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Micromanipulation Accuracy in Pointing and Tracing Investigated with a Contact-Free Measurement System

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Abstract— **This study examines micromanipulation accuracy in pointing and in tracing a circle, using a novel contact-free measurement system. Three groups of subjects enable us to investigate the influence of age and micromanipulation expertise. The results show that, for all groups of subjects, a 10x magnification increases accuracy, but larger magnification does not improve it further. Expertise leads to reduced error, and grip force does not affect accuracy in the magnified condition.**

I. Introduction

A main concern in microsurgery is the inaccuracy of human hand motion. Manual inaccuracy is primarily caused by physiological tremor, defined as the inherent rhythmic small movements which exists due to interaction among several factors, arising from both mechanical and neural origins [1]. However, there are other kinds of deviations due for example to visually controlled motion. Measurement of limb tremor were initially conducted with accelerometers [2], [3], [4], [5], [6], however, this requires segregation from the influence of gravity and is not targeted to evaluate the position and velocity errors determining the accuracy, as well as some aspects of tremor [7].

Motion tracking devices such as mechanical structures with encoders now allow direct recording of position data at high sampling rate, enabling tremor analysis without depending on accelerometers. In [8], we used such a device to study the pointing accuracy. We could then examine the influence of posture on the error, and found that pointing error decreases with magnification until about 10x, after which it does not change with higher magnification. We also found that the grip force does not affect pointing accuracy.

However, the mechanical impedance due to the inertia and viscosity of the mechanism used in [8] may have filtered the hand oscillations. A contact-free position sensing system has been developed [9] in order to avoid these possible confounds. In this study we use this novel device to study manual microscopic accuracy (Fig.1). In addition to a pointing task, we examine how the subjects perform a circular movement. Three groups of subjects are tested: naive subjects as in [8], age matched medical students with surgery knowledge, and older, experienced surgeons.

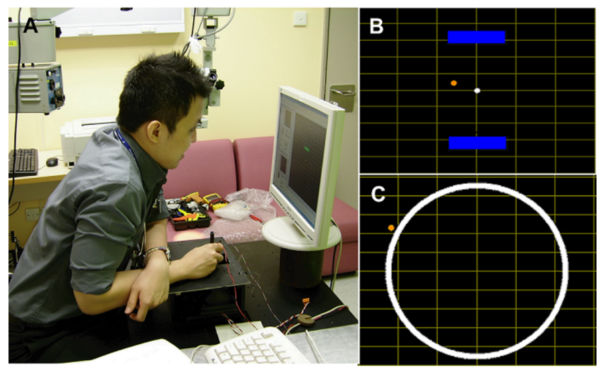

Fig. 1. Subject performing the accuracy experiment (A). (B) shows the screenshot for pointing task with orange cursor and blue rectangles indicating a too large grip force. (C) shows the screenshot for the tracing task.

II. Experiment

A. Measurement Device

The M2S2 optical micro motion sensing system developed by the Biorobotics group of NTU uses a pair of orthogonally placed position sensitive detectors (PSD) to track 3D displacement of the tip of a microsurgical instrument in real-time (Fig.2A, [9]). An IR diode illuminates a 5*mm* diameter ball attached to the tip of an intraocular shaft (Fig.2B), reflecting IR rays onto the PSDs. This device provides a measurement at 250*Hz* in a 10x10x10mm^3 workspace, with a peak to peak static error of $3.1\mu m$.

A stylus with similar mass characteristics to a typical surgical forceps was designed to hold a reflector ball for tracking the stylus movement (Fig.2C). A (FSG15N1A, Honeywell Inc., USA) force sensor was mounted on this stylus to estimate the grip force. This sensor can measure forces up to 15*N*. The force data are acquired using a data acquisition card (PD2-MF-16-150, United Electronic Industries, USA) with 16-bit resolution.

Static error is obtained by measuring known position of a stationary ball for a period of time. A total of 27 recordings for static error was taken within the workspace of $10mm^3$. Dynamic error of the system may differ slightly from static

The experiments were conducted at Nanyang Technological University and National University Hospital, Singapore.

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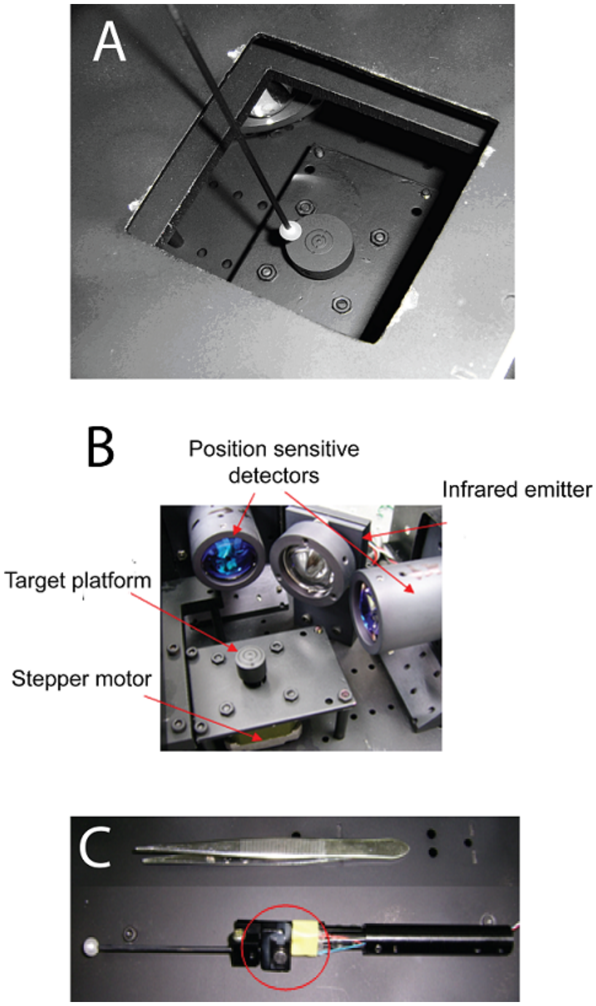

Fig. 2. (a) M2S2 system for microscopic motion capture with the reflector ball, attached to a stylus, pointed within the workspace. (b) Interior of the M2S2 measurement system. (c) Stylus with force sensor.

TABLE I

STATIC AND DYNAMIC ERRORS OF THE M2S2 MEASUREMENT DEVICE

	static	$8Hz$	$12Hz$
RMSE(μm)	0.91	1.2	1.0
peak-to-peak maximum error (μm)	3.1	2.9	2.4

error. It was measured at different frequencies up to 12*Hz*, as tremor band was expected to peak between 2-12*Hz*, using a sinusoidal motion with known magnitude and frequency produced by a nano-positioning device (P-561.3CD, Physik Instrumente, Germany). Static and dynamic errors are shown in Table I.

B. Experiment protocol

The 15 right-handed subjects who participated in this study comprised 6 experienced micro-surgeons between the ages of 30-40 years (1 female), 5 medical students (3 females) and 4 male subjects with no medical background. All subjects gave informed consent prior to the test and reported no physical or cognitive impairments.

The subjects were seated facing the monitor screen placed about 70*cm* away from the edge of the table. They had their wrists rested on a small platform of the M2S2 and were asked to take a comfortable seating position. They had to hold the stylus between their index finger and thumb in order to ensure that all subjects have similar grip across trials. The tip of the stylus was pointed near the centre of the M2S2 workspace.

To perform the *pointing task*, two dots were displayed (Fig.1B): one fixed white dot and another orange dot which will move according to the user's tool tip position. The user was required to keep the orange dot overlapping the white dot for 30*s*. Visual magnification and grip force were altered to study how these factors affect the accuracy. Rectangular colored bars above and below the white dot indicated the force level. Users were asked to maintain the bar color at green, indicating that their level of grip force was within range. The bars color changed to red when the user applied too low a force and to blue when too large a force was exerted.

Visual feedback was provided on a 19" flat LCD monitor. Three magnifications: 1x, 10x and 20x were tested, as well as three different levels of grip force: 1-2*N*, 2.5-3.5*N* and 4-5*N*. Data was collected at 250*Hz*.

In the *tracing task*, a 4*mm* diameter white circle was drawn on the display. The subject was then instructed to move along the circle clockwise as accurately as possible during 30*s* with the small orange-colored dot used as the cursor (Fig.1C). Only magnification was altered in this tracing task, i.e. the subjects were allowed to use their own comfortable grip force, as they had difficulty constraining their grip force during tracing.

Once the subject was ready to start a trial, a keyboard press sets the cursor at the center of the screen (by convention at (0,0)) and data is collected for 30*s*. For the pointing task, this means the cursor overlaps the target and the subject only has to keep this position. In the tracing task, the cursor is at the center of the circle and the subject has to bring it to the circumference of the circle.

The subjects performed two trials for each different setting with approximately one minute break in between settings. All subjects carried out the tests in the same order of magnification and grip force. Data analysis was performed as in [8].

III. RESULTS

A. Pointing Task

For each of the three groups, the error decreased significantly between 1x and 10x ($p < 0.003$ for surgeons; $p<0.01$ for medical students; $p<0.04$ for non-medical students) but no significant reduction of error was detected between 10x and 20x ($p> 0.5$ for all three groups) (Fig. 3). This confirmed the results of [8] and justified a-posteriori the use of only 3 levels of magnification.

Results from the grip force test showed that the grip force had negligible influence on pointing task accuracy ($p >0.1$ for all pairwise comparisons of force levels in each of

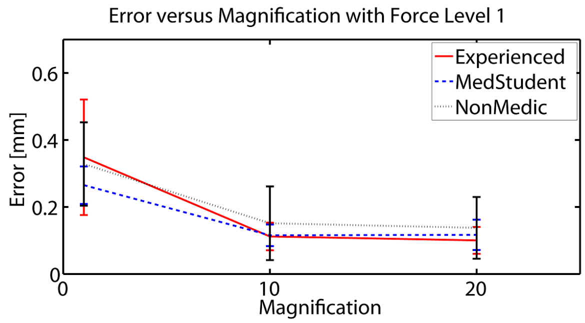

Fig. 3. Pointing error versus magnification for different groups of subjects at force level 1.

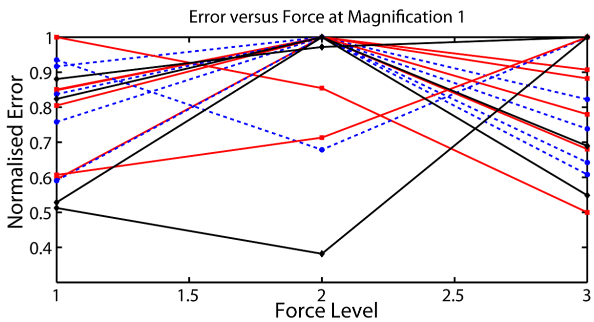

Fig. 4. Error due to effect of grip force for each subject at 1x magnification. Surgeons are in red, medical students in blue and non-medical students in black.

the three groups), as we had found in [8]. However, at 1x magnification, 10/15 subjects or 8/11 of trained subjects had clearly less error both on the smallest and largest grip force ranges than in the medium range (Fig. 4).

Tremor is frequently analysed in the frequency domain using power spectral density [10]. We see in Fig.5A that magnification only plays a role in the low frequency band of 0-2*Hz* where voluntary motion is dominant. Total power in this band decreased with magnification 10x ($p<0.001$), but not beyond that ($p>0.4$). Pairwise comparisons in the other frequency bands did not show an effect on displacement power at any magnification level ($p>0.6$).

As in Fig. 4, grip force appeared to have an effect on power intensity without magnification (Fig.6): power in the 0-2*Hz* region was significantly higher when grip force was at force level 2 as compared to force level 1 ($p<0.02$) or 3 ($p<0.043$). Again, grip force did not seem to affect power at higher magnifications (in any of the bands).

B. Tracing Task

Fig.7A shows typical trajectory of a subject performing the tracing task at different magnifications. As in the pointing task, the error decreased significantly with magnification 10x (Fig. 7B) for the surgeons and non-medical student groups ($p<0.001$). The medical students group showed no significant difference of error between 1x and 10x ($p>0.2$), but had relatively low error at 1x. When the data of all subjects were grouped, the 10x magnification reduced the error significantly ($p<0.001$) but by only about 1/3, while it

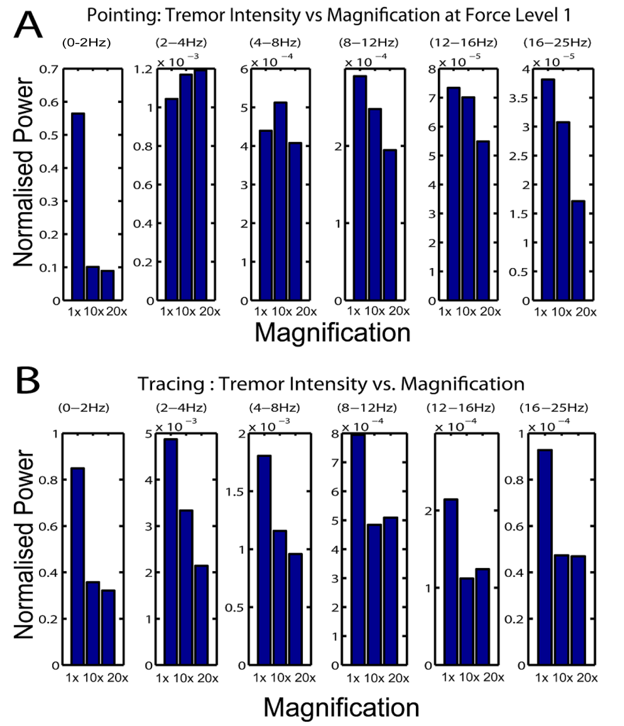

Fig. 5. Effect of magnification on tremor intensity at different frequency bands for the pointing task (A) and for the tracing task (B).

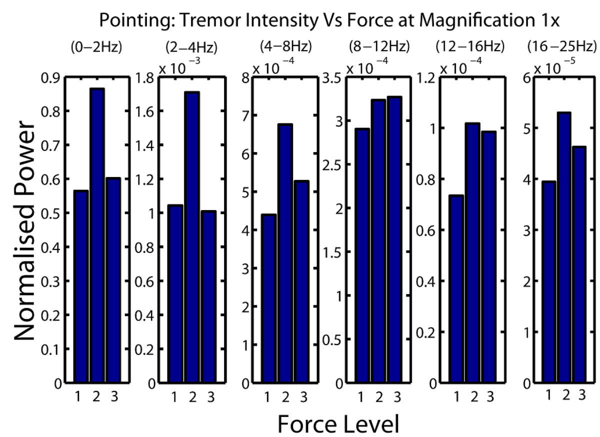

Fig. 6. Effect of grip force on tremor intensity during pointing at different frequency bands.

reduced by 2/3 in the pointing task. Similar to the pointing task, no significant difference of error was detected between 10x and 20x magnifications ($p>0.5$) in all groups.

For the tracing task, it was found that magnification does influence power to a certain extent until 8*Hz* (Fig. 5B). In the 0-2*Hz* band, total displacement power decreased with magnification 10x ($p<0.001$) but not between 10x and 20x ($p>0.6$), as was found in the pointing task. However, in both the 2-4*Hz* and 4-8*Hz* bands, there was a significant decrease between 1x and 20x ($p<0.01$) (but not between 1x and 10x). No significant difference was detected in the other frequency bands.

In both pointing and tracing tasks, no significant dif-

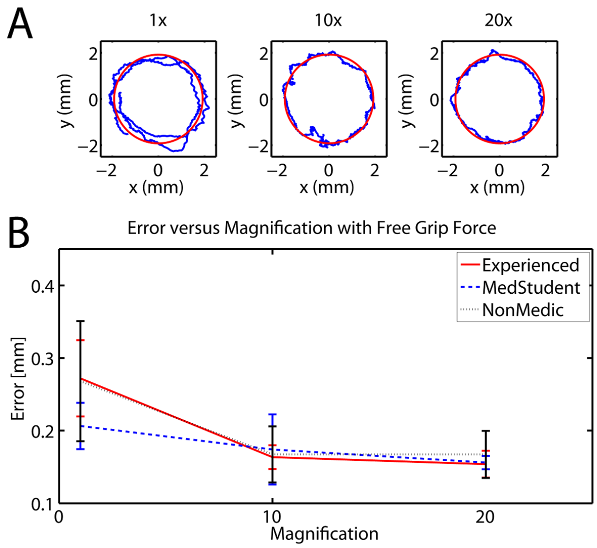

Fig. 7. Tracing error due to effect of magnification.

ferences in performance were detected among the groups, although the error was generally smaller for the surgeons and medical students than for the non-medical students (Fig. 3).

IV. DISCUSSION

No significant difference was detected in all conditions when comparing performances of experienced surgeons, medical students and subjects who are not medically trained. However, it is noteworthy that the mean error of the surgeons in most of the settings were lower than, if not closely similar to, the younger non-medical students' although age is expected to cause greater tremor in human hand [11], [12].

When comparing the two student groups of the same age range (21-26 years), the medical student group consistently outperformed the students who had no medical training, although this difference is not statistically significant. The surgeons and medical students may have compensated their natural physiological tremor with better motor control, breathing patterns and composure.

Magnification of the microscope was found to help in improving accuracy in both pointing and tracing tasks until 10x, confirming our previous study, but this time with a contact-free measurement system, and so without any impedance confound. However, increasing the magnification level beyond 10x does not help to further improve accuracy. As the complexity of the task increased from pointing to tracing, the positive effect of magnification becomes less apparent. Total power is similarly reduced until 10x magnification at low frequency region of 0-2Hz.

Grip force does not significantly affect accuracy. This may be due to the force range specified in the experiment as higher force beyond comfortable levels may play a role in influencing accuracy. However, without magnification, i.e. when visual feedback is shown to not affect accuracy [8], total power in the 0-2Hz region was affected by grip force, where it was highest at force level 2 (2.5-3.5N) compared to the 1-2N and 4-5N force levels. A similar effect was also found in time domain for most of the subjects.

This suggests an interesting non-monotonic effect of grip force on accuracy. It is usually believed that motor noise, thus inaccuracy, increases with the exerted force. While this holds true for one finger [13], the co-contraction of the opposing fingers and the resulting increase of impedance may reduce variability as in [14]. This interesting effect, which may have been masked in our previous study using a mechanical passive device for position measurement, deserves a further study.

V. ACKNOWLEDGMENTS

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