A Tactile Magnification Instrument for Minimally Invasive Surgery

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Abstract. The MicroTactus is a family of instruments that we have 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. We constructed an enhanced arthroscopic surgical probe and tested it in detecting surface defects of a cartilage-like material. Elastomeric samples were cut at different depths and mixed with blank samples. Subjects were asked to detect the cuts under four conditions: no amplification, with haptic feedback, with sound feedback, and with passive touch. We found that both haptic and auditory feedback significantly improved detection performance, which demonstrated that an enhanced arthroscopic probe provided useful information for the detection of small cuts in tissue-like materials.

1 Introduction

Minimally invasive surgery benefits patients by the small size of incisions, less pain, less trauma and shorter healing periods; the surgeon, however, must cope with loss of direct tactile information and reduced visual information. It has been demonstrated that even partial restoration of the sense of touch improves performance in teleoperation and virtual environments [2,4,3,5]. "Augmented reality" can be used to improve human performance in surgical applications, however systems often have features in the graphics domain but provide little in terms of haptic feedback [1]. With this in mind, we have designed and tested a new tool to improve the sense of touch during minimally invasive surgical procedures.

During arthroscopic surgery in a joint, a surgeon inserts a small camera in one incision and a surgical instrument in another. It is common for cartilage to be damaged in regions that cannot be seen arthroscopically, in which cases a surgeon must rely completely on haptic feedback obtained from a surgical instrument. One common arthroscopic instrument has a metal tip and a handle. 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.

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We have developed an integrated system designed to improve the sense of touch of a surgeon holding an instrument during tissue examination. Our device is an arthroscopic instrument that 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 heighten sensitivity to small details even further.

We have fabricated an arthroscopy hook shown in Fig. 1, integrated an accelerometer near the tip, and custom-designed an actuator that was embedded in the handle. The complete system was simple and easy to manufacture. We conducted preliminary experiments in which an acceleration signal was amplified and processed with bandpass 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.

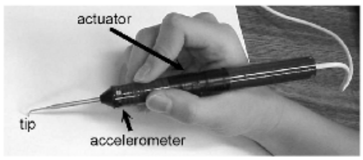

Fig. 1. Application of the MicroTactus concept to an augmented arthroscopic probe.

2 The MicroTactus Touch Magnification Instrument

We determined which signal(s) to detect and amplify by considering the motion of a probe as it interacts with a surface. Motion depends on the forces applied, which for a probe are (1) interaction contact forces and (2) user's grip forces. These combined forces are the forcing term of the probe's dynamics, which in turn are its rigid-body dynamics and structural dynamics. The user's tactile information is derived entirely from the deformation of the tissues of the hand holding the probe, whether the action is to press on, drag over, or tap a surface; this deformation is highly dependent on the dynamics of the probe, and on the size and shape of the probe's tip. Each of these actions, or any combination thereof, informs the user of the probe of properties of the tissues under test.

From this analysis we concluded that the sensory function of the probe is to transfer the movements of its tip to movements of the tissues at the interface with the hand. Since acceleration signals entirely describe the movement of any object (with appropriate integration constants) we concluded that the information to be amplified for tactile enhancement purposes is embodied in the acceleration of the tip of probe, and that sensing force and/or strain is unnecessary.

This analysis also suggested that the appropriate tactile transducer is an actuator that can accelerate the handle. Moreover, because the acceleration signal is highly structured and spectrally rich, if it is converted into an acoustic signal then it might be usefully processed by the auditory system for multi-modality interpretation.

Hardware Design. We applied these principles to the design of an active arthroscopic probe, which we wanted to be similar in structure and use to a conventional probe. As shown in Fig. 2, a biocompatible metal hook was attached to a handle made from carbon fiber tubing that was 15 mm in diameter. An accelerometer was mounted where the probe's metal tip connected to the handle. Preliminary trials 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.

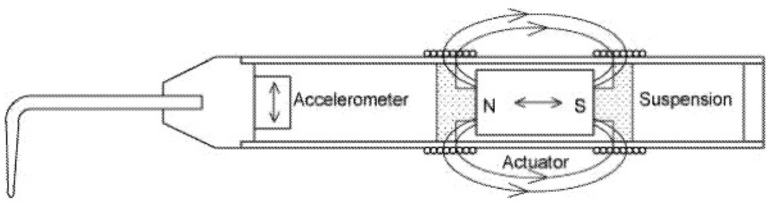

Fig. 2. Main structural components of the probe. The digital signal processing hardware and software is not shown here.

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. To a good approximation the field lines escaping the magnet crossed the loops of two coils at right angles, thereby developing a Lorentz force between the magnet and the handle when current flowed. 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 to our immediate needs.

Maximizing acceleration of the handle's shell required (1) minimizing the mass of the shell, (2) maximizing the mass of the moving part, and (3) maximizing force. We found that our prototype met an appropriate tradeoff: 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 spectral requirements, enabled us to use an ordinary audio amplifier to drive the device.

We designed the device so that the accelerometer detected the radial components of the acceleration, whereas the actuator would create axial accelerations. This had the effect of dynamically decoupling the input from the output, which was necessary because forces would be transferred through the probe's structure. The device thereby remained stable, even with high feedback gains.

Signal Processing. A digital signal-processor subsystem (Analog Devices Blackfin533) was used to perform filtering and signal shaping. The processor also enabled us to conveniently record and play tactile signals. Accelerations were sampled with 16-bit resolution at 48 kHz.

The signal was first anti-aliased by digital filtering with oversampling. The anti-aliasing filter was a low-pass Finite Impulse Response filter of order 64, with a 3 dB cut-off frequency at approximately 500 Hz and a stopband attenuation of approximately 50 dB. The stopband was needed to filter out high frequency components that contributed little to tactile sensation, while keeping the passband as flat as possible. After anti-aliasing, the signal was down-sampled to 2,400 Hz. Downsampling increased the stability of the feedback system and eased the design of filters, which targeted only the frequency range of tactile sensations. Much remains to be done however to improve system performance and increase robustness in the presence of imperfect decoupling.

Configurations. Because the actuator was driven by a signal 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 was 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 was possible to have an assistant scratch and tap a surface while a user experienced 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 experienced during arthroscopy and play back the experience to one or several trainees for instruction. Because of its spectral characteristics, the signal could also be recorded, played back, or monitored with an ordinary audio system.

3 Preliminary Study

To demonstrate 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 was sufficiently deep relative to the radius of the probe tip, and/or if the normal force was 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. Typical examples of signals are shown in Fig. 3.

We tested the ability of subjects to detect such cracks under various uses of the MicroTactus arthroscopy probe.

Surface Preparation. In order to approximate the conditions of tear detection during arthroscopy, we prepared 3 mm-thick-pads made of Viton, a high-

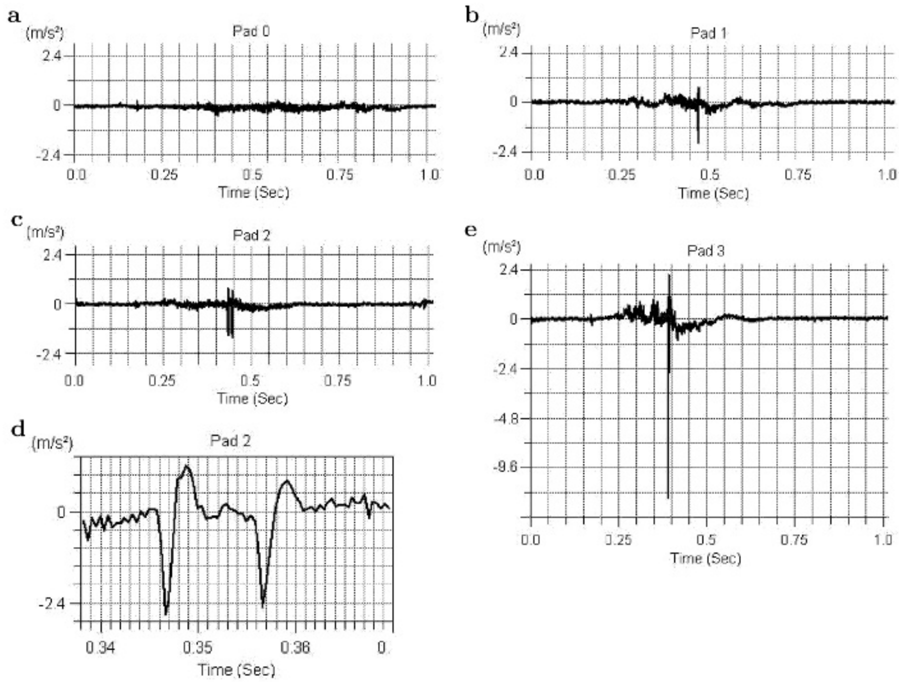

Fig. 3. a) Texture amplitude was modulated by varying the pressure of the probe on the surface. **b**) A small crack produced a single transient. **c**) A double crack produced a double transient. **d**) Enlarged view of **c**. **e**) A large transient given by a deep cut.

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. One pad had no cut, another had a 1.5 mm-deep-crack, another had two 1.5 mm-deep-cracks, and yet another was completely cut 3 mm-deep.

Subjects. We recruited 8 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 not know the details of its design.

Procedure. Two identical MicroTactus probes were connected to the signal-processing system. Subjects sat at a table, held one probe with their dominant hand, and used the probe to explore 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, each pad being presented 6 times. Subjects were asked to detect if there was a cut in the pad. They had to decide rapidly and answered by pressing keys labeled YES and NO. 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`: 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 use a probe without tactile or audio feedback.

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

Results. Fig. 4 summarizes the results (a) by condition and (b) by pad. Fig. 4a 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%. 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 $p = 0.055$ 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 ($p > 0.05$).

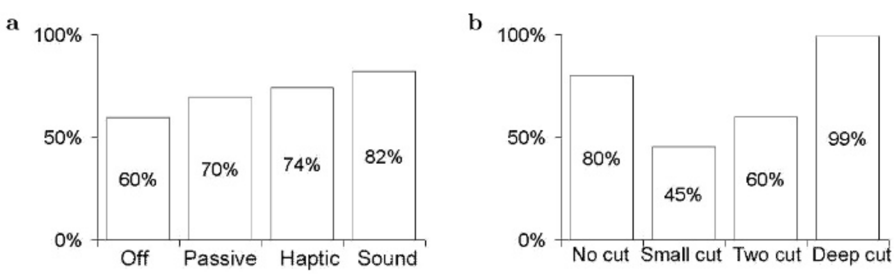

Fig. 4. Results summarized (**a**) by condition, (**b**) by pad.

More detailed data is presented in Table 1. 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.

Table 1. Pooled results in percentile in the 4 conditions and for the different cuts.

Condition	No cut	small cut	two cuts	deep cut
`Off`	92	15	33	100
`Haptic`	90	44	65	100
`Audio`	90	63	77	100
`Passive`	50	60	65	98

Discussion. The results for each pad are presented in Figure 4b and Table 1. 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 or audio feedback, remote detection would of course be impossible and yet our subjects performed remarkably well: the 2% miss rate for remote detection may well have been due to a single error made when the subject entered the data.

Figure 4b 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 figures in Table 1, we concluded that without feedback, the existence of cuts were hard to detect. With either auditory or haptic feedback, the detection rate increases. Thus the system was able to improve the performance of subjects in detecting superficial cuts in a cartilage-like material.

Figure 4a summarizes the performance for each condition. The test of significance indicated that haptic and auditory feedback had positive influences on the performance. As for 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 actively, 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 Table 1. For pads with small cuts, the performance in the `Remote` condition is similar to `Off` and `Haptic` conditions.

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 our auditory system is more able to detect small transients out of a noisy background than is our 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 attempt to eliminate sensor noise. Even though 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.

4 Conclusion

We have introduced the first example of a family of instruments designed to enhance touch while probing a surface. Our preliminary study found that significant task improvement happened when either haptic or auditory feedback were presented. The device also made it possible to experience a surface remotely. The device can be used as a texture-recording/play instrument, with considerable potential for use in surgical simulation and training. The device might also be useful for other judgment and detection tasks.

This project is still at an early stage, and many improvements are possible building on the basic principle described here. The device's structural dynamics might also be modeled and quantified, and a toolbox of signal processing algorithms can be developed to enhance the performance of specific tasks.

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