of a tool tip when it drags on a surface and by amplifying the signal to produce more noticeable vibrations. Subjects will also be able to hear sounds arising from this acceleration signal. Both touch and audition will be use to help subject make judgments about different surfaces such as surfaces with very small amounts of roughness or with small features including micro-cracks or sub-micrometric steps. Among other uses, such hand-held probes could eventually be of interest to surgeons to detect small defects in tissues that would otherwise be unnoticeable.

The haptic probe used in this project delivers vibrations to the hand of the human operator as well as sounds through a speaker (or headphones), while he or she uses it to explore a surface. The acceleration is sensed by a accelerometer housed inside the handle and is amplified by a small power amplifier to produce vibrations and sounds. Two coils interferes magnetically with a magnet hidden inside the handle produce the vibrations. The sounds are played through ordinary speakers or headphones.



METHODOLOGY

Subjects. McGill University students and staff. Subjects will be paid for their participation. Subjects will be recruited by using flyers posted around campus.

Experimental procedure. Subjects will use the probe to explore surfaces with or without vibration and sound feedback. Subjects will be asked whether or not a step or a crack in the surface can be detected. They will also be asked to make judgments about roughness. A typical experiment session will last approximately 60-90 minutes, including rest breaks. It may be necessary to have participants return for more than one session.

Consent forms. At the beginning of the experiment, each subject will be presented with the attached consent form to sign. Subjects will also be allowed to withdraw from the experiments at any time. Subject's identity will remain confidential in any reports (written or oral) on the experimental results.

Potential hazards. As our participants would use a probe of about the weight of an ordinary pen, for about 60-90 minutes per session (with adequate rest breaks within the session), fatigue is not a concern. The level of the vibration is similar to that produced by an ordinary cellular phone put in vibration mode. The sound from the headphone is of reasonable volume. The probe interface does not present risks of electric shock either (12V DC powered).

For these reasons, we consider that the potential hazards of this research are negligible.

CONSENT FORM.

You are being invited to participate in a research project run by Dr. Vincent Hayward, Professor of Computer and Electrical Engineering at McGill University. The study evaluates the benefits of an probe-like instrument used to explore a surface. This probe is a pen-like device with a metal tip. You will hold it like you hold a pen. You will be asked to explore surfaces using the tip and answer questions about them. You will also wear a headphone during the experiment and hear sounds through it. By studying your performance as well as that of other participants, we try to determine how this probe affects your tactile sensations.

The safety concerns of this study are minimal. The device will not vibrate more than a cellular phone rings in vibration mode. The sound you will hear from the headphone will be of reasonable volume and adjustable. The researchers that designed this study have used this probe extensively and have had no problems whatsoever. They have put every effort to prepare safe and comfortable experimental conditions for you.

The experiment will last for about _______________. You will have adequate breaks to rest. You will be paid ______ for your participation. For experimental analysis purposes, we will ask you for your age, sex, preferred hand and profession. This information and your identity will remain completely confidential in any report(s) of results of this study. Please note that you are free to withdraw from this study at any time, and that you are entitled to have the researcher explain to you the purpose of the study after you have completed it.

Finally, should you have any concerns or complaints about this study, you may contact Professor Hayward at x5006.

I have read and understood this consent form. I have agreed to participate voluntarily in this study.

Participant's name and signature: ________________________________

Today's date: ________________

Witness: ____________________

DEBRIEFING FORM

Recently, a number of haptic interface systems, such as the one you used in this experiment, have been developed. Some of these interfaces deliver force feedback to the hand of a human operator by means of vibrations. Such systems are potentially valuable for performing a variety of teleoperation tasks (e.g., telerobotics, telemedicine) and for exploring and acting on a real and virtual environments (e.g., virtual training systems for teaching complex surgical procedures). They have also recently be introduced in force feedback mice, game pads for computer games and in certain high end cars. In all these tasks, the operator can feel and hear the environment they are interacting with.

In this experiment you were trying to detect a tiny crack in the surface of a soft pad using a haptic tool. This tool was designed to make human hands more capable to detect small variations on a surface and hence gave you more detection capability than an ordinary probe. The tool provided feedback to you is in form of both vibrations and sound. If you are interested in reading more about this area, you might consult the references at the end of this document.

As a special favor, if you enjoyed your participation in this study and plan to suggest your friends to sign-up to participate in the experiment, please don't share the details of this experiment with them. This is because if your friends participate while knowing what this is about, they may be able to perform better. This would mess-up our whole study. Of course, you and your friends can share experiences after all of you have completed the experiment.

Thank you very much for helping us with our research.

REFERENCES.

1. M. MacFarlane, J. Rosen, B. Hannaford, C. Pellegrini, M. Sinanan, 'Force Feedback Grasper Helps Restore the Sense of Touch in Minimally Invasive Surgery.,' Journal of Gastrointestinal Surgery, vol. 3, pp. 278-285, 1999.
2. Vanessa B. Chial, Stephanie Greenish, Allison M. Okamura: On the Display of Haptic Recordings for Cutting Biological Tissues. Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems 2002: 80-87

Appendix C

Experiment Data of User Studies

```
Subject Session Pad Ans Result Count Percentage Correctness
V Haptic 0 No Right 4 66.7%
V Haptic 0 No Right
V Haptic 0 No Right
V Haptic 0 No Right
V Haptic 0 Yes Wrong
V Haptic 0 Yes Wrong
V Haptic 1 No Wrong 5 83.3%
V Haptic 1 No Right
V Haptic 1 No Right
V Haptic 1 Yes Right
V Haptic 1 Yes Right
V Haptic 1 Yes Right
V Haptic 2 No Right 6 100.0%
V Haptic 2 No Right
V Haptic 2 No Right
V Haptic 2 Yes Right
V Haptic 2 Yes Right
V Haptic 2 Yes Right
V Haptic 3 Yes Right 6 100.0%
V Haptic 3 Yes Right
V Haptic 3 Yes Right
V Haptic 3 Yes Right
V Haptic 3 Yes Right
V Haptic 3 Yes Right
V Off 0 No Right 5 83.3%
V Off 0 No Right
V Off 0 No Right
V Off 0 No Right
V Off 0 Yes Wrong
V Off 0 No Right
V Off 1 No Wrong 0 0.0%
V Off 1 No Wrong
V Off 1 No Wrong
V Off 1 No Wrong
V Off 1 No Wrong
V Off 1 No Wrong
V Off 2 No Wrong 0 0.0%
V Off 2 No Wrong
V Off 2 No Wrong
V Off 2 No Wrong
V Off 2 No Wrong
V Off 2 No Wrong
V Off 3 Yes Right 6 100.0%
V Off 3 Yes Right
V Off 3 Yes Right
V Off 3 Yes Right
V Off 3 Yes Right
V Off 3 Yes Right
V Passive 0 Yes Wrong 1 16.7%
V Passive 0 Yes Wrong
V Passive 0 Yes Wrong
V Passive 0 Yes Wrong
V Passive 0 Yes Wrong
V Passive 0 No Right
V Passive 2 Yes Right 4 66.7%
V Passive 2 Yes Right
V Passive 2 No Wrong
V Passive 2 Yes Right
V Passive 2 Yes Right
V Passive 2 No Wrong
V Passive 1 Yes Right 6 100.0%
V Passive 1 Yes Right
V Passive 1 Yes Right
V Passive 1 Yes Right
V Passive 1 Yes Right
V Passive 1 Yes Right
V Passive 3 Yes Right 6 100.0%
V Passive 3 Yes Right
V Passive 3 Yes Right
V Passive 3 Yes Right
V Passive 3 Yes Right
V Passive 3 Yes Right
V Sound 0 No Right 3 50.0%
V Sound 0 No Right
V Sound 0 Yes Wrong
V Sound 0 Yes Wrong
V Sound 0 Yes Wrong
V Sound 0 No Right
V Sound 2 Yes Right 6 100.0%
V Sound 2 Yes Right
V Sound 2 Yes Right
V Sound 2 Yes Right
V Sound 2 Yes Right
V Sound 2 Yes Right
V Sound 1 Yes Right 6 100.0%
V Sound 1 Yes Right
V Sound 1 Yes Right
V Sound 1 Yes Right
V Sound 1 Yes Right
V Sound 1 Yes Right
V Sound 3 Yes Right 6 100.0%
V Sound 3 Yes Right
V Sound 3 Yes Right
V Sound 3 Yes Right
V Sound 3 Yes Right
V Sound 3 Yes Right
G Haptic 0 No Right 6 100.0%
G Haptic 0 No Right
G Haptic 0 No Right
G Haptic 0 No Right
G Haptic 0 No Right
G Haptic 0 No Right
G Haptic 2 No Wrong 3 50.0%
G Haptic 2 Yes Right
G Haptic 2 No Wrong
G Haptic 2 No Wrong
G Haptic 2 Yes Right
G Haptic 2 Yes Right
G Haptic 1 No Wrong 3 50.0%
G Haptic 1 Yes Right
G Haptic 1 No Wrong
G Haptic 1 Yes Right
G Haptic 1 Yes Right
G Haptic 1 No Wrong
G Haptic 3 Yes Right 6 100.0%
G Haptic 3 Yes Right
G Haptic 3 Yes Right
G Haptic 3 Yes Right
G Haptic 3 Yes Right
G Haptic 3 Yes Right
G Off 0 No Right 4 66.7%
G Off 0 Yes Wrong
G Off 0 No Right
G Off 0 No Right
G Off 0 Yes Wrong
G Off 0 No Right
G Off 2 No Wrong 2 33.3%
G Off 2 No Wrong
G Off 2 Yes Right
G Off 2 No Wrong
G Off 2 No Wrong
G Off 2 Yes Right
G Off 1 No Wrong 2 33.3%
```

```
G Off 1 No Wrong
G Off 1 No Wrong
G Off 1 Yes Right
G Off 1 No Wrong
G Off 1 Yes Right
G Off 3 Yes Right 6 100.0%
G Off 3 Yes Right
G Off 3 Yes Right
G Off 3 Yes Right
G Off 3 Yes Right
G Off 3 Yes Right
G Passive 0 No Right 4 66.7%
G Passive 0 No Right
G Passive 0 No Right
G Passive 0 Yes Wrong
G Passive 0 No Right
G Passive 0 Yes Wrong
G Passive 2 Yes Right 4 66.7%
G Passive 2 Yes Right
G Passive 2 No Wrong
G Passive 2 Yes Right
G Passive 2 Yes Right
G Passive 2 No Wrong
G Passive 1 No Wrong 3 50.0%
G Passive 1 Yes Right
G Passive 1 Yes Right
G Passive 1 Yes Right
G Passive 1 No Wrong
G Passive 1 No Wrong
G Passive 3 Yes Right 6 100.0%
G Passive 3 Yes Right
G Passive 3 Yes Right
G Passive 3 Yes Right
G Passive 3 Yes Right
G Passive 3 Yes Right
G Sound 0 No Right 6 100.0%
G Sound 0 No Right
G Sound 0 No Right
G Sound 0 No Right
G Sound 0 No Right
G Sound 0 No Right
G Sound 2 Yes Right 3 50.0%
G Sound 2 Yes Right
G Sound 2 No Wrong
G Sound 2 Yes Right
G Sound 2 No Wrong
G Sound 2 No Wrong
G Sound 1 Yes Right 5 83.3%
G Sound 1 No Wrong
G Sound 1 Yes Right
G Sound 1 Yes Right
G Sound 1 Yes Right
G Sound 1 Yes Right
G Sound 3 Yes Right 6 100.0%
G Sound 3 Yes Right
G Sound 3 Yes Right
G Sound 3 Yes Right
G Sound 3 Yes Right
G Sound 3 Yes Right
H Haptic 0 No Right 5 83.3%
H Haptic 0 No Right
H Haptic 0 No Right
H Haptic 0 Yes Wrong
H Haptic 0 No Right
H Haptic 0 No Right
H Haptic 2 Yes Right 1 16.7%
H Haptic 2 No Wrong
H Haptic 2 No Wrong
H Haptic 2 No Wrong
H Haptic 2 No Wrong
H Haptic 2 No Wrong
H Haptic 1 No Wrong 1 16.7%
H Haptic 1 No Wrong
H Haptic 1 Yes Right
H Haptic 1 No Wrong
H Haptic 1 No Wrong
H Haptic 1 No Wrong
H Haptic 3 Yes Right 6 100.0%
H Haptic 3 Yes Right
H Haptic 3 Yes Right
H Haptic 3 Yes Right
H Haptic 3 Yes Right
H Haptic 3 Yes Right
H Off 0 No Right 6 100.0%
H Off 0 No Right
H Off 0 No Right
H Off 0 No Right
H Off 0 No Right
H Off 0 No Right
H Off 2 No Wrong 1 16.7%
H Off 2 No Wrong
H Off 2 Yes Right
H Off 2 No Wrong
H Off 2 No Wrong
H Off 2 No Wrong
H Off 1 No Wrong 0 0.0%
H Off 1 No Wrong
H Off 1 No Wrong
H Off 1 No Wrong
H Off 1 No Wrong
H Off 1 No Wrong
H Off 3 Yes Right 6 100.0%
H Off 3 Yes Right
H Off 3 Yes Right
H Off 3 Yes Right
H Off 3 Yes Right
H Off 3 Yes Right
H Passive 0 Yes Wrong 2 33.3%
H Passive 0 No Right
H Passive 0 Yes Wrong
H Passive 0 No Right
H Passive 0 Yes Wrong
H Passive 0 Yes Wrong
H Passive 2 No Wrong 3 50.0%
H Passive 2 No Wrong
H Passive 2 Yes Right
H Passive 2 No Wrong
H Passive 2 Yes Right
H Passive 2 Yes Right
H Passive 1 Yes Right 4 66.7%
H Passive 1 Yes Right
H Passive 1 Yes Right
H Passive 1 No Wrong
H Passive 1 Yes Right
H Passive 1 No Wrong
H Passive 3 Yes Right 6 100.0%
H Passive 3 Yes Right
H Passive 3 Yes Right
H Passive 3 Yes Right
H Passive 3 Yes Right
H Passive 3 Yes Right
H Sound 0 No Right 5 83.3%
H Sound 0 No Right
H Sound 0 No Right
```

```
H Sound 0 No Right
H Sound 0 Yes Wrong
H Sound 0 No Right
H Sound 2 Yes Right 6 100.0%
H Sound 2 Yes Right
H Sound 2 Yes Right
H Sound 2 Yes Right
H Sound 2 Yes Right
H Sound 2 Yes Right
H Sound 1 No Wrong 3 50.0%
H Sound 1 No Wrong
H Sound 1 No Wrong
H Sound 1 Yes Right
H Sound 1 Yes Right
H Sound 1 Yes Right
H Sound 3 Yes Right 6 100.0%
H Sound 3 Yes Right
H Sound 3 Yes Right
H Sound 3 Yes Right
H Sound 3 Yes Right
H Sound 3 Yes Right
J Haptic 0 No Right 6 100.0%
J Haptic 0 No Right
J Haptic 0 No Right
J Haptic 0 No Right
J Haptic 0 No Right
J Haptic 0 No Right
J Haptic 2 No Wrong 4 66.7%
J Haptic 2 No Wrong
J Haptic 2 Yes Right
J Haptic 2 Yes Right
J Haptic 2 Yes Right
J Haptic 2 Yes Right
J Haptic 1 Yes Right 6 100.0%
J Haptic 1 Yes Right
J Haptic 1 Yes Right
J Haptic 1 Yes Right
J Haptic 1 Yes Right
J Haptic 1 Yes Right
J Haptic 3 Yes Right 6 100.0%
J Haptic 3 Yes Right
J Haptic 3 Yes Right
J Haptic 3 Yes Right
J Haptic 3 Yes Right
J Haptic 3 Yes Right
J Off 0 No Right 6 100.0%
J Off 0 No Right
J Off 0 No Right
J Off 0 No Right
J Off 0 No Right
J Off 0 No Right
J Off 2 Yes Right 6 100.0%
J Off 2 Yes Right
J Off 2 Yes Right
J Off 2 Yes Right
J Off 2 Yes Right
J Off 2 Yes Right
J Off 1 No Wrong 1 16.7%
J Off 1 No Wrong
J Off 1 No Wrong
J Off 1 No Wrong
J Off 1 Yes Right
J Off 1 No Wrong
J Off 3 Yes Right 6 100.0%
J Off 3 Yes Right
J Off 3 Yes Right
J Off 3 Yes Right
J Off 3 Yes Right
J Off 3 Yes Right
J Passive 0 No Right 4 66.7%
J Passive 0 No Right
J Passive 0 No Right
J Passive 0 Yes Wrong
J Passive 0 Yes Wrong
J Passive 0 No Right
J Passive 2 Yes Right 4 66.7%
J Passive 2 No Wrong
J Passive 2 Yes Right
J Passive 2 Yes Right
J Passive 2 No Wrong
J Passive 2 Yes Right
J Passive 1 No Wrong 3 50.0%
J Passive 1 Yes Right
J Passive 1 No W
J Passive 1 No Wrong
J Passive 1 Yes Right
J Passive 1 Yes Right
J Passive 3 Yes Right 6 100.0%
J Passive 3 Yes Right
J Passive 3 Yes Right
J Passive 3 Yes Right
J Passive 3 Yes Right
J Passive 3 Yes Right
J Sound 0 No Right 5 83.3%
J Sound 0 No Right
J Sound 0 Yes Wrong
J Sound 0 No Right
J Sound 0 No Right
J Sound 0 No Right
J Sound 2 Yes Right 6 100.0%
J Sound 2 Yes Right
J Sound 2 Yes Right
J Sound 2 Yes Right
J Sound 2 Yes Right
J Sound 2 Yes Right
J Sound 1 Yes Right 4 66.7%
J Sound 1 Yes Right
J Sound 1 Yes Right
J Sound 1 No Wrong
J Sound 1 Yes Right
J Sound 1 No Wrong
J Sound 3 Yes Right 6 100.0%
J Sound 3 Yes Right
J Sound 3 Yes Right
J Sound 3 Yes Right
J Sound 3 Yes Right
J Sound 3 Yes Right
M Haptic 0 Yes Wrong 5 83.3%
M Haptic 0 No Right
M Haptic 0 No Right
M Haptic 0 No Right
M Haptic 0 No Right
M Haptic 0 No Right
M Haptic 2 Yes Right 6 100.0%
M Haptic 2 Yes Right
M Haptic 2 Yes Right
M Haptic 2 Yes Right
M Haptic 2 Yes Right
M Haptic 2 Yes Right
M Haptic 1 Yes Right 4 66.7%
M Haptic 1 Yes Right
M Haptic 1 Yes Right
M Haptic 1 Yes Right
M Haptic 1 No Wrong
```

```
M Haptic 1 No Wrong
M Haptic 3 Yes Right 6 100.0%
M Haptic 3 Yes Right
M Haptic 3 Yes Right
M Haptic 3 Yes Right
M Haptic 3 Yes Right
M Haptic 3 Yes Right
M Off 0 No Right 6 100.0%
M Off 0 No Right
M Off 0 No Right
M Off 0 No Right
M Off 0 No Right
M Off 0 No Right
M Off 2 Yes Right 4 66.7%
M Off 2 Yes Right
M Off 2 No Wrong
M Off 2 Yes Right
M Off 2 Yes Right
M Off 2 No Wrong
M Off 1 Yes Right 4 66.7%
M Off 1 No Wrong
M Off 1 No Wrong
M Off 1 Yes Right
M Off 1 Yes Right
M Off 1 Yes Right
M Off 3 Yes Right 6 100.0%
M Off 3 Yes Right
M Off 3 Yes Right
M Off 3 Yes Right
M Off 3 Yes Right
M Off 3 Yes Right
M Passive 0 Yes Wrong 2 33.3%
M Passive 0 Yes Wrong
M Passive 0 Yes Wrong
M Passive 0 Yes Wrong
M Passive 0 No Right
M Passive 0 No Right
M Passive 2 Yes Right 6 100.0%
M Passive 2 Yes Right
M Passive 2 Yes Right
M Passive 2 Yes Right
M Passive 2 Yes Right
M Passive 2 Yes Right
M Passive 1 Yes Right 2 33.3%
M Passive 1 Yes Right
M Passive 1 No Wrong
M Passive 1 No Wrong
M Passive 1 No Wrong
M Passive 1 No Wrong
M Passive 3 Yes Right 6 100.0%
M Passive 3 Yes Right
M Passive 3 Yes Right
M Passive 3 Yes Right
M Passive 3 Yes Right
M Passive 3 Yes Right
M Sound 0 No Right 6 100.0%
M Sound 0 No Right
M Sound 0 No Right
M Sound 0 No Right
M Sound 0 No Right
M Sound 0 No Right
M Sound 2 Yes Right 6 100.0%
M Sound 2 Yes Right
M Sound 2 Yes Right
M Sound 2 Yes Right
M Sound 2 Yes Right
M Sound 2 Yes Right
M Sound 1 Yes Right 6 100.0%
M Sound 1 Yes Right
M Sound 1 Yes Right
M Sound 1 Yes Right
M Sound 1 Yes Right
M Sound 1 Yes Right
M Sound 3 Yes Right 6 100.0%
M Sound 3 Yes Right
M Sound 3 Yes Right
M Sound 3 Yes Right
M Sound 3 Yes Right
M Sound 3 Yes Right
S Haptic 0 No Right 6 100.0%
S Haptic 0 No Right
S Haptic 0 No Right
S Haptic 0 No Right
S Haptic 0 No Right
S Haptic 0 No Right
S Haptic 2 No Wrong 1 16.7%
S Haptic 2 No Wrong
S Haptic 2 No Wrong
S Haptic 2 Yes Right
S Haptic 2 No Wrong
S Haptic 2 No Wrong
S Haptic 1 No Wrong 1 16.7%
S Haptic 1 No Wrong
S Haptic 1 No Wrong
S Haptic 1 Yes Right
S Haptic 1 No Wrong
S Haptic 1 No Wrong
S Haptic 3 Yes Right 6 100.0%
S Haptic 3 Yes Right
S Haptic 3 Yes Right
S Haptic 3 Yes Right
S Haptic 3 Yes Right
S Haptic 3 Yes Right
S Off 0 No Right 6 100.0%
S Off 0 No Right
S Off 0 No Right
S Off 0 No Right
S Off 0 No Right
S Off 0 No Right
S Off 2 No Wrong 0 0.0%
S Off 2 No Wrong
S Off 2 No Wrong
S Off 2 No Wrong
S Off 2 No Wrong
S Off 2 No Wrong
S Off 1 No Wrong 0 0.0%
S Off 1 No Wrong
S Off 1 No Wrong
S Off 1 No Wrong
S Off 1 No Wrong
S Off 1 No Wrong
S Off 3 Yes Right 6 100.0%
S Off 3 Yes Right
S Off 3 Yes Right
S Off 3 Yes Right
S Off 3 Yes Right
S Off 3 Yes Right
S Passive 0 No Right 6 100.0%
S Passive 0 No Right
S Passive 0 No Right
S Passive 0 No Right
S Passive 0 No Right
S Passive 0 No Right
S Passive 2 Yes Right 4 66.7%
```

S Passive 2 No Wrong
S Passive 2 Yes Right
S Passive 2 Yes Right
S Passive 2 No Wrong
S Passive 2 Yes Right
S Passive 1 No Wrong 3 50.0%
S Passive 1 Yes Right
S Passive 1 Yes Right
S Passive 1 Yes Right
S Passive 1 No Wrong
S Passive 1 No Wrong
S Passive 3 Yes Right 6 100.0%
S Passive 3 Yes Right
S Passive 3 Yes Right
S Passive 3 Yes Right
S Passive 3 Yes Right
S Passive 3 Yes Right
S Sound 0 No Right 6 100.0%
S Sound 0 No Right
S Sound 0 No Right
S Sound 0 No Right
S Sound 0 No Right
S Sound 0 No Right
S Sound 2 No Wrong 0 0.0%
S Sound 2 No Wrong
S Sound 2 No Wrong
S Sound 2 No Wrong
S Sound 2 No Wrong
S Sound 2 No Wrong
S Sound 1 No Wrong 0 0.0%
S Sound 1 No Wrong
S Sound 1 No Wrong
S Sound 1 No Wrong
S Sound 1 No Wrong
S Sound 1 No Wrong
S Sound 3 Yes Right 6 100.0%
S Sound 3 Yes Right
S Sound 3 Yes Right
S Sound 3 Yes Right
S Sound 3 Yes Right
S Sound 3 Yes Right
Y Haptic 0 No Right 5 83.3%
Y Haptic 0 No Right
Y Haptic 0 Yes Wrong
Y Haptic 0 No Right
Y Haptic 0 No Right
Y Haptic 0 No Right
Y Haptic 2 Yes Right 4 66.7%
Y Haptic 2 Yes Right
Y Haptic 2 Yes Right
Y Haptic 2 No Wrong
Y Haptic 2 Yes Right
Y Haptic 2 No Wrong
Y Haptic 1 Yes Right 1 16.7%
Y Haptic 1 No Wrong
Y Haptic 1 No Wrong
Y Haptic 1 No Wrong
Y Haptic 1 No Wrong
Y Haptic 1 No Wrong
Y Haptic 3 Yes Right 6 100.0%
Y Haptic 3 Yes Right
Y Haptic 3 Yes Right
Y Haptic 3 Yes Right
Y Haptic 3 Yes Right
Y Haptic 3 Yes Right
Y Off 0 No Right 5 83.3%
Y Off 0 No Right
Y Off 0 No Right
Y Off 0 No Right
Y Off 0 Yes Wrong
Y Off 0 No Right
Y Off 2 No Wrong 0 0.0%
Y Off 2 No Wrong
Y Off 2 No Wrong
Y Off 2 No Wrong
Y Off 2 No Wrong
Y Off 2 No Wrong
Y Off 1 No Wrong 0 0.0%
Y Off 1 No Wrong
Y Off 1 No Wrong
Y Off 1 No Wrong
Y Off 1 No Wrong
Y Off 1 No Wrong
Y Off 3 Yes Right 6 100.0%
Y Off 3 Yes Right
Y Off 3 Yes Right
Y Off 3 Yes Right
Y Off 3 Yes Right
Y Off 3 Yes Right
Y Passive 0 No Right 4 66.7%
Y Passive 0 Yes Wrong
Y Passive 0 No Right
Y Passive 0 Yes Wrong
Y Passive 0 No Right
Y Passive 0 No Right
Y Passive 2 No Wrong 1 16.7%
Y Passive 2 No Wrong
Y Passive 2 Yes Right
Y Passive 2 No Wrong
Y Passive 2 No Wrong
Y Passive 2 No Wrong
Y Passive 1 Yes Right 6 100.0%
Y Passive 1 Yes Right
Y Passive 1 Yes Right
Y Passive 1 Yes Right
Y Passive 1 Yes Right
Y Passive 1 Yes Right
Y Passive 3 Yes Right 5 83.3%
Y Passive 3 Yes Right
Y Passive 3 Yes Right
Y Passive 3 Yes Right
Y Passive 3 Yes Right
Y Passive 3 No Wrong
Y Sound 0 No Right 6 100.0%
Y Sound 0 No Right
Y Sound 0 No Right
Y Sound 0 No Right
Y Sound 0 No Right
Y Sound 0 No Right
Y Sound 2 No Wrong 5 83.3%
Y Sound 2 Yes Right
Y Sound 2 Yes Right
Y Sound 2 Yes Right
Y Sound 2 Yes Right
Y Sound 2 Yes Right
Y Sound 1 No Wrong 3 50.0%
Y Sound 1 No Wrong
Y Sound 1 Yes Right
Y Sound 1 Yes Right
Y Sound 1 No Wrong
Y Sound 1 Yes Right
Y Sound 3 Yes Right 6 100.0%
Y Sound 3 Yes Right
Y Sound 3 Yes Right

```
Y Sound 3 Yes Right
Y Sound 3 Yes Right
Y Sound 3 Yes Right
E Haptic 0 No Right 6 100.0%
E Haptic 0 No Right
E Haptic 0 No Right
E Haptic 0 No Right
E Haptic 0 No Right
E Haptic 0 No Right
E Haptic 2 Yes Right 6 100.0%
E Haptic 2 Yes Right
E Haptic 2 Yes Right
E Haptic 2 Yes Right
E Haptic 2 Yes Right
E Haptic 2 Yes Right
E Haptic 1 No Wrong 0 0.0%
E Haptic 1 No Wrong
E Haptic 1 No Wrong
E Haptic 1 No Wrong
E Haptic 1 No Wrong
E Haptic 1 No Wrong
E Haptic 3 Yes Right 6 100.0%
E Haptic 3 Yes Right
E Haptic 3 Yes Right
E Haptic 3 Yes Right
E Haptic 3 Yes Right
E Haptic 3 Yes Right
E Off 0 No Right 6 100.0%
E Off 0 No Right
E Off 0 No Right
E Off 0 No Right
E Off 0 No Right
E Off 0 No Right
E Off 2 Yes Right 3 50.0%
E Off 2 Yes Right
E Off 2 Yes Right
E Off 2 No Wrong
E Off 2 No Wrong
E Off 2 No Wrong
E Off 1 No Wrong 0 0.0%
E Off 1 No Wrong
E Off 1 No Wrong
E Off 1 No Wrong
E Off 1 No Wrong
E Off 1 No Wrong
E Off 3 Yes Right 6 100.0%
E Off 3 Yes Right
E Off 3 Yes Right
E Off 3 Yes Right
E Off 3 Yes Right
E Off 3 Yes Right
E Passive 0 Yes Wrong 1 16.7%
E Passive 0 Yes Wrong
E Passive 0 Yes Wrong
E Passive 0 Yes Wrong
E Passive 0 No Right
E Passive 0 Yes Wrong
E Passive 2 Yes Right 5 83.3%
E Passive 2 No Wrong
E Passive 2 Yes Right
E Passive 2 Yes Right
E Passive 2 Yes Right
E Passive 2 Yes Right
E Passive 1 No Wrong 2 33.3%
E Passive 1 Yes Right
E Passive 1 Yes Right
E Passive 1 No Wrong
E Passive 1 No Wrong
E Passive 1 No Wrong
E Passive 3 Yes Right 6 100.0%
E Passive 3 Yes Right
E Passive 3 Yes Right
E Passive 3 Yes Right
E Passive 3 Yes Right
E Passive 3 Yes Right
E Sound 0 No Right 6 100.0%
E Sound 0 No Right
E Sound 0 No Right
E Sound 0 No Right
E Sound 0 No Right
E Sound 0 No Right
E Sound 2 Yes Right 5 83.3%
E Sound 2 No Wrong
E Sound 2 Yes Right
E Sound 2 Yes Right
E Sound 2 Yes Right
E Sound 2 Yes Right
E Sound 1 No Wrong 3 50.0%
E Sound 1 Yes Right
E Sound 1 Yes Right
E Sound 1 Yes Right
E Sound 1 No Wrong
E Sound 1 No Wrong
E Sound 3 Yes Right 6 100.0%
E Sound 3 Yes Right
E Sound 3 Yes Right
E Sound 3 Yes Right
E Sound 3 Yes Right
E Sound 3 Yes Right
```