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Test of Tracing Performance with an Active Handheld Micromanipulator

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***Abstract*— This paper demonstrates tremor compensation for human subjects using an active handheld micromanipulator. This instrument uses optical and inertial sensing to detect its own motion, estimates tremor using linear filtering, and a flexure-based manipulator to actuate the tip. Compensation results while tracing a line with the tool are presented for both novice users and a trained surgeon. Learning effects from repetition of the trials over a ten-day period are described.**

I. Introduction

Involuntary tremor hinders and even makes certain handheld micromanipulation tasks impossible. This physiological tremor is a complex phenomenon that has traditionally been thought to be roughly sinusoidal with a bandwidth between 8-12 Hz [1]. However, it has become clear through previous studies [2] and work in our laboratory that involuntary motion has lower frequency components below 1 Hz that need to be considered in order to achieve the goal accuracy of 10 μm [3].

A variety of robotic solutions to compensating tremor for microsurgical procedures have been studied. Teleoperated robots have been used to perform motion scaling and filtering [4,5]. Another approach is the “steady hand” robot where both the robot and the surgeon hold the tool together [6]. A third approach that has been developed in our laboratory is called “Micron,” a completely handheld instrument that can sense its own motion, distinguish between desired and undesired motion, and actuate its tip to compensate the tremor in real time [7].

One aspect of Micron that has not been studied previously is the effect of training on cancellation performance. The length of this curve is significant in both general and robotic surgical applications and is important to understand in order to accurately assess results [8,9]. This paper describes tremor compensation results with human users in a line tracing task, with an examination of learning curve effects in six novices and one trained surgeon.

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II. Methods

A. Design of Micron

Micron currently uses a 5-dof optical sensing system called “ASAP” (Apparatus to Sense Accuracy of Position) [10] to provide information about the tool tip which is used for feedback. A pair of orthogonal accelerometers provides the additional dof that gives information about the rotation of Micron about the long axis of the tool. ASAP uses two diffuse light emitting spheres that are fixed to the tip of the tool that are shown in Fig. 1. The LED’s inside the spheres are pulsed with square waves of differing frequencies, one at 2 kHz and the other at 3 kHz. These two signals are then demodulated after being sensed by orthogonal position-sensitive detectors (PSD’s) (DL10, UDT Sensors Inc., Hawthorne, CA, USA). The PSD’s as well as the ASAP setup can be seen in Fig. 2. The noise for ASAP is about 0.5 μm rms.

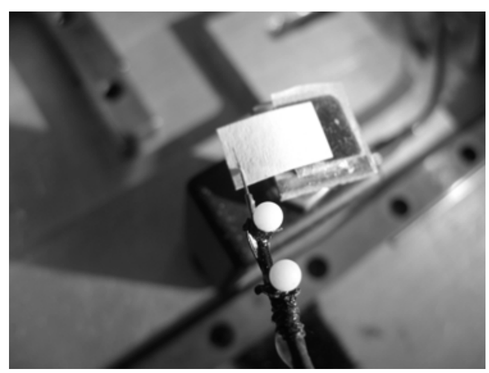


Fig. 1. There is an LED inside of each of the spheres that are attached to the tip of the instrument. The LED’s are pulsed and detected by a two PSD’s that make up the optical tracking system. There is a line drawn on the cantilevered paper that is traced during each trial.

The manipulator in Micron is a flexure based 3-dof parallel manipulator that uses three piezoelectric stack actuators (P-885.50, Polytec PI, Inc., Karlsuhe, Germany) whose motion is mechanically amplified with a set of lever arms [11]. The range for the manipulator is about 400 μm in the transverse axes of the tool and about 80 μm in the axial direction. Due to the current limited range in the axial direction, compensation was only performed in the transverse directions.

B. Experimental Procedure

Seven human users participated in a tracing performance test; six novice users and one expert user who is an ophthalmologic surgeon. The experimental setup, shown in Fig. 2, includes a stereo operating microscope at 25x magnification and approximates conditions during general vitreoretinal surgery. A block for the tool to rest upon provided support for the users, a condition that simulates bracing of the tool during surgery. A 3 mm line was drawn on a cantilevered sheet of paper 8x8 mm (Fig. 1). An LED light was used to illuminate the workspace without interfering with the PSD's. The shadow of the needle as well as the flexibility of the paper provided additional visual depth cues.

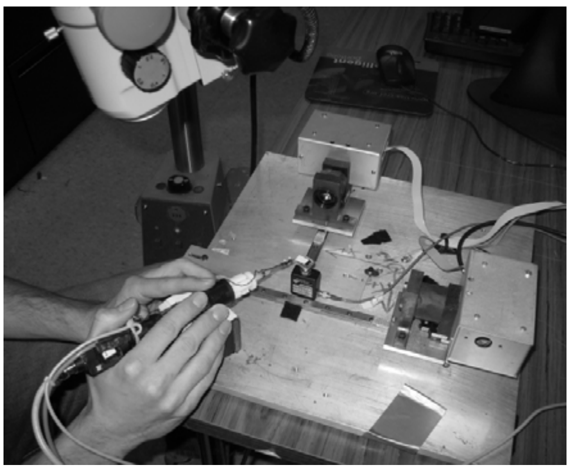
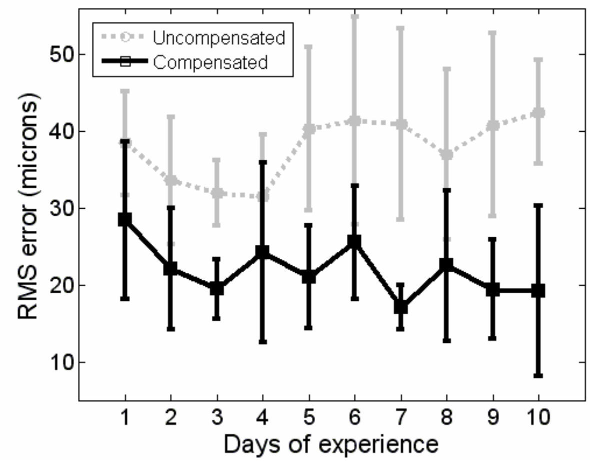


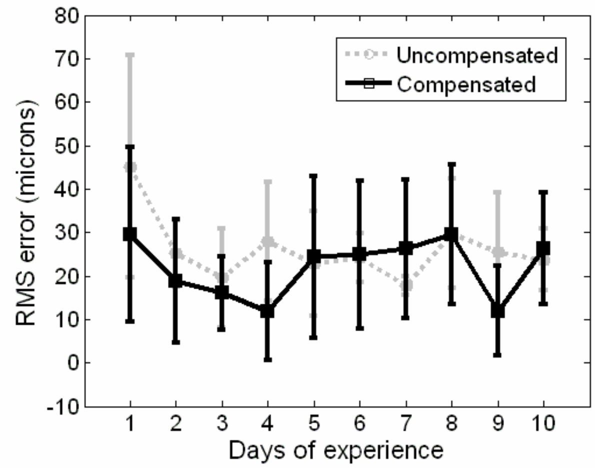
Fig. 2. Experimental setup showing the ASAP optical tracking system. The instrument is shown resting on a block. The two rectangular boxes that house the PSD's and the microscope are shown.

During each trial, the subject attempted to trace the line as accurately as possible with motion primarily in the axial direction of the tool. This tracing task roughly approximates a cannulation task in vitreoretinal microsurgery. Subjects were told to keep the tip of the needle as close to the plane of the paper as possible throughout the trials. For each day, each subject performed this tracing task 12 times: six times without active tremor compensation and six times with compensation. There were also six familiarization trials to get the subject comfortable with the task but were not included in the analysis. The order of the trials was balanced between the subjects to account for ordering effects.

Each subject repeated this 12 trial test for a period of 10 days and their rms and maximum error with respect to the perpendicular distances of a linear regression were analyzed for each day. For the analysis, the tip positions were projected onto the plane of the paper because of the difficulty of depth control. The results of novices and expert were also compared. A two-tailed Student *t* test was used to determine the statistical significance (defined to be significant for $P<0.05$) of the results.



(a)



(b)

Fig. 3. The average rms error for the (a) novices and (b) surgeon over 10 days, both with and without compensation. Error bars show one standard deviation above and below the mean.

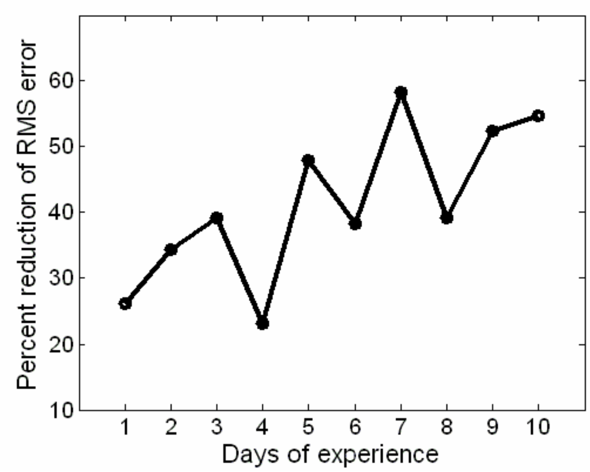
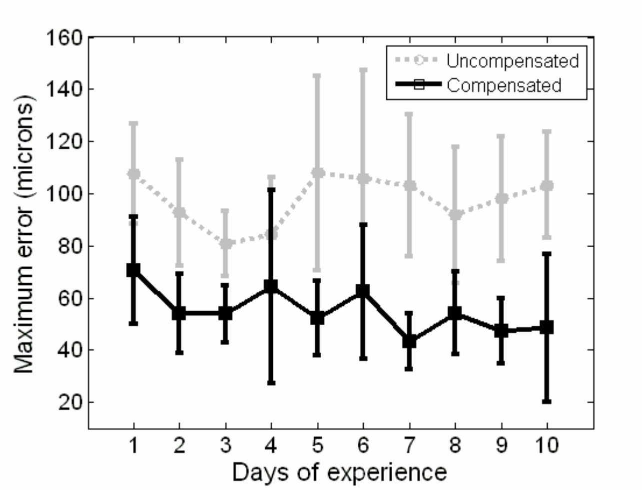


Fig. 4. Percent reduction of rms error for novice users over 10 days.



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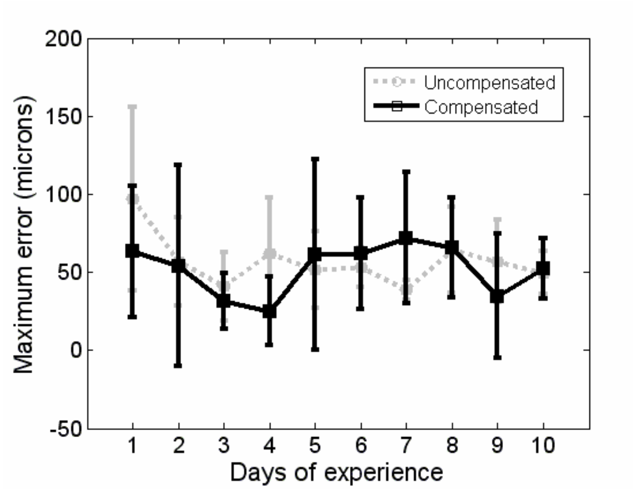

(b)

Fig. 5. The average maximum error for the (a) novices and (b) surgeon over 10 days, both with and without compensation. Error bars show one standard deviation above and below the mean.

III. Results

Fig. 3 shows the compensated and uncompensated average rms error for the six novice users and surgeon. Ten days of experience are shown in each of the figures. The difference between the average rms errors with and without compensation for the novice users was statistically significant except for days 1 (P=0.07) and 4 (P=0.24). The surgeon's difference between rms errors with and without compensation was not statistically significant except for day 4.

Fig. 4 shows the percent reduction of error with compensation for the novice users. There is a general increase in the reduction of undesired motion starting with 23% reduction in rms error and ending with 56% reduction on day 10.

Fig. 5 shows the compensated and uncompensated average of the maximum error for the six novice users and surgeon. The maximum error compensation for novice users was statistically significant except for days 4 (P=0.28) and 6 (P=0.054). The surgeon's reduction of maximum error with compensation was not statistically significant.

Fig. 6 compares the surgeon's uncompensated rms results with the novice user's compensated and uncompensated results. The greatest learning of the uncompensated results takes place after the first day of experience. The average P value between the surgeon's uncompensated results and the novice's compensated results after the first day was 60%. The average P value between the surgeon and novice's uncompensated results after the first day was 12%.

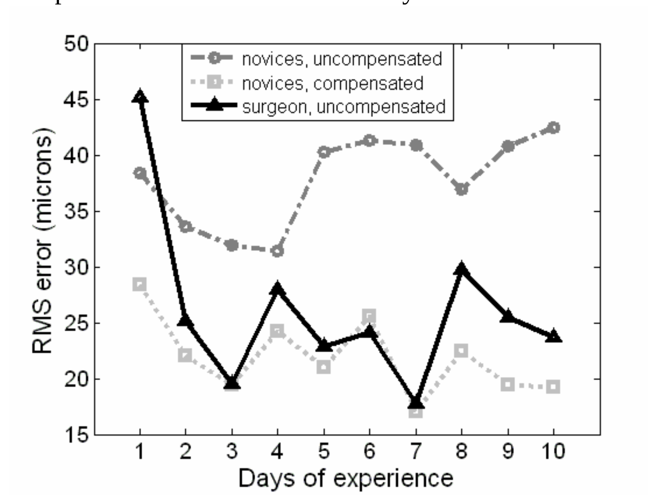

Fig. 6. The rms error of the surgeon's uncompensated rms result is plotted with the novice user's compensated and uncompensated rms results. This figure seems to indicate novices using the instrument with active compensation on can improve their rms error close to that of a trained surgeon.

IV. Discussion

The results show that Micron can attenuate undesired motion during a line tracing task for novice users. In addition, there is a general trend for novices to improve in their use of Micron over time. Fig. 6 and the P values presented in the results suggest that novices have higher errors in the tracing task than the surgeon but that the active tremor compensation may offer the potential to improve their micropositioning accuracy to the level of more experienced users. Experiments with larger numbers of trained surgeons are needed in order to clarify the question.

The surgeon's trials did not show a significant level of improvement in tremor reduction. This may be because the surgeon's tremor is already nearing the limit of the accuracy Micron can currently provide; as the accuracy of Micron itself is improved, learning effects in expert users may become more evident. Among other factors, the surgeon tends to use a faster technique that reduces the low frequency error which is a large component of the total error [12], thus leaving less error to be compensated. Further testing is required to better understand these effects.

In terms of the learning curve, the novices seemed to exhibit a learning effect in the compensated trials but not in the uncompensated trials. The inverse is true for the surgeon: there is improvement in the uncompensated trials especially after the first day but no currently detectable learning in the compensated results. The lack of a more distinct learning curve may be due to the simplicity of the trial. A study of learning in a virtual reality laparoscopic system has shown that multiple plateaus in performance may occur and that these effects may go beyond 30 repetitions [13]. Longer training periods and more complex tasks may bring to light further learning effects.

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