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The Role of Posture, Magnification, and Grip Force on Microscopic Accuracy

Basil Safwat,[1] Eileen L. M. Su,[1] Roger Gassert,[1] Chee Leong Teo,[2] and Etienne Burdet[1]

[1]Department of Bioengineering, Imperial College London, South Kensington Campus, SW7 2AZ London, UK; and [2]Department of Mechanical Engineering, National University of Singapore, 119260 Singapore, Singapore

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Abstract—While tremor has been studied extensively, the investigations thus far do not give detailed information on how the accuracy necessary for micromanipulations is affected while performing tasks in microsurgery and the life sciences. This paper systematically studies the effects of visual feedback, posture and grip force on the trial error and tremor intensity of subjects holding a forceps-like object to perform a pointing task. Results indicate that: (i) Arm support improves accuracy in tasks requiring fine manipulation and reduces tremor intensity in the 2–8 Hz region, but hand support does not provide the same effect; hence freedom of wrist movement can be retained without a significant increase in trial error. (ii) Magnification of up to ×10 is critical to carry out accurate micromanipulations, but beyond that level, magnification is not the most important factor. (iii) While an appropriate grip force must be learned in order to grasp micro-objects, such as a needle, without damaging them, the level of grip force applied does not affect the endpoint accuracy.

Keywords—Microscopy, Manipulation, Accuracy, Posture, Magnification, Grip force, Microsurgery.

INTRODUCTION

Microsurgery and Fine Motor Control

The execution of goal-directed movements by humans involves the combined use of several factors including visual input,[5,29] proprioceptive feedback,[9,29] and motor control strategies.[12] Some factors specifically affect the accuracy of fine motor tasks such as microsurgery or other manipulations carried out under the microscope (e.g., in the life sciences). Knowledge of how these limiting factors interact and to what extent they each affect overall performance will help suggest strategies on how to maximize performance in micromanipulation.

One factor, easily addressed, is the limit of human vision. Surgeons performing manipulations on small blood vessels or nerves will often use a microscope or other magnifying device in an attempt to increase accuracy.[10,22] Indeed, some of the objects operated on would be indistinguishable without magnification. The range of magnifications used begins at ×2.5 to ×8.0 (for surgical loupes) and increases to ×40 (for operating microscopes). Another simple method is to adopt a posture with appropriate support to increase control and accuracy.[1]

Other factors limiting the accuracy are less easy to address. These include tremor,[10] delays in sensory-motor pathways,[27] and inaccurate interpretations of sensory information.[30]

Physiological Tremor

Physiological tremor is the name given to the apparently involuntary, approximately rhythmical oscillations present in the motion of a limb. These oscillations result from both peripheral and central origins.[7] The frequency band of physiological tremor is often quoted as lying at 8–12 Hz, although this figure does not take into account the mechanical properties of the body part where the frequency is being measured, which may have an altering effect. Because of this, peaks are reported in the regions around 2–4, 8–12, 20–25 Hz, and occasionally 40 Hz.[13,28] Much previous work has centered on investigating the effect of peripheral loading on finger tremor; in these studies, the mechanics of a limb is changed (e.g., by the use of weights) and the effect of this change on the tremor and electromyographic (EMG) recordings is explored.[28] In the current study, the effect of posture, grip force and visual feedback on tremor recordings was investigated.

Address correspondence to Etienne Burdet, Department of Bioengineering, Imperial College London, South Kensington Campus, SW7 2AZ London, UK. Electronic mail: bsafwat@gmail.com, e.su06@imperial.ac.uk, gassertr@ethz.ch, e.burdet@imperial.ac.uk

The experiments were carried out at National University of Singapore and at Imperial College London.

Posture and Accuracy

During microsurgical training, importance is placed on correct posture.[1] Despite this, little work exists to quantify the effects of posture on tremor and accuracy. The relative tremor outputs of different limb segments in a pointing task has previously been investigated,[13] where it was found that the finger, forearm, and upper arm segments are more associated with a large power 8–12 Hz peak, while the hand is more associated with a large 2–4 Hz peak. While in that study the posture remained the same throughout, we have varied the posture while investigating the effect on tremor output at one segment (the fingers).

Visual Feedback and Accuracy

The effect of visual feedback on the accuracy of fine motor tasks was initially quantified by use of indirect methods. For example, to investigate a surgeon's accuracy when using loupes vs. when using microscopes, a comparison of the pregnancy rate was investigated following reversal of sterilization operations.[21] In another study, an assessment was made of hand function following nerve repair.[17] These studies concluded that magnification was not the most important factor in the success of the microsurgical operation. A more recent review into the merits of loupe vs. microscope microsurgery similarly concludes that ''loupe-aided microsurgery might represent a natural progression for the experienced microsurgeon. Microsurgical skills and experience outweigh the importance of the magnification factor''.[20] Not all research supports this view, however. A study quantitatively investigating precision of an orthosis task using ×3.5–4.0 loupe magnification and ×8–30 microscope magnification concluded that the mean accuracy was higher to a statistically significant degree in the group using the higher magnification microscopes.[22]

Other studies have investigated the effect of increased magnification on tremor intensity as well as on trial error. The results here are also conflicting to some degree. While some studies report a decrease in trial error and no change in tremor intensity,[3,31] other studies report an increase in both trial error and tremor intensity.[13,18] The reasons for these differences are unclear but the large differences in experimental design between studies may be a significant factor. Lubahn *et al.*[15] conclude with the assertion that ''for the neophyte microsurgeon… the conscious recognition of excess hand movement prompts escalation in its magnitude''. Although this statement is not further qualified, it offers a personal view of the effect of visual feedback on tremor by an experienced practitioner.

Grip Force

A certain amount of grip force is required in order to manipulate microscopic objects. For instance, to perform a suture, a microsurgeon must grasp the needle holder with a suitable level of grip force; beginners generally tend to employ too large a force, which will deform the needle. Physiological studies suggest that movement deviation generally increases with increasing force level.[11,14] However, in the case of micromanipulation, the grip force corresponds to the coactivation of the two opposing fingers, and in some cases of coactivation, it was shown that deviation may decrease.[2,4,24] It is therefore unclear how the grip force will affect pointing accuracy; this factor is investigated in the current study.

Tremor Assessment Methods

One reason why it was necessary to use indirect methods in early studies was because of the data capturing technologies available at the time. The first kinematic measurements of limb tremor were obtained using accelerometers[32] and this approach is still dominant when it comes to tremor physiology investigations. Accelerometers provide fine information about the signal spectrum but cannot give direct measures of position. The accelerometer has a low inertial component and a large frequency response[6] although gravitational effects are often hard to determine with only acceleration data.[25] More recently, alternative techniques have begun to appear. The first of these is the result of improvements in motion capture technology. Using optical sensors, relatively high resolution position data can be recorded and analyzed. The current study makes use of an alternative setup: a haptic interface with low apparent inertia and friction that can track motion and orientation of the stylus at high frequency and with high resolution (Fig. 1). One advantage of this system is that data-processing can be performed during the servo-loop of the device, before information is presented to the subject, allowing the feedback to be manipulated easily.

Current Study

This study investigates kinematic and static factors which may affect accuracy in a simple pointing task (Fig. 1). We first examine the effect of increasing magnification in such a task. Unlike previous studies investigating pointing or magnification,[13,31] we investigated a wider range of magnification factors (×1 to ×60) and designed an experiment closer to applied micromanipulation and microsurgery (Fig. 2b). We also investigated the effect of supporting successive

FIGURE 1. Experimental setup. The movement of the stylus measured by the PHANTOM desktop interface is displayed as a disc on the screen. The subjects must maintain this disc in a nominal position. In some trials the subject must additionally maintain the required grip force within a given range as measured by the force sensor.

limb segments against gravity (Fig. 2a), and the effect of using a specific grip force (Fig. 2c) on accuracy and tremor intensity in a pointing task.

METHODS

Materials

The position recording device used in this investigation was the PHANTOM Desktop haptic interface (SensAble Technologies, Inc., Woburn, MA, USA, Fig. 1)—a device consisting of a stylus attached to a number of low inertia, low friction rotators that allow stylus movement in six degrees-of-freedom.[16] This system provides detection of stylus position at 1000 Hz, and has a nominal position resolution of 1100 dpi or approximately 0.023 mm. The position of the stylus in the vertical plane was detected by the PHANTOM interface and was displayed on a monitor. The default factor between the displacement of the manipulandum and on-screen movement was calculated as 62.5. This factor was used to calibrate the magnification factors for the following investigations.

The FSG15N1A force sensor manufactured by Honeywell Inc., USA was used in the experiment. This sensor can measure force up to 15 N. The sensor output voltage is ratiometric to the supply voltage. Using a 12 V supply voltage, an NI-PCI 6024E data acquisition card with 12-bit resolution and some

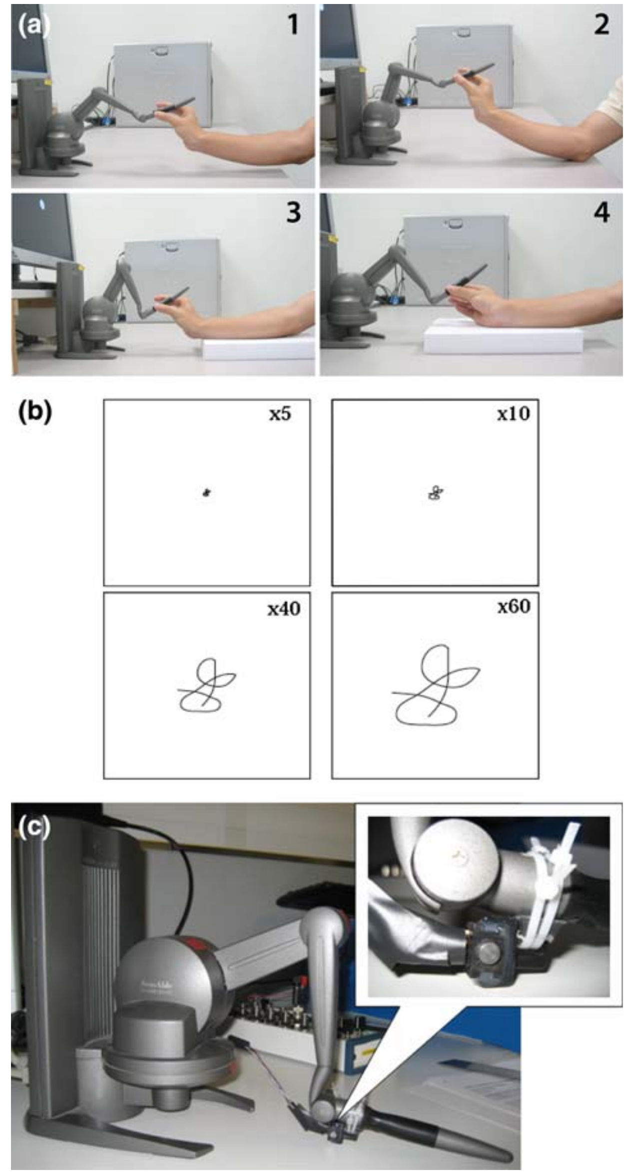

FIGURE 2. Experimental conditions. Four different postures were first examined (a), then magnifications up to $\times 60$ (b). The influence of grip force was also investigated using a force sensor attached to the PHANTOM stylus (c).

precision weights, calibration was carried out to determine the relationship between the measured output voltage and the applied force. The force sensor was affixed to a mounting bracket using Araldite, and the pair was then fixed to the stylus near the rotating joint, as shown in Fig. 2c.

Experimental Protocol

The subjects, all males between 20 and 30 years old with normal visual acuity with or without glasses, gave their informed consent prior to performing the experiment. Five subjects performed the posture and grip force experiments, and another four subjects performed the magnification experiment. Each subject was to sit comfortably, hold the stylus of the PHANTOM interface and control it using the visual feedback of its position as displayed on screen which was placed 70 cm from the edge of the table (Fig. 1). Two discs of equal diameter were displayed on screen against a black background. A green disc corresponded to the position of the stylus and a red disc in the center of the display, the target (Fig. 1).

The task was to maintain the cursor spot on the target spot or as close to it as possible during a 30 second trial. Position data (x; y) relative to the target spot was collected by the PHANTOM at its default sampling rate of 1 kHz and saved as a tab-delimited text file. The (x; y) plane was defined as the axes of the vertical plane, that is, the same as the plane of the screen. Note that magnifications larger than $\times 60$ would cause normal movement of the hand to move the cursor out of the screen boundaries, and that $\times 60$ is also larger than the upper limit of magnification commonly used during microsurgery.

Posture Test

Each session consisted of four trials of 30 s duration each. In each trial, the subject was asked to adopt a different posture while carrying out the pointing task with cursor and target discs of 25 mm diameters. Each posture successively supported more of the arm and hand against gravity. The four postures used were (Fig. 2a):

- i. Arm held above the table at a height of 5–10 cm.
- ii. Elbow resting on the table.
- iii. Forearm resting on the table (up to but not including wrist).
- iv. Side of the hand resting on the table (side opposite to thumb).

The stylus was held between the index finger and thumb only; care was taken to ensure no other fingers were touching or otherwise supporting the grip as this would result in mechanical damping of the tremor. Asking subjects to adopt this grip also helped minimize grip differences between trials. While the exact height of the arm above the table in posture 1 was not crucial, it was important that the position was comfortable and that the arm received no support from the table for the length of the trial. To achieve posture 3 (forearm resting on table, up to but not including wrist), the arm was placed on a slightly raised platform such that the hand was free to rotate about the wrist.

Before each posture test, the subject would adopt the relevant posture comfortably and the height of the PHANTOM would then be adjusted to bring the target spot to a natural position for the subject. If necessary, the position of the target spot could also be further adjusted using the keyboard; the software would then reset its reference point (0; 0) to this position.

To begin the trial, the subject would adopt the relevant posture, move the cursor to the target and indicate when he or she was ready. The experimenter would then begin the test with a key press, at which point data would begin being collected from the PHANTOM. After 30 s, data collection would automatically stop and the target spot would move down a short distance to indicate that the trial was complete. Six sessions of each of the four postures were carried out over the course of 2 days (three sessions per day, 5 min break between sessions). Of the five subjects, three carried out the four postures in order (posture 1 to posture 4) and two carried out the tests in reverse order, to check for any learning effects.

Magnification Test

While preliminary tests showed that the size of cursor and target discs did not influence accuracy, a smaller diameter of circle was used in this experiment to place the visual emphasis of the task on accuracy. Subjects were asked to maintain the cursor on top of the target spot as before. The variable being altered this time was the on-screen magnification of the stylus movement.

Eight different conditions were investigated: seven magnifications $\{\times 1, \times 5, \times 10, \times 15, \times 20, \times 40$, and $\times 60\}$ and a 'blind' case with no visual feedback. For the seven magnification conditions, subjects would adopt posture 3 (for reasons of comfort and movement freedom, see section "Results" for further discussion of this) and the test would begin on the subject's command as in the posture test above. Larger magnifications would produce a greater on-screen displacement of the cursor from the same stylus movement (Fig. 2b). The 'blind' condition was identical (subjects would line up the cursor on the target spot) but on pressing the key to begin the test, the screen would be blanked for the duration of the trial; subjects were asked to keep their hand as steady as possible, and look at the screen and not at their hand.

These eight conditions were repeated six times for the four subjects. Two subjects carried out the test in increasing order of magnification, and two in decreasing order to examine for any learning effects.

Grip Force Test

In this test, the grip force applied by the subjects during trials was measured and compared against position data. The subjects were asked to maintain a fixed cursor position while applying a grip force within one of the following ranges: 1.0–2.0, 2.5–3.5, 4.0–5.0 N. To achieve this, subjects were asked to grasp the force sensor between index finger and thumb while pressing it to produce the required force. The grip force was fed back to the subject through the cursor's color: green indicating a force within the correct range, red for too small a force and blue for too large a force.

To perform the test, subject would adopt the comfortable posture 3 of previous experiment, in which the forearm leans on the table, and would apply appropriate pressure to the sensor to keep the cursor green. Note that this is the posture resulting in most accurate pointing, with more freedom of movement, based on results from the posture test (see section "Results"). When the subject was ready, the experimenter would start the trial and positional data relative to the target spot would be recorded. After a period of 30 s, data collection would automatically stop, with a buzzer indicating that the test was complete. Each subject underwent two trials at each force level. Position data relative to the target spot and grip force exerted by the user were collected at a rate of 1000 Hz.

Five subjects participated in this experiment, each starting with the free grip force condition. Three of the subjects had force conditions in increasing order of magnitude and the other two in descending order to examine possible effects of learning or fatigue.

Data Analysis

The recorded position data (x and y deviations from the target) was used to compute two measures, trial error and tremor intensity. Data processing and statistical analysis routines were written using MATLAB software (The MathWorks, Natick, MA, USA).

Trial Error

Trial error measures the overall accuracy of the subject in attempting to maintain a constant position on the target point. This was computed relative to the initial position:

$$r(t) = \sqrt{x(t)^2 + y(t)^2} \quad (1)$$

The mean displacement from the target spot was calculated from the six trials for each subject. To allow the subjects' data to be grouped together, each set of data was normalized. The normalization process is described below in detail for the posture test results.

i. Each set of trials consisted of four posture conditions. This set of four trials was repeated six times for each subject.
ii. The mean displacement of each of the four trials in a set was calculated for each subject.
iii. All the means in a particular set were divided by the largest of these means (the maximum mean). This is the normalization step.
iv. Now the five subjects' normalized means for each condition could be grouped, by condition, to produce a set of five values for one condition.
v. The means and standard deviations of these five means were then calculated to give the final results.

In this way, subject data could be grouped in spite of any subject differences. The magnification test results were normalized in the same way, but with seven conditions (the seven magnifications) per set of trials instead of four.

In addition to calculating the mean and standard deviation of the normalized means as described above, the mean and standard deviation of three further measures were calculated. These were the normalized medians, normalized standard deviations, and normalized maxima. Comparing the mean with the median would reveal if the mean had been skewed by a small number of very large values (e.g., a large accidental deviation in one trial) as the median would not be affected by this event in the same way. The standard deviation was also calculated. Some previous work[3] has shown that some subjects tend to maintain a position slightly above or below a target on pointing tasks—the standard deviation in this case would measure the deviation around this selected mean. The maxima were calculated to investigate any pattern of large displacements across the trials. As similar results were obtained with these four measures only the mean and standard deviation are analyzed in this paper. Complete results can be found in Safwat.[23]

Removing Drift in 'Blind' Comparison

A comparison between the condition without visual feedback and $\times 1$ magnification was carried out. The results were grouped by normalizing across the two conditions in the manner displayed above, but the data was first processed to remove the very low frequency drift resulting from not being able to see the cursor. To do this we used a high-pass filter on both the 'blind' and $\times 1$ conditions (Fig. 3). To select the minimum cut-off frequency required, a simple program was written that filtered the data and iterated the cut-off frequency until a requested mean value for the drift was reached. This method allowed us to select the lowest possible cut-off frequency required so that the data would be unchanged as much as possible.

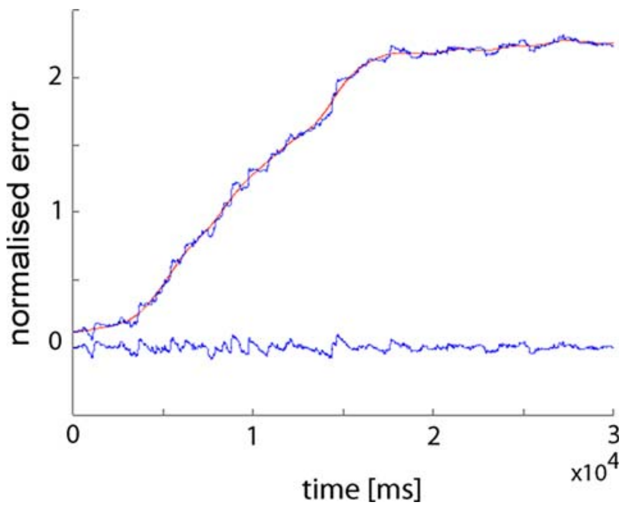

FIGURE 3. Effect of high-pass filtering on raw data. The original data is the jagged line, drifting away from zero. The smooth line laid over this is a low-pass filtered version of the data; note the tight fit of this curve with the original data. The jagged line along the *x*-axis is the high-pass filtered data; the very low frequency drift (<0.27 Hz) has been removed while retaining the higher frequency movement.

Tremor Intensity

Tremor intensity is a measure describing the physiological tremor that exists in a set of raw data. The intensity and characteristics of physiological tremor are traditionally described by its frequency.[7,8] Frequency analysis of the data was calculated in four bandwidths, 2–4 Hz, 4–8 Hz, 8–12 Hz and 12–25 Hz. The two major frequencies revealed by previous analyses of physiological tremor are found in the 2–4 and 8–12 Hz regions. The 4–8 Hz region was also investigated to verify that no significant change in frequency characteristics occurs here. The 12–25 Hz bandwidth would reveal any high-frequency dependence on the conditions being investigated.

A number of measures have been employed to investigate tremor intensity and its components. In this study we looked at the effect of the conditions on the proportional power of the four bandwidths. To do this, the raw displacement data was converted to the frequency domain using a Fourier transform to obtain the power spectrum. The spectrum was integrated over the bandwidth being investigated to provide power associated with this region. Each subject's power spectra was normalized with his or her own maximum total power to determine the influence on power in relation to the factors being investigated.

Subject Differences and Learning Effects

There were considerable differences between the performance of different subjects. The data for each subject was normalized as described above; the normalization factors used give an indication of the relative trial error associated with each subject. The range of normalization factors in the magnification test is 0.106; the range is larger in the posture test, at 0.171.

We examined the effects of learning or fatigue by comparing the results of the subjects who had carried out the posture, magnification and force tests in increasing order of magnitude with those who had carried out the tests in reverse order. No significant differences in the slopes of these comparisons were found, and we therefore proceeded to use the combined, normalized data in the manner described above.

Statistical Treatment

The significance of differences observed between conditions was assessed using Student's *t*-test for paired data at 5% significance level. The *p*-values reported as a result of the *t*-tests were adjusted using the Bonferroni correction based on the number of comparisons carried out. For examining the influence of posture, comparisons were carried out between postures 1–2, 2–3, and 3–4 because we can expect a monotonic (decreasing) error. Similarly, for the influence of magnification, only consecutive magnification factors were tested.

RESULTS

Influence of Posture

Overall, the increase in support against gravity and movement provided by successive postures resulted in a reduction in the trial error (excursion of the cursor from the central target). This effect is illustrated in the plots in Fig. 4; the measures of posture 1 are shown to be around three times larger than those for postures 3 and 4. The difference in trial error was highly significant ($p < 0.001$, Bonferroni correction) between postures 1 and 2 but less significant between 2 and 3 ($p < 0.02$) and between postures 3 and 4, a non-significant reduction in trial error was observed ($p > 0.5$).

The frequency analysis was carried out as described in the section "Tremor Intensity". The results of the frequency analysis showed a similar pattern of change to the trial errors with the proportional power of the 2–4 and 4–8 Hz peak decreasing significantly ($p < 0.05$) with successive support, except between postures 3 and 4 (as before), where a small non-significant decrease was observed. The subsequent bands of 8–12 Hz, and 12–25 Hz revealed no significance between any pairwise comparisons ($p > 0.05$).

Influence of Magnification

Eight conditions were tested to investigate the effects of magnification on trial error and tremor intensity. Recording showing deviations at various

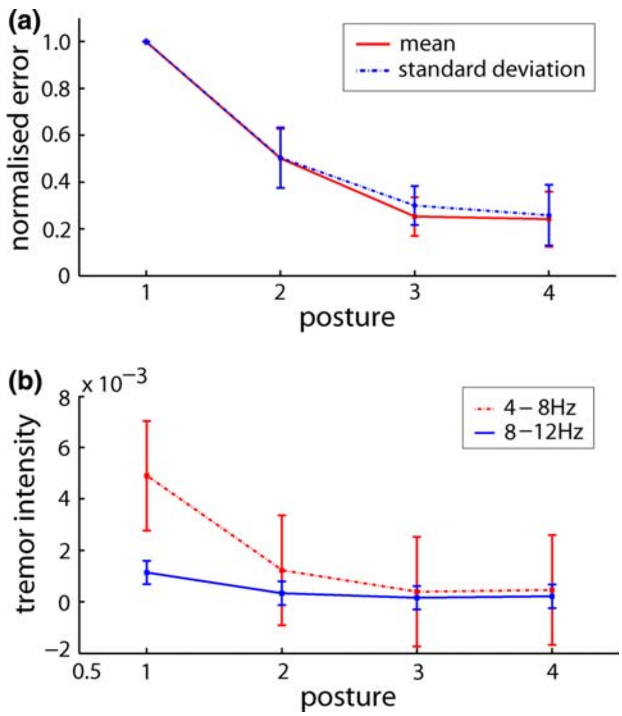

FIGURE 4. Influence of postures 1–4 described in Fig. 2a on accuracy and tremor. Shown are the mean and standard deviation of error (a), as well as the integral of power spectrum in the 4–8 and 8–12 Hz bands (b).

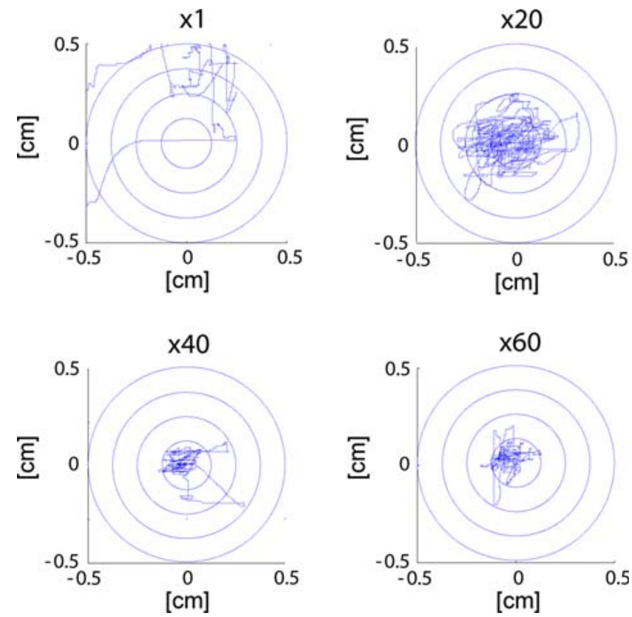

FIGURE 5. An example path of the stylus at various magnifications by a typical subject.

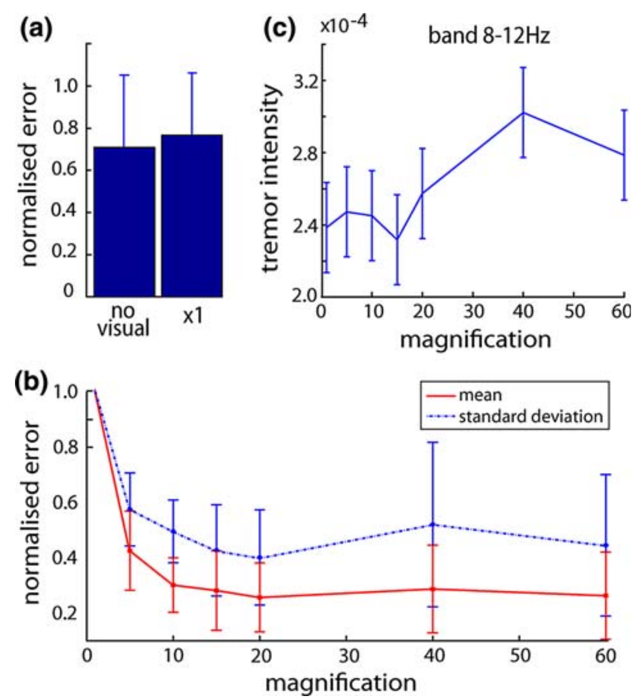

FIGURE 6. Mean position error (over the subjects) at various magnifications (±standard deviation). (a) Comparison of error in the 'blind' and ×1 magnification conditions. (b) Analysis of how the error depends on magnification. (c) Proportional power for 8–12 Hz bandwidth for increasing magnification (×1, ×20, ×40, ×60).

magnifications are shown in Fig. 5. Findings from experimental data suggest that magnification helps in reducing the error, but that the trend is not so clear for a magnification larger than ×10.

The first condition was a test with no visual feedback, which, when compared with the magnification condition, would suggest whether the presence of visual feedback itself had an effect on tremor. As described in the section ''Magnification Test'', when comparing these two conditions, data was highpass filtered to remove the very low frequency drift associated with the trials. Figure 6a shows the deviation for the 'blind' condition as compared with the ×1 condition. While the measure is slightly smaller in the blind condition, this difference is not significant ($p > 0.808$).

As expected, increasing the magnification from ×1 to ×5 decreased the error significantly ($p < 0.001$) (Fig. 6b). Similarly, a magnification of ×10 resulted in less error than ×5 ($p < 0.001$). However, further increasing the magnification past ×10 had no significant effect on pointing accuracy ($p > 0.7$ in all cases). Similar effects were found for the standard deviation (Fig. 6b).

No significant change was detected in any of the frequency regions 2–4, 4–8, 8–12 Hz (Fig. 6c) or 12–25 Hz. In the 0–2 Hz region, there was a significant decrease ($p < 0.001$) with increasing magnification until ×5 as described above, suggesting that the improvement of accuracy was due to this frequency range.

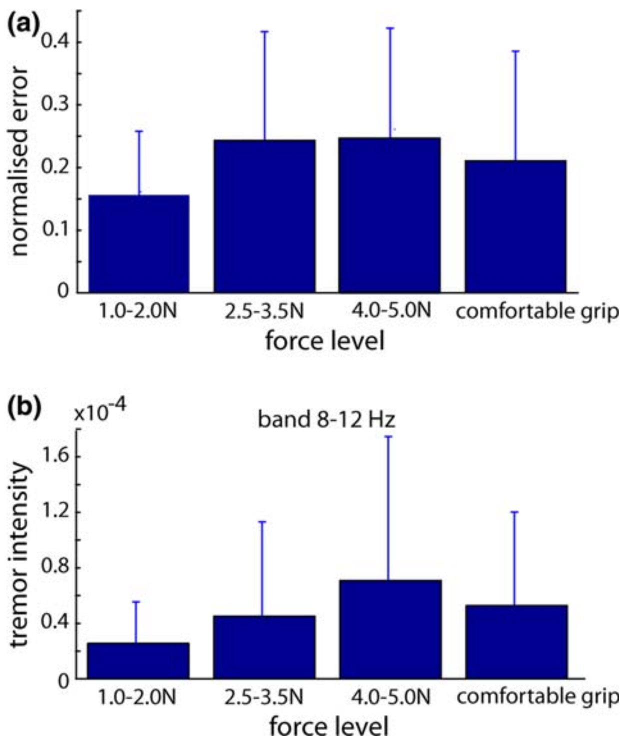

FIGURE 7. Effect of grip force on targeting error and tremor amplitude (±standard deviation). (a) Error vs. force at magnification ×10. (b) Illustrates the proportional power for 8–12 Hz bandwidth for different levels of grip force (1.0–2.0, 2.5–3.5, 4.0–5.0 N and subject's own comfortable grip).

Influence of Grip Force

The results from the grip force test showed that the grip force had no significant effect on trial error or tremor intensity (Fig. 7). The trial error was not significantly different at any force level ($p > 0.500$). Analysing tremor intensity for different force levels in the 0–2, 2–4, 4–8, 8–12, and 12–25 Hz frequency bands revealed no significant differences ($p > 0.412$).

DISCUSSION

In this investigation, we studied the effects of posture, magnification and grip force on performance in a stationary pointing task.

Posture

Increased support of arm segments against gravity and movement resulted in significant reduction in trial error. The greatest improvement was seen between postures 1 and 2, which brought the elbow into contact with the table. The change seen between postures 2 and 3 (supporting the forearm up to the wrist) was also significant. These results support previous investigations into the contributions of limb segments to arm tremor.[19] The number of limb segments used directly corresponds to the resulting levels of tremor and trial error.

An interesting result to note is the lack of significance between trial errors in postures 3 (arm supported up to wrist: wrist free to move) and 4 (wrist and side of hand in contact with the table). Although an additional limb segment has been stabilized (the wrist), this does not result in a statistically significant decrease in trial error. This result is interesting for a number of reasons. Previous studies have shown that successive limb segments introduce their own contributions to tremor.[19] As these segments are supported, the amplitude of the tremor decreases. That the freedom of the wrist is not a major factor in tremor amplitude is of interest in terms of microsurgery and any other tasks requiring fine motor control. Freedom of wrist movement may afford the operator advantages in comfort, and extends movement range.

The results of the frequency analysis revealed a similar pattern of change to the tremor amplitude for the different postures. There were significant differences between postures 1–2 and 2–3, but not between 3–4. The decrease in tremor intensity corresponds with previous work that has investigated multi-segment tremor, and suggests that each limb segment contributes a level of tremor of its own.

Magnification

Magnification significantly improved performance for this task. Comparisons between no magnification (×1) and subsequent magnifications showed significant improvement. This improvement was also apparent when comparing ×5 magnification with ×10 and higher magnifications. In previous studies, the poor performance at the ×1 level has been partly attributed to problems with screen resolution, where it has been correctly stated that with no magnification, the smallest movement registered on screen would be half of the effective resolution per line of the display.[31]

The display used in this experiment was of a higher resolution than that used in the previous study (L1825 Flat Panel Monitor, Hewlett-Packard Company, Palo Alto, CA) with a pixel pitch of 0.281 mm (compared with 0.356 mm), and a minimum movement detection of 0.141 mm (compared with 0.178 mm). The previous study concludes that while this low resolution "undoubtedly interfered with the subject's ability to resolve position errors at magnification ×1…all subjects except Subject 10 had trial errors of a magnitude greater than 0.18 mm. The visual feedback at ×1, therefore, did impart the inaccuracy of their positions".

To investigate this further, we included a 'blind' trial in our tests. This was identical to the other trials in the magnification test except that the visual feedback was present before the trial so that the subject could line up the cursor and target, and then was removed for the duration of the trial. The results of this test showed that when the very low-frequency drift at 0.27 Hz was removed from the results using a 2nd order Butterworth filter (section ''Data Analysis''), the blind trials were statistically indistinguishable from the ×1 magnification condition. This suggests that a baseline error exists, independent of visual feedback, and that this error is, as suspected, larger than the resolution limit of the apparatus used.

With further magnification past ×5, trial error flattens off; subsequent increase in magnification does not result in improved accuracy, including up to ×60 magnification, past the limit of previous investigations.[13,31] This supports the work of Vasilakos *et al.*[31] and McManamny[17] who conclude that magnification level is not the key factor in carrying out successful microsurgical procedures. It is also interesting to note that these results disagree with the work of Keogh *et al.*,[13] in which it is suggested that the use of magnification increases RMS error in pointing tasks. The Vasilakos study reports a plateau in improvement as occurring at ×4 magnification. Despite the differences in experimental design and procedure (accelerometer and laser vs. stylus and haptic device), the current result of a plateau on the error curve beyond ×5 magnification corresponds very well with the previous result, and suggests strongly that a level of magnification between ×5 and ×10 provides the maximum amount of useful visual information for carrying out micromanipulations.

Our results showed that tremor intensity remained constant with increasing levels of magnification across all frequency bands being investigated: these results are consistent with those of Vasilakos *et al.*[31] and earlier work by Stephens and Taylor[26] (1974, referenced from[31]) who find no change in tremor intensity as a function of magnification. While the results are consistent with these studies, it is instructive to note the main differences in the setup of these investigations, which relate to position; the current investigation uses a stylus gripped between thumb and index finger, with the hand free to rotate about the wrist, while the previous investigation uses a laser placed on a flat surface attached to the index finger, with the hand and index finger immobilized in a brace up to the metacarpophalangeal joint. The use of the stylus in our study brings the nature of the task closer to that of a microsurgical one, where a surgeon must manipulate objects of a significant mass. Therefore, we submit that the experiment provides a more relevant model of accuracy during microsurgical tasks than studies that investigate isolated finger movement.

The results indicate that visual control does not have an effect on tremor. This is suggested by the insignificant change in error in the ×1 trial relative to the blind trial and the constancy of tremor intensity in all investigated frequency bands with increasing magnification. These results suggest that the physiological tremor observed in normal subjects is not negatively affected by attempts at visually controlling the precision.

Grip Force

The control of finger forces is critical to accurate tool use and skillful manipulation. As motor noise generally increases with muscle activation,[11,14] one could expect the position deviation to increase with grip force level. At the same time the position of the grip, with the opposing fingers acting as two parallel elastic actuators, should increase impedance, which may attenuate noise.[4,24] Our results suggest that neither of these effects dominate, and that the microscopic deviation is not affected by the grip force level.

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