Surgical Forces and Tactile Perception During Retinal Microsurgery

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Abstract. Purpose: Vitreoretinal surgery involves the manipulation of delicate retinal membranes with a required surgical accuracy often on the order of tens of microns, a scale at or near the limit of human positional ability. In addition, forces imposed by the tissue on the surgical tool are exceedingly small. Here we investigate the magnitude of forces generated during retinal surgery in cadaveric porcine eyes and compare the results with the magnitude of forces discernable by retinal surgeons. This data will be used as a design guideline for robotic surgical augmentation systems currently under development. Methods: The study was performed in two phases. First, retinal surgeons manipulated the retina of porcine cadaver eyes with a calibrated 1-axis force sensing retinal pick while data was simultaneously recorded. In the second phase, blindfolded subjects held the pick and were instructed to press a button whenever an "event" was felt. Events were generated by slowly tapping the end of the pick with varying force while both the magnitudes of forces applied and the responses of the subjects were recorded. The magnitudes of forces generated during retinal surgery were then compared with those that could be discerned by the subjects. Results: Roughly 75% of all forces measured during retinal microsurgery were found to be less than 7.5 mN in magnitude, however, only $19.3 \pm 8.1\%$ (N=492) of events generated at this level could be felt by the subjects. Conclusions: The results of this study indicate that a majority of retinal surgery is probably performed without the surgeon being able to "feel" interactions between retinal tissue and the surgical tool. Prior studies have indicated that relying on visual feedback alone increases the length of manual manipulation tasks and reduces task accuracy. The lack of tactile sensation during retinal surgery similarly could adversely affect surgical outcome.

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1. Introduction

Retinal microsurgery is a complex manual manipulation task requiring judgement, microscopic visualization and precision [1,2]. In addition, we feel that the delicate nature of microsurgical procedures probably provides limited tactile sensation to the surgeon about the tissue manipulation being performed. A lack of tactile information during similar manual manipulation tasks has been shown to reduce both speed and accuracy of manipulation [3]. With an end goal of developing microsurgical augmentation devices capable of enhancing positional accuracy and tactile sensation [4], we investigate the threshold of tactile sensation during retinal microsurgery. This study will be used as a design guideline for such augmentation systems.

2. Background

Vitreoretinal ophthalmic microsurgery deals with the vitreous chamber and the associated retina, which covers the inner surface of the eye and is responsible for vision (figure 1). Sometimes the retina becomes diseased such as in diabetic retinopathy [5] where scar tissue forms on the surface of the retina, requiring the gentle peeling off of the thin membrane without compromising vision. Vitreoretinal procedures involve placing instruments through the sclera while observing the visual field through the cornea and lens using a steromicroscope [6].

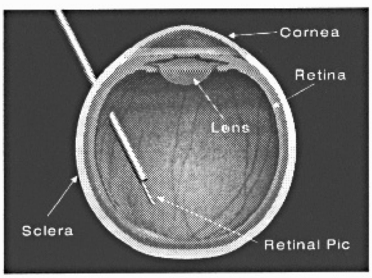

Fig. 1. Basic anatomy of the eye along with sample insertion of surgical pick.

Manipulation of retinal membranes is very delicate and generates forces believed to be below what the surgeon can feel. In studies by Howe et. al. and Patkin [7], the lack of tactile feedback drastically slowed the manipulation and resulted in positional errors possibly as a result of slow visual pathways [8]. Tactile feedback, through touch, pressure, or vibration, results from the stimulation of one or more of four types of mechanoreceptors [3,9]. The minimum threshold for these receptors can be affected by many variables, from such things as age and gender to inhomogeneity of the body surface noted by Weber [10]. Weinstein found the fingers to have a threshold range of 50-100 mg (0.5 - 1 mN) over an area of less than 1 mm^2.

A particular sense can convey more information concerning a particular aspect of an occurrence than another sense could provide [11]. For example, vision is most perceptive to spatial changes, while tactile sensations are sensitive to such things as force/pressure changes. Microsurgery is a manual manipulation task performed primarily using visual feedback. Therefore, in microsurgery, the visual sense predominates followed by touch [12]. However, if these sensory inputs are synergistically integrated, performance could be improved substantially through intersensory integration.

Vitreoretinal surgery is a delicate microsurgical procedure that possibly lacks sufficient tactile feedback. Three interesting topics to investigate in this study are the nature of the forces during retinal microsurgery, the tactile perception thresholds in a simulated microsurgical environment, and the comparison of the two categories to assess the need of enhancing tactile sensation through such robotic platforms as the "steady hand" micromanipulator.

3. Methods

The study was performed in two phases. First, retinal surgeons manipulated the retina of porcine cadaver eyes with a calibrated force sensing retinal pick. In the second phase, blindfolded subjects held the pick and were instructed to press a button whenever a simulated "event" was felt. The magnitudes of forces generated during retinal surgery were then compared with the magnitudes of forces that could be perceived by the subjects.

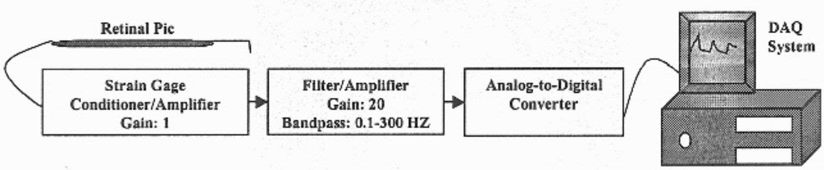

Fig. 2. Block diagram for the experimental setup. Strain gages placed on the retinal pick are conditioned using a strain gage amplifier, filtered prior to A/D conversion at 1 kHz and then stored in data files on a computer.

3.1 Data Acquisition System

The shaft of a retinal pick was flattened and fitted into an ergonomic surgical handle. Foil gages (Measurement Group, Model #EA-06-030LB-120) were affixed with adhesive in a half-bridge configuration and coated with a layer of silicone and shrink wrap tubing. The half-bridge was connected to a strain gage conditioner/amplifier system (Measurements Group, System 2100) with unity gain. The amplifier output was filtered with a bandpass of 0.1-300 Hz and was amplified as a single-ended referenced input with a gain of 20. The signal was digitized at 1 kHz using a PC based (450 MHz Dell computer) analog-to-digital converter (National Instruments, Model PCI 6024E) into files using a custom LabView (National Instruments) application (figure 2). The raw voltage values were converted to forces using a predetermined calibration curve (R^2 = 0.9995, Rice Lakes Weighing Systems, Model #0F51, Class F).

3.2 Experimental Protocol

Retinal Manipulation Porcine cadaver eyes were used to determine the force range experienced during retinal manipulation (figure 3). An eye was placed in the socket of a model head. The cornea and lens were removed, exposing the anterior chamber and the iris. The calibrated instrumented retinal probe was then inserted through the pupil to the retina. The subject manipulated the retina while observing the procedure through a microscope. The strain resulting from the soft tissue forces on the pick during manipulation was acquired for approximately 2 minutes. Care was taken so that the pick shaft did not come in contact with the iris at the point of insertion to avoid extraneous data. This was repeated with 10 subjects.

Fig. 3. Ten subjects manipulated the retina of porcine cadaver eyes with a calibrated force sensing retinal pick while force data was continuously recorded.

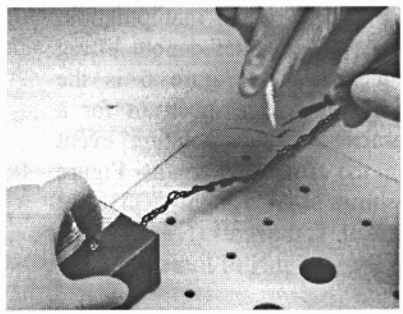

Fig. 4. Blindfolded subjects held the pick and were instructed to press a button whenever an "event" was felt. Events were generated by slowly tapping the end of the pick with varying force.

Threshold Testing of Tactile Perception The threshold values of tactile perception were determined using the same instrumented retinal pick (figure 4). The subject, wearing surgical gloves, held the pick using a wrist rest, mimicking a vitreoretinal surgical procedure. The subject then closed his/her eyes while maintaining the surgical position. A twisted paper towel then was used to create distinct unique events at the tip of the pick. If the event was felt by the subject, the subject would push a button. A time span of at least 1 second passed between events to allow the subject a chance to respond to the stimuli. The events varied in amplitude. Between 40-60 events were produced per subject. The subject was allowed trial runs to become accustomed to the stimuli.

4. Results

A total of 10 subjects were tested, 6 medical doctors, including residents, fellows, and attending surgeons, all with microsurgical experience and 4 non-experienced personnel without medical degrees. The age range was from 21 to 45 years old. The range of surgical experience amongst those medical doctors was from 1 to 18 years.

4.1 Retinal Manipulation

The force traces from the two most experienced vitreoretinal surgeons of the group were used as indicative measures of the magnitudes and frequencies of forces that are exerted during retinal manipulations. Figure 5 depicts a typical 30 second force trace during retinal manipulation. The positive values denote lifting of the retina. Figure 6 is the associated power spectrum for a characteristic manipulation event from the same 30 seconds. Figure 7 shows that roughly 75% of manipulation events (N=181) used less than 7.5 mN of force.

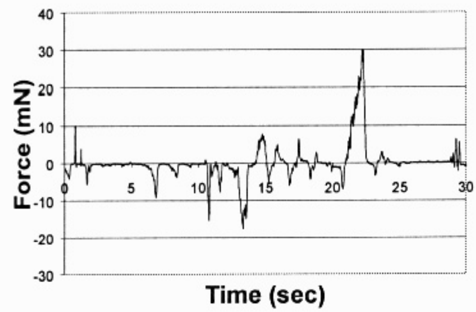

Fig. 5. A sample 30 second force trace during retinal manipulation. The positive values denote lifting of the retina.

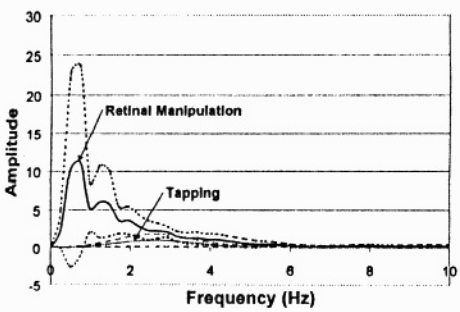

Fig. 6. Power spectrum comparing the average frequency content of typical retinal manipulation events with tapping events generated during the threshold testing for tactile perception. Dotted lines signify 95% confidence intervals.

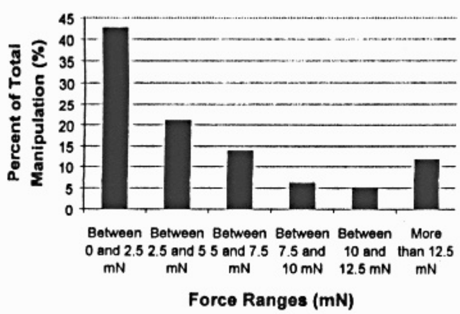

Fig. 7. Shows the percentage of events that fell within each force range during retinal manipulation. Note that 75% of all manipulations are less than 7.5 mN.

4.2 Threshold testing of tactile perception

Data from all ten subjects were used in the analysis. Figure 8 shows a 20 second sample of the tapping test. The solid black spikes denote an event. The downshift of the lighter grey lines denotes tactile sensation. Figure 6 shows the power spectrum of a characteristic induced event. A total of 492 events were recorded. Since 75% of all manipulations occurred less than 7.5 mN, the data was divided into two groups based on this value. The percent of detection within the two groups was determined (figure 9). Only 19.3 ± 8.1% of events less than 7.5 mN could be detected, while 59.2 ± 28.2% of events greater than 7.5 mN were perceived. This difference was found to be highly significant (p=0.0005) using the F-test.

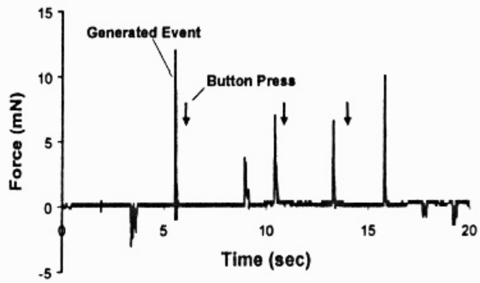

Fig. 8. A 20 second sample demonstrating how the threshold measurements were taken. The solid black spikes denote stimuli. The arrows below the time axis denote tactile sensation.

5. Discussion

It was crucial to obtain both data sets with the same measuring device and under similar operating conditions in order to minimize variables that could alter data correlation. It is important to realize the other variables that can affect the data from one individual to another, such as fatigue, stress, and level of training.

The presented data demonstrates that the majority of retinal surgery is performed without being able to "feel" tool-tissue interactions since most of the manipulative events are below the

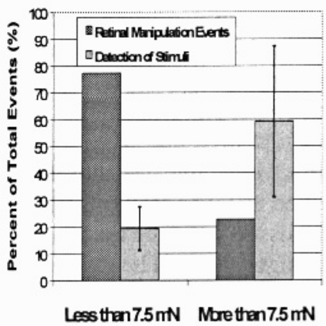

Fig. 9. Only 19.3 ± 8.1% of events less than 7.5 mN, which made up 75% of all retinal manipulations, could be detected, while 59.2 ± 28.2% of events greater than 7.5 mN, which made up only 25% of manipulations, were perceived.

threshold of tactile sensation. This supports the theory that most microsurgery is performed utilizing predominately visual feedback alone, which is slower and not as accurate as when combined with from tactile sensation.

The threshold values obtained in this study are higher than those from Weinstein's study. This is probably attributed to using a blunt instrument handle instead of Weinstein's pointed stimulator [10] since the area of application of the blunt surface is more, and hence a greater force is needed to reach the threshold pressure. In the microsurgical environment, the interfacing surfaces are blunt, thus requiring a higher amount of force to elicit a tactile sensation. There are also other factors that may contribute to the difference, such as wearing surgical latex gloves in addition to sitting in a more stressful position.

In addition to the magnitudes of forces, another interesting parameter to consider is the power spectrum. The frequency content of the events during retinal manipulation was compared to that of the stimuli during the sensitivity test to determine whether or not the events being produced were indicative of those that are actually experienced during vitreoretinal microsurgery (figure 6). The DC component of the frequencies was eliminated by subtracting the mean of the magnitude of the data sets before running a power spectral analysis on them. From the spectrum plot, it can be seen that though the two data sets are predominately composed of low frequencies (less than 20 Hz), the frequency content of the events generated during the threshold testing of tactile perception seems to be higher than that of retinal manipulation. A way of generating events that better follow the power spectrum of retinal manipulation is currently being explored.

Tactile Augmentation With intense training, surgical performance can be further enhanced, though as can be seen by the presented data, much of what is done during retinal surgery cannot be felt. However, via tactile surgical augmentation, enhanced tactile sensation will allow for further increase in performance encompassing accuracy, speed, and safety. One solution incorporates force sensing and tactile feedback into the "steady-hand" micromanipulator, an augmentative approach conceived at Johns Hopkins University [4]. In this system, the forces that exist at the tool tip-tissue interface are monitored by the robot's controller and are used in control system algorithms. The result is force scaling which would enhance tactile sensation by detecting and amplifying the forces described above to a level perceptible by human touch. The end result would be enhanced positional accuracy and augmented tactile sensation during microsurgical procedures such as retinal manipulation.

6. Conclusions

Though modern day microsurgical instruments and procedures have revolutionized ophthalmologic surgery, human performance is still limited. Scientifically exploring these limitations will lead to novel augmentative surgical devices that will remove some of these limitations, such as with tactile sensation. This could potentially lead to new microsurgical techniques that are not currently possible.

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