THREE-DIMENSIONAL ACCURACY ASSESSMENT OF EYE SURGEONS

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Abstract – **Overall manual accuracy in simulated microsurgery has been studied. Three eye surgeons have been tested thus far. Subjects attempted to hold a microsurgical instrument still for 30 s and its 3-D tip position was recorded. RMS error, overall motion range were calculated and spectral analysis was performed for each axis. The RMS error was between 54 μm and 118 μm and the overall range of motion was between 239 μm and 588 μm, depending on the axis. Substantial low frequency motion was present. Between 73.5% and 83.7% of the total power was found to be below 3 Hz, depending on the axis.**
Keywords –**Microsurgery, accuracy, optical sensing**

I. INTRODUCTION

Many involuntary and inadvertent components are present in normal human hand movement. These include physiological tremor [1], jerk [2], and low frequency drift [3]. Suppression or cancellation of these components would improve existing surgical practice and possibly allow the development of new procedures. Research into microsurgical error suppression has involved teleoperated systems [2], cooperative-control "steady-hand" systems [4], and active hand-held instruments [5,6]. However, precise quantification of the performance baseline of unassisted surgeons against which such systems should be compared has thus far been lacking.

Precise values for tremor amplitude and overall tool-positioning accuracy are important for comparative evaluation of microsurgical accuracy enhancement systems. Knowledge of the bandwidth of voluntary motion in microsurgery is needed in order to correctly specify bandwidth requirements for these systems. If the bandwidth is too low, a system feels sluggish [7]. It has been reported that the average dominant wrist motion for 24 activities of daily living is about 1 Hz [8] and that the bandwidth for writing and drawing is as high as 6 Hz [9]. While it is assumed that the necessary bandwidth for microsurgery is considerably lower than this latter value, this assumption must be tested.

Riviere and Khosla reported on three-dimensional (3-D) microscopic hand motion of unskilled subjects, but not trained microsurgeons [3]. Several 1-D studies have been reported on trained micro-surgeons [1,10] and medical students [11]. Some examined only physiological tremor [1,11], but others have also considered the overall range of motion of surgeons [3,10]. The present paper presents preliminary results of an ongoing study quantifying physiological tremor amplitude, overall accuracy, and user bandwidth in 3-D.

II. METHODS

Three ophthalmological surgeons at The Johns Hopkins Hospital participated in the experiment. Tests were conducted in a surgical suite with a binocular microscope (Storz Ophthalmic, Inc.). In each test the subject held a microsurgical instrument with the tip inserted in a sclerotomy in the eye of a vitreoretinal surgical testbed, as Fig. 1 shows. The subject attempted to hold the instrument motionless for the duration of each recording. The forearm of the subject was roughly parallel to the Y axis of the sensing apparatus. Data for each test were recorded for 30 s at 1500 Hz.

The Apparatus to Sense Accuracy of Position (ASAP) [12], an optical tracking system, was used within the testbed to detect the position of the tip of the instrument. ASAP uses an infrared light-emitting diode, modulated at 5 kHz, to illuminate the workspace. A small reflective ball is attached to the tip of the microsurgical tool. The 3-D tip position is found by using two 2-D position-sensitive detectors (PSDs) to sense the reflected light. The signals from the PSDs went through signal conditioning circuitry, to demodulate the signal, before being recorded. The modulation/demodulation scheme provides better noise immunity and better accuracy. At the time of the data collection, ASAP was operating at a noise level of 5 μm RMS per coordinate direction.

Recordings were analyzed both in their 30-second entirety, and in 15-second intervals. Both the 15 s and 30 s recordings were normalized, down-sampled to 150 Hz, and passed through a lowpass filter with a 25 Hz cutoff frequency. RMS error and overall range were calculated. Spectral analysis was performed. Physiological tremor was estimated by passing the data through a bandpass filter with corner frequencies at 7 and 13 Hz, and computing the rms amplitude and overall range of motion for each recording.

III. RESULTS

Figures 2 and 3 present sample Z-axis and Y-axis recordings from an individual subject, for a 15 s and 30 s duration, respectively. Drift is noticeable, particularly in the longer recording. Tables 1 and 2 present the RMS amplitude for each axis. The overall range of motion for each axis is presented in Tables 3 and 4.

Figures 4, 5, and 6 display the averaged power spectral density for the X-axis, Y-axis, and Z-axis, respectively, for the full 30 s. A low frequency component is clearly visible for each of the axes. Tables 5 and 6 present the percentage of total power present in various frequency bands for the 15 s and 30 s duration, respectively. The majority of the power present was at the low end of the spectrum.

There is a tremor peak visible at roughly 10 or 11 Hz in the power spectrum in Figures 4, 5, and 6. The results for the bandpass-filtered data for both cases are presented in Table 7. The range varies from 25 μm to 51 μm, depending on the axis. These values are similar for the 15 s and 30 s cases. Figure 7 displays a portion of the result of one sample recording passed through the bandpass filter.
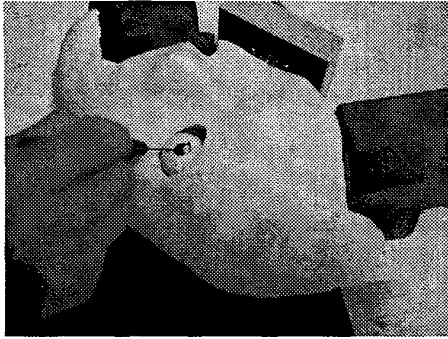

Figure 1. Vitreoretinal surgical testbed using ASAP for instrument tracking. The reflective marker ball is visible at the tip of the microsurgical instrument.

TABLE 1
RMS AMPLITUDE OF RECORDED MOTION FOR 15 S DURATION

Axis	Mean(μm)	s. d. (μm)	Min. (μm)	Max (μm)
X	54	29	25	91
Y	55	32	19	88
Z	87	51	35	167

TABLE 2
RMS AMPLITUDE OF RECORDED MOTION FOR 30 S DURATION

Axis	Mean(μm)	s. d. (μm)	Min. (μm)	Max (μm)
X	80	33	25	91
Y	67	40	19	88
Z	118	42	35	167

TABLE 3
OVERALL RANGE OF RECORDED MOTION FOR 15 S DURATION

Axis	Mean(μm)	s. d. (μm)	Min. (μm)	Max (μm)
X	239	135	121	447
Y	260	150	95	412
Z	446	301	186	951

TABLE 4
OVERALL RANGE OF RECORDED MOTION FOR 30 S DURATION

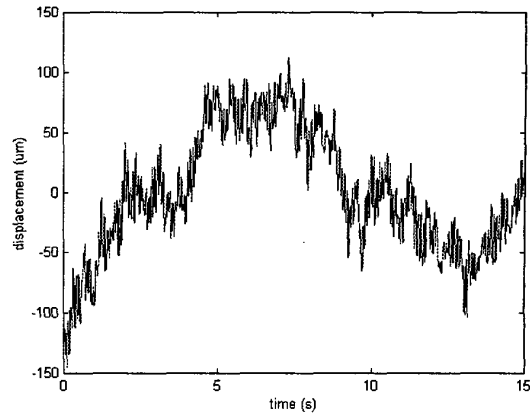| Axis	Mean(μm)	s. d. (μm)	Min. (μm)	Max (μm)
X	356	155	177	447
Y	348	201	132	530
Z	588	316	374	952

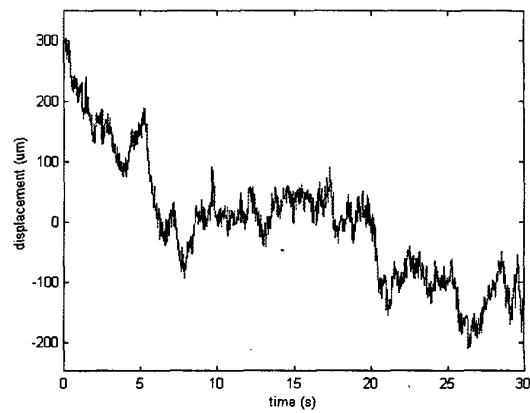Figure 2. Sample recording from an individual subject in Z-axis for 15 s.

Figure 3. Sample recording from an individual subject in Y -axis for 30 s.
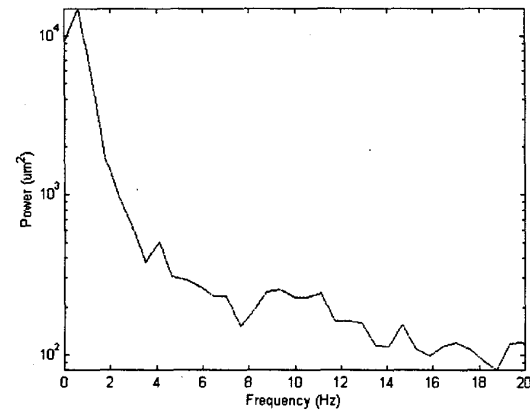

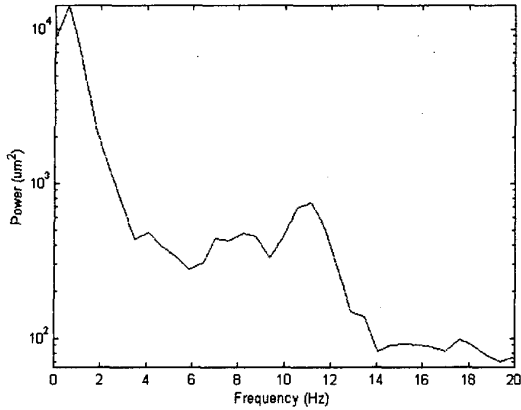Figure 4. Average power spectral density of X-axis for 30 s duration.

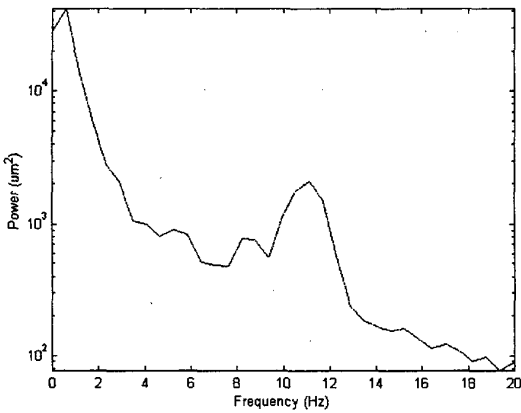Figure 5. Average power spectral density of Y-axis for 30 s duration.

Figure 6. Average power spectral density of Z-axis for 30 s duration.

TABLE 5
PERCENTAGES OF TOTAL POWER AT SELECTED FREQUENCIES FOR 15 S DURATION

Axis	Below 0.6 Hz	Below 1.2 Hz	Below 1.8 Hz	Below 2.4 Hz	Below 3 Hz
X	53.0	72.6	79.1	82.3	83.7
Y	46.5	62.6	69.6	73.2	75.6
Z	52.2	66.5	72.6	76.0	78.5

TABLE 6
PERCENTAGES OF TOTAL POWER AT SELECTED FREQUENCIES FOR 15 S DURATION

Axis	Below 0.6 Hz	Below 1.2 Hz	Below 1.8 Hz	Below 2.4 Hz	Below 3 Hz
X	43.3	59.1	66.4	71.1	73.5
Y	45.4	61.2	67.3	71.5	73.7
Z	50.2	65.3	70.7	74.4	76.7

TABLE 7
OVERALL RANGE OF 7-13 HZ COMPONENT

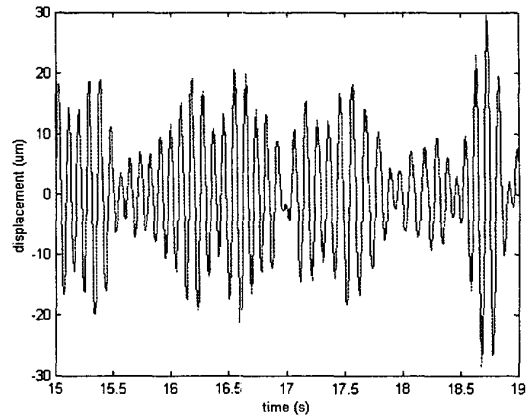| Axis	15 s duration		30 s duration	
	Mean (μm)	s. d. (μm)	Mean (μm)	s. d. (μm)
X	25	4	30	4
Y	35	6	34	5
Z	51	9	50	8

Figure 7. Component of motion from an individual subject in the approximate frequency band of physiological tremor (7–13 Hz).

IV. DISCUSSION

The results in Tables 1 and 2 offer a baseline for RMS error, or standard deviation of motion, from a desired location during instrument manipulation. As expected, these values are higher than those measured for the 1-D case [10]. Tables 3 and 4 quantify the size of the windows within which surgeons are able to maintain the instrument tip. Drift has a considerable effect on the results for overall range of motion. The overall range for the Z-axis is greater than those for the X and Y axes, most likely due to the difficulty of determining position along the line of sight of the microscope. Further data will be collected using a more clearly visible target marker to provide a visual reference for the test subjects, as in [3] and [10].

Physiological tremor includes both a neurogenic component, around 8-12 Hz, and a "mechanical reflex" component dependent on mechanical properties, which has been measured at 8-12 Hz in the wrist and 17-30 Hz in the metacarpophalangeal joint [13]. The existing literature on canceling of position error to improve manual precision in surgery mostly focuses on canceling the physiological tremor for the frequencies stated above. Spectral analysis for each axis does show an 8–12 Hz component, but most of the power is in the lower frequency range, below 3 Hz. Correcting this error is difficult due to its overlap in frequency with voluntary components of motion. Methods to suppress low frequency error in microsurgery are currently being investigated [14].

In the time since the collection of the data presented herein, the measurement noise of ASAP has been decreased to 1 μm RMS, enabling more precise analysis. Future work includes further data collection from a larger number of microsurgeons. Additional experimental tasks that include voluntary components of movement will be introduced so as to allow quantification of voluntary motion bandwidth, as well as any interdependence of involuntary and voluntary components of motion.

V. CONCLUSION

Involuntary 3-D hand motion of eye surgeons has been studied in static targeting tasks. Values for RMS error, overall range of motion, tremor amplitude, and frequency content for each axis have been presented.

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