Factors of Micromanipulation

Accuracy and Learning

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Declaration

I herewith certify that all material in this dissertation which is not my own work has been properly acknowledged.

Eileen Su Lee Ming
Abstract

Micromanipulation refers to the manipulation under a microscope in order to perform delicate procedures. It is difficult for humans to manipulate objects accurately under a microscope due to tremor and imperfect perception, limiting performance. This project seeks to understand factors affecting accuracy in micromanipulation, and to propose strategies for learning improving accuracy.

Psychomotor experiments were conducted using computer-controlled setups to determine how various feedback modalities and learning methods can influence micromanipulation performance. In a first experiment, static and motion accuracy of surgeons, medical students and non-medical students under different magnification levels and grip force settings were compared. A second experiment investigated whether the non-dominant hand placed close to the target can contribute to accurate pointing of the dominant hand. A third experiment tested a training strategy for micromanipulation using unstable dynamics to magnify motion error, a strategy shown to be decreasing deviation in large arm movements. Two virtual reality (VR) modules were then developed to train needle grasping and needle insertion tasks, two primitive tasks in a microsurgery suturing procedure. The modules provided the trainee with a visual display in stereoscopic view and information on their grip, tool position and angles. Using the VR module, a study examining effects of visual cues was conducted to train tool orientation. Results from these studies suggested that it is possible to learn and improve accuracy in micromanipulation using appropriate sensorimotor feedback and training.
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1 Introduction

1.1 Background

Micromanipulation refers to action performed on small objects under visual amplification of the microscope (The American Heritage Dictionary, 2007), for example suturing during microsurgery, biological cell injection and attaching test probes onto small or medium scale integrated circuits for microelectronics industry. In many cases, the microassembly task is performed by humans using tweezers and microscopes or high precision pick-and-place robots. However, humans are still preferred over automated systems to perform these tasks because of their high flexibility, their superior sensory motor capabilities, and unique nature of tasks. In microsurgery, the human surgeons play a crucial role because their medical knowledge, decision-making capability and adaptation in a dynamic environment cannot be substituted.

As human interaction is required in many micromanipulation tasks, human factors would directly affect the outcome of the task. It requires years of practice to perform difficult procedure and increase accuracy because it is difficult for humans to manipulate objects accurately under a microscope. During the task, the operator manipulate objects indirectly using micro-tools, and could not feel or hear the tool interact with its target, therefore must rely on visual feedback to control their fingers (Wang et al., 2004). The visual perception through the the microscope is difficult because of image scaling, reorientation and reduced depth relative to usual vision, requiring adaption and calibration of visuo-motor coordination. In addition, identification of features and their location is difficult due to the narrow field of view, shallow depth of field, occlusion and poor
contrast. It is crucial to learn how to make full use of available sensory cues to optimize micromanipulation performance. Therefore an operator requires significant learning and practice to acquire sufficient technical and psychomotor skill for the task.

Conventional micromanipulation training would have an operator learn a specific skill through repetitive practice in order to perfect their technique. One example is in microsurgery training where microsurgeons trained through hands-on workshops which are normally conducted for a stretch of between two to five days (Power and Tan, 2007; Abreo and Sivathasan, 2009). These workshops mainly focus on highly specific surgical techniques and place little emphasis on micromanipulation accuracy. Movement inaccuracies can occur during micro-movement due to tremor, inaccurate interpretations of feedbacks (van Beers et al., 2002) or delays in sensory-motor pathways (Harwell and Ferguson, 1983; Tass et al., 1995). New methods for precise control during micromanipulation and to minimize inaccuracies must be identified to improve micromanipulation outcome.

There is much on-going research in the development of assistive tools for micromanipulation (Ward et al., 1998; Jensen et al., 1997; Taylor, 1999; Schenker et al., 1995; Fatikow, 1998; Riviere and Khosla, 2003; Win et al., 2009), illustrating the importance of improving precision in micromanipulation. Improving accuracy in micromanipulation requires a thorough investigation of human factors, and may be in part be performed by suitable training. While various strategies and learning methods have been proposed and tested for motor skill acquisition in the macro-domain, little is known about learning in the micro-domain.

Advancement in computing capability and hardware precision has enabled the creation of virtual reality (VR) environments to test ideas in micromanipulation quickly, cheaply and with high degree of flexibility. Commonly, user will have multi-sensory feedback to enhance realism in particular visual, audio and haptic feedbacks. To develop a real environment for training consumes more time and material, not to mention, it will be challenging to isolate parameters for testing. Using VR, countless environments can be developed using the same hardware
setup. In this project, the concept of VR is fully utilized in the development of several virtual reality experiment modules to investigate issues related to micromanipulation accuracy.

1.2 Objective and Approach

The main objective of this project is to evaluate how micromanipulation performance can be influenced by various factors and to propose ways to help people improve it. Psychophysical experiments were conducted for this purpose using computer-controlled environments. In addition, two VR based modules were developed to train typical tasks of microsurgery. Experiment was conducted with naive subjects using the training modules to determine the effect of providing visual cues for training.

Micromanipulation Accuracy in Pointing and Tracing

During a micromanipulation procedure, the human operator has visual feedback of his or her workspace and tactile sensation of the tool between the grip. It would be interesting to examine how visual magnification and grip force, which the operator has control over, could each influence movement.

The first experiment was designed to investigate the effect of magnification and grip force during a static pointing task and a dynamic tracing task, two primitive tasks in micromanipulation. Different visual magnification and grip force levels were used during the task. By recruiting different subject populations, the study also examined how expertise influenced performance.

Role of Bimanual Coordination in Accuracy

The use of both hands is often required during micromanipulation, for example in microsurgical procedures. A bimanual task is more attention demanding and may thus be performed less accurately and consistently than a similar unimanual task. Conversely, the proprioceptive information from one hand may be used to position the second hand more accurately.
The second experiment quantified the difference between bimanual strategy compared to unimanual in a target-reaching movement within a small workspace. Subjects were asked to perform reaching tasks under both bimanual and unimanual conditions with full visual information of the workspace and additionally, when the start point of their movement was not visible. This emulates the scenario when the human operators have to move their hand out of the viewing region and bring it back to continue the task at hand.

**Learning of Unstable Dynamics in Micromotion**

While many learning methods have been tested and proven to be effective for macro-movements (Balasaheb et al., 2008; Ford et al., 2009; Shadmehr and Thoroughman, 1997; Burdet et al., 2001; Franklin et al., 2007), their application to the micro-domain have not been studied yet. Some motor skill acquisition theories formulated for domains such as athletics and psychology have been proposed for surgical skill acquisition, e.g. distributed learning (Moulton et al., 2006), motor imagery (Hall, 2002; Sanders et al., 2008), apprenticeship and explicit demonstrations (Kirk, 2006), but the focus was on techniques rather than motor performance such as accuracy.

The third experiment investigated learning using unstable dynamics in the form of a divergent force field to enhance movement accuracy in micromanipulation. Similar experiments had been conducted by various groups for macro-scale arm movement and had shown promising results (Burdet et al., 2001; Franklin et al., 2007). This study examined if similar decrease in deviations from a target trajectory can be observed in the micro-environment and the potential of using force as a learning cue. Performance of subjects who trained with haptic amplification were compared to another group that was given repetitive null-field training.
Virtual reality modules for microsurgery training

In recent years, much interest has been shown in computer-based training modules for surgery (McCloy and Stone, 2001; Seymour et al., 2002; Wang et al., 2006; Verma et al., 2003; Eversbusch and Grantcharov, 2004). Computer-based systems could allow reliable and systematic assessment and feedback while giving trainee the option of distributed learning without relying on the presence of an instructor, stopping and repeating the activity as often as required. Simulator-based training could reduce the usage of animal cadavers for testing, which are under stringent control. For faster and better learning, a complex task could be learned in basic steps rather than all at once (Frederiksen and White, 1989; Fabiani et al., 1989). In virtual reality based training, this can be easily achieved by designing modules to practise on sub-tasks before combining them to learn a complex skill.

In this project, two modules were developed to train needle grasping and needle insertion for a suturing task, as part of training for microsurgery. The modules calculated parameters such as grip position and insertion angles to let trainees know how they perform during a task. Using the training module, an experiment was conducted to determine the influence of visual cues during training.

1.3 Thesis Outline

Chapter 2 describes micromanipulation accuracy in pointing and in tracing a circle when visual magnification and grip force were varied.

Chapter 3 investigates the contribution of second hand in a bimanual micromanipulation task compared to a unimanual task.

Chapter 4 examines how training in an unstable dynamics environment could help in improving micromanipulation performance as compared to repetitive training.

Chapter 5 presents the computer-based training modules for needle grasping and needle insertion, part of a training simulator for microsurgery. The results
of an experiment using visual cues for training are also presented.

Chapter 6 analyzes the contributions of this thesis, the limitations and future work arising as a continuation to this study.
2 Micromanipulation Accuracy in Pointing and Tracing

2.1 Introduction

In critical domains of micromanipulation, such as microsurgery, inaccuracy can be detrimental. A low-quality hand-sewn anastomosis and inaccurately placed suture would contribute to lower patency rate and vascular failure (Holm et al., 2009). In bio-manipulation of tissue cells currently performed by highly-skilled operators, the success rate is not very high and a tiny error will damage the fragile cell (Zhang et al., 2008; Kapoor et al., 2003).

Many factors work together to influence the accuracy in micromanipulation and among them are human vision, skill level (Keogh, 2005), tremor (Harwell and Ferguson, 1983), delays (Tass et al., 1995) and noise in sensory motor commands (van Beers et al., 2002). Understanding how the factors interact and how they affect performance will help in identifying ways to optimize micromanipulation outcome. One of the main factors that directly causes inaccuracy is hand tremor. Physiological tremor is the inherent rhythmic small movements which exists naturally due to interactions from both mechanical and neural origins (Elble and Koller, 1990). Deviation caused by tremor would have large implications on objects in the micro-world. Tremor can increase or decrease based on loading on the finger (Vaillancourt and Newell, 2000), but it was not clear how exertion of finger forces would influence tremor. A certain amount of grip force is certainly required in order to hold microscopic objects and this force is dependent on object properties and task constraints such as mass, size, and texture (West-
ling and Johansson, 1984; Voelcker-Rehage and Alberts, 2005). For instance, during suturing, a microsurgeon must grasp the needle holder with a suitable level of grip force. Beginners generally tend to exert too much force, which will deform the needle and tire the hand unnecessarily. Physiological studies suggest that movement deviation generally increases with increasing force level. This was proven in the study of Sutton and Sykes (1967) when measuring force used to press a button, error power spectra increased linearly with force. However, Harwell and Ferguson (1983) did not find a relation of tremor with muscle tension in an experiment where subjects were asked to grip a wire. In the case of micromanipulation, the grip force corresponds to the co-activation of two opposing fingers and in more recent studies examining co-activation of muscles, it was shown that co-activation acted as a low-pass filter between force fluctuations and movement kinematics (Selen et al., 2005). Therefore it is unclear how the grip force will affect pointing accuracy; a factor which will be investigated in the current study.

Human vision also affects accuracy to a large extent. To improve accuracy, surgeons use microscopes and loupes to magnify visual feedback while suturing on small blood vessels and nerves (Harwell and Ferguson, 1983; Rooks et al., 1993). However, magnification from visual feedback amplifies perception of hand tremor. While surgeons could try to reduce their hand deviations with magnification, perceiving tremor which was amplified visually may also escalate their error instead of helping to reduce it (Lubahn et al., 2002; Harwell and Ferguson, 1983). In periodontal dentistry, there are some who still do not use magnification because of the believe that normal vision is sufficient to deal with dentistry work (Shanelec, 2003). Choosing between the loupes with lower magnification and microscope that offers possibility of higher magnification but less freedom-of-use, some surgeons advocated the use of loupes because of the low cost and convenience of changing vantage point without restrictions (Ross et al., 2003; Pieptu and Luchian, 2003). Based on their research on previous surgeries conducted with the loupes or microscopes, the loupe-surgery did not fare worse than
microscope-surgery. However, the lower magnification offered by the loupe, between 2x - 6x, might have affected the accuracy somewhat. In fact, Rooks et al. (1993) found performance to be slightly worse with the loupe based on edge of suture placement which was smaller with the microscope to a statistically significant degree although distance between suture placements was not different. This study attempts to identify how and which level of magnification would influence accuracy so that an optimum level can be selected for micromanipulation tasks.

Accuracy has been measured in many different ways depending on the data capturing technology available. In earlier studies, indirect means were used, for example, pregnancy rate was used as a measure of accuracy in sterilization reversal procedures. Accelerometers enabled the measurement of limb tremor (Wyatt, 1968; Hömberg et al., 1987; Morrison and Newell, 1996; Halliday et al., 1999; Vaillancourt and Newell, 2000), 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 (Pellegrini et al., 2004). Motion tracking devices such as mechanical structures with encoders now allow direct recording of position data at high a sampling rate, enabling tremor analysis without depending on accelerometers. In an earlier study with five subjects (Safwat et al., 2009), an encoder-based system had been used for measurement but the mechanical impedance due to the inertia and viscosity of the mechanism may have filtered the hand tremor. A linkage-free position sensing system (Win et al., 2007) has been developed to avoid these possible confounds.

The main objective of this work is to investigate the influence of magnification and grip force in accuracy of micromanipulation. In addition to a pointing task, the performance during circular movements was examined. These two tasks of pointing and tracing are thought to be primitive and important in micromanipulation. For example, it is essential for a microsurgeon to be able to insert a suture needle at exact location on a vessel edge, and to make smooth incision with least amount of damage. In this study, the novel linkage-free measure-
ment device was used to study manual microscopic accuracy (Fig. 2.1). Three groups of subjects were tested: naive subjects, age matched medical students with surgery knowledge, and older, experienced surgeons. By recruiting subjects from different backgrounds, the influence of expertise can also be compared.

Figure 2.1: (A) Subject performing the accuracy experiment. (B) Screenshot for pointing task with orange cursor and blue rectangles indicating a too large grip force. (C) Screenshot for the tracing task.

2.2 Experiment

2.2.1 Measurement Device

The M2S2 optical micro motion sensing system (Win et al., 2007) used a pair of orthogonally placed position sensitive detectors (PSD) to track 3D displacement of the tip of a microsurgical instrument in real-time (Fig. 2.2A). An IR diode illuminated a 5mm diameter ball attached to the tip of an intraocular shaft (Fig. 2.2B), reflecting IR rays onto the PSDs. This device provided a measurement at 250Hz in a 10x10x10mm³ workspace, with a peak to peak static error of 3.1µm.

A stylus with similar mass characteristics to a typical surgical forceps was designed to hold a reflector ball for tracking the stylus movement (Fig. 2.2C). A force sensor (FSG15N1A, Honeywell Inc., USA) was mounted on this stylus to
Figure 2.2: (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 2.1: Static and dynamic errors of the M2S2 measurement device

<table>
<thead>
<tr>
<th></th>
<th>static</th>
<th>8Hz</th>
<th>12Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE(µm)</td>
<td>0.91</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>peak-to-peak maximum error (µm)</td>
<td>3.1</td>
<td>2.9</td>
<td>2.4</td>
</tr>
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estimate the grip force. This sensor can measure forces up to 15 N. The force data was acquired using a data acquisition card (PD2-MF-16-150, United Electronic Industries, USA) with 16-bit resolution.

Static error was 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 1000 mm³. Dynamic error of the system may differ slightly from static error. It was measured at different frequencies up to 12 Hz, as the 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 of the M2S2 unit are shown in Table 2.1.

2.2.2 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. The age of the two groups of students were between 21-25 years. 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 had similar grip across trials. The tip of the stylus was pointed near the center of the M2S2 workspace.
To perform the *pointing task*, two dots were displayed (Fig. 2.1B): 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 30s. 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 force and to blue when too large 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: 1-2N, 2.5-3.5N and 4-5N. Data was collected at 250Hz.

In the *tracing task*, a 4mm diameter white circle was drawn on the display. The subject was then instructed to move along the circle clockwise as accurately as possible during 30s with the small orange-colored dot used as the cursor (Fig. 2.1C). 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 set the cursor at the center of the screen, by convention at (0,0), and data was collected for 30s. For the pointing task, this meant the cursor overlapped the target and the subject only had to keep this position. In the tracing task, the cursor was at the center of the circle and the subject had to bring it to the circumference of the circle.

The subjects performed the test twice for each setting with approximately one minute break in between settings. All subjects carried out the tests in the same order of magnification and grip force because preliminary tests had shown that the order of experiment had no significant influence on experimental data.
2.2.3 Data Analysis

Data processing and statistical analysis were computed using Matlab software (The Mathworks, USA). Two main measurements were used as performance comparisons: trial error and tremor intensity.

![Figure 2.3: Pointing error of a typical subject at magnification 10x.](image)

**Trial Error**

The trial error measured displacement from the origin (i.e. the starting point) using positional recordings in time series of $x(t)$ and $y(t)$. The trial error, $r$ (Fig. 2.3) was computed as

$$r(t) = \sqrt{x^2(t) + y^2(t)}. \quad (2.1)$$

The mean and standard deviation of displacement was calculated for each subject. The graphs in the subsequent Results’ section showed actual values of deviation to indicate how the different subject groups compare. However, to determine effects of magnification and grip force using subjects’ grouped data, each subject’s data was normalized with their individual maximum mean across trials.

The normalization process for the magnification test of pointing task is de-
scribed below:

1. For every subject, the mean trial error for the magnification test during pointing task was calculated. This gave 6 values per subject because subjects were tested twice for each of the 3 magnification levels.

2. All the means in a particular set were divided by the largest of these means. This is the normalization step.

3. Now, all subjects’ normalized means for this test condition could be grouped by their respective category, either surgeons, medical students or non-medical students.

4. For each category of subjects, the means and standard deviations of these subjects’ (six) means were then calculated to give the final representation of results per test condition.

The steps were repeated for the magnification test of tracing task and similarly, for the different force ranges in the grip force test.

**Tremor Intensity**

Tremor is frequently analyzed in the frequency domain using power spectral density (Randall and Stiles, 1964; Elble and Koller, 1990; Elble and Randall, 1976). Raw displacement data was converted to frequency domain using Fourier transform to obtain the power spectrum. The spectrum was then integrated over the bandwidth being investigated to provide power associated with this region. In this study, frequency analysis of the data was calculated in six typical bandwidths (Halliday and Redfearn, 1956; Wyatt, 1968; Stiles and Randall, 1967; Morrison and Newell, 2000; Raethjen et al., 2000): 0-2Hz, 2-4Hz, 4-8Hz, 8-12Hz, 12-16Hz and 16-25Hz to determine the effect of test conditions on the proportional power of the six bandwidths. Similar to trial error, each subject’s power spectra was first normalized with his or her own maximum total power before being grouped to determine the influence on power in relation to the factors being investigated.
Statistical analysis

Methods of statistical analysis similar to those applied by other researchers working in the visuo-motor or motor skills research (Ghilardi et al., 1995; Villanueva et al., 2007; O’Toole et al., 1999) were used. The data were initially subjected to a one-way ANOVA, to determine the impact of magnification levels or grip force range during the experiment. Following significance in ANOVA, comparisons between two sets of condition were analyzed with paired t-tests to identify which condition (e.g. magnification level) contributed to the change in performance. Paired t-test examined the difference between the two sets of data and calculated the probability that the actual mean difference between the pair was zero. Data were assumed to be drawn from a normally distributed population. The tests were performed using data analysis package of Matlab with level of significance for the tests set to 5%.

2.3 Results

Pointing Task

Fig. 2.4 shows a subject’s deviation from the starting point. At magnification 1x, the deviation was typically more than 0.4 mm radius from the target. Both errors at magnification 10x and 20x were small, within the 0.2 mm radius.

Figure 2.4: Typical error displacement at magnification 1x, 10x and 20x.

When examining the influence of magnification on accuracy, for each of the three groups, the error decreased significantly between magnification 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. 2.5). This confirmed the results of the earlier experiment with five subjects conducted with an encoder-based measurement unit (Safwat et al., 2009) and justified a-posteriori the use of only three levels of magnification. Surgeons performed with lowest errors compared to medical students and non-medical students at magnification 20x. Interestingly, they had the highest errors at magnification 1x for both force levels 1 and 2. When using force level 3, surgeons had slightly higher error compared to medical students but still lower than non-medical student. As for medical students, their performance were closely matched to surgeon performance at magnification 10x and 20x except when using the highest force range at 20x visual magnification, they performed with larger error compared to the surgeons. The medical students recorded the lowest error at magnification 1x. Non-medical students performed the worst in most of the conditions tested. They performed slightly better than the surgeons only at magnification 1x using the low and medium force range.

While magnification clearly affected accuracy, grip force had negligible influence on pointing task accuracy (p>0.1 for all pairwise comparisons of force levels in each of the three groups). Fig. 2.6 shows error versus forces at different magnifications. At 1x magnification, the mean error are significantly higher than at magnification 10x and 20x. But, interestingly, in this 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. Error was similar for all levels of grip force at magnification 10x and 20x.

Tremor is frequently analyzed in the frequency domain. Fig. 2.7 shows the effect on magnification of tremor intensity at different frequency bands for pointing task. Magnification only played a role in the low frequency band of 0-2Hz where voluntary motion was 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.
Figure 2.5: Pointing error versus magnification for different groups of subjects at force level 1, 2 and 3.
Figure 2.6: Pointing error versus force for different groups of subjects at magnification 1x, 10x and 20x.
Figure 2.7: Effect of magnification on tremor intensity at different frequency bands for the pointing task. X-axis label [1 2 3] corresponds to magnification [1x 10x 20x] respectively.

Figure 2.8: Effect of force on tremor intensity at different frequency bands for the pointing task.
at any magnification level (p>0.6).

Grip force appeared to affect tremor intensity without magnification in a similar way as it affected accuracy. Fig. 2.8 shows the magnitude of tremor intensity versus grip force at different frequency bands for the pointing task. Power in the 0-2Hz 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). However, grip force did not seem to affect power at higher magnifications (in any of the bands).

**Tracing Task**

Fig. 2.9A shows typical trajectories of a subject performing the tracing task at different magnifications. All subjects managed to trace the circle but at magnification 1x, subjects made more deviations compared to magnifications 10x and 20x. As in pointing task, the deviations of tracing tasks at magnification 10x and 20x were similar. Fig. 2.9B shows the measured tracing error, which was the deviations from the circumference of the circle. Error decreased significantly with magnification 10x 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 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.

Fig. 2.10 shows the effect of magnification on tremor intensity at different frequency for the tracing task. Magnification did influence tremor to a certain extent until 8Hz. In the 0-2Hz band, total 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 2-4Hz and 4-8Hz 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 differences in performance
Figure 2.9: (A) Typical trajectories of a subject performing tracing task at different magnifications. (B) Effect of magnification on tracing error for different groups of subjects.

Figure 2.10: Effect of magnification on tremor intensity at different frequency bands for the tracing task. X-axis label [1 2 3] corresponds to magnification [1x 10x 20x] respectively.
were detected among the groups, although the error was generally smaller for the surgeons and medical students than for the non-medical students.

2.4 Discussion

When comparing performances of experienced surgeons, medical students and subjects who are not medically trained, no significant difference was detected in all conditions. 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 (Voelcker-Rehage and Alberts, 2005; Keogh, 2005). 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 was not statistically significant. The surgeons and medical students may have compensated their natural physiological tremor with better motor control, breathing patterns and composure due to more experience working with microscopes. For example, a microsurgeon participant of this study, who recorded very small deviations, shared that he held his breath during the short tasks to avoid his breathing to affect accuracy. This was something he did habitually during critical points of an actual operation, i.e. when performing incision, to avoid making large deviations.

Magnification was found to help in improving accuracy in both pointing and tracing tasks until 10x, however, increasing the magnification level beyond 10x did not help to further improve accuracy. The result here was consistent with earlier studies which found accuracy to improve with visual gain, but had a limiting factor which was hand tremor (Vasilakos et al., 1998). These results contrasted with Keogh (2005) who found tremor to increase with magnification. Differences in experimental design and tasks may have contributed to this difference in findings. The current investigation used a linkage-free measurement system where subjects held a stylus designed with width similar to a pair of forceps, and gripped between the thumb and index fingers for all the tasks. This was a
closer resemblance to a micromanipulation task where an operator had to grip some mass using tweezers, while other studies investigated postural pointing of isolated finger (Vasilakos et al., 1998; Keogh, 2005). Therefore, this experiment should provide a closer model of accuracy during micromanipulation tasks than previous studies. In addition to static pointing, the dynamic tracing task was investigated. As the complexity of the task increased from pointing to tracing, the positive effect of magnification became less apparent.

Difference in tremor intensity was detected for the 0-2 Hz band, indicating intended motion, for both pointing and tracing tasks when visual magnification was at 10x. No difference was detected in all other bands suggesting that trying to control precision with visual gain would not affect physiological tremor. The findings regarding magnification indicate that an operator could employ a magnification factor up to 10x to help improve accuracy by visual feedback and higher magnification may not be necessary, although the higher magnification would not have a negative impact on tremor. Further improvements on accuracy may require additional effort for example, expertise and practice.

Grip force was found to vary with movement as subjects were unable to contain their forces within the specified range when performing circular motion. However, grip force did not significantly affect accuracy. This could be due to the rather low force ranges specified in this particular experiment (maximum 5 N) as higher forces beyond comfortable levels, which increased muscle tension largely, may influence accuracy. Without magnification, total power in the 0-2 Hz region was affected by grip force, where it was highest at 2.5-3.5 N (force level 2) compared to the 1-2 N and 4-5 N 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, which could be further explored. It is usually believed that motor noise, thus inaccuracy, increases with the exerted force. While this holds true for one finger (O'Sullivan et al., 2009), the co-contraction of the opposing fingers and the resulting increase of impedance may reduce variability as was shown in arm movements (Burdet et al., 2001;
Osu, 2004). Osu (2004) and Visser et al. (2004) have shown that co-activation in fact increases with accuracy demands.


3 Role of Bimanual Coordination in Accuracy

3.1 Introduction

Human naturally involve both hands in many tasks, such as handwriting, slicing and carpentry. In bimanual operations, one hand is usually used for fine manipulations while the other provides a reference for the first hand (Guiard, 1987). Although the left hand may not be directly involved in the execution of the task, it still plays a role for postural support for example in sketching where the hand is used to hold the paper in place (Hinckley, 1996). Microsurgery, an example of micromanipulation, is essentially a bimanual task which require the coordinated use of both hands to complete an operation. By involving two hands, the tasks can be distributed to reduce switching time. One scenario is during suturing when forceps on the left hand are used to hold onto a needle during tissue exit while waiting for the right hand to retrieve it again with the needle holder. The left hand is also used to hold onto tissues during suturing to facilitate needle insertion and retrieval. Frequently during a micro-suturing procedure, the microsurgeon has to move the tool out of the viewing zone, e.g. to change tools or to pull the suture away, and then bring a tool back to the initial position. The effect of the left hand during the execution of such a simple micromanipulation task is unclear. However, in the event of missing visual feedback, the presence of the left hand could perhaps be used to help guide the reaching hand towards the right location. Existence of a common plan for two hands in a bimanual task can perhaps be exploited to improve movement accuracy.
Bimanual coordinations can be grouped into four classes: symmetric - synchronous, asymmetric - synchronous, symmetric - asynchronous and asymmetric - asynchronous (Ulinski et al., 2009; Guiard, 1987). For symmetric tasks, each hand performs identical actions while in asymmetric task, the hands perform coordinated actions to accomplish the same task. Both symmetric and asymmetric tasks can be performed synchronously or asynchronously. Several studies have been conducted to investigate performance of bimanual performance during manipulation of computer programs (Gribnau and Hennessey, 1998; Buxton and Myers, 1986; Owen et al., 2005; Balakrishnan and Hinckley, 2000). Buxton and Myers (1986) showed that tasks could be performed better by splitting the sub-tasks of compound continuous tasks between the two hands or when the tasks were performed sequentially. In the experiment of Balakrishnan and Hinckley (1999), subjects controlled the view of a graphical scene with the left hand while the right hand had to perform target selection. Target selection was 20% faster if done with the bimanual method compared to unimanual.

Bimanual coordination have also been investigated in the context of psychology and motor learning (Franz et al., 2002; de Poel et al., 2007; Peper et al., 1995; Mechsner et al., 2001; Heuer, 1993; Boessenkool et al., 1999; Domkin et al., 2005). Some studies suggested that the kinesthetic sense or proprioception may supplement vision and help in coordinating bimanual movements (Hinckley et al., 1997; van Beers et al., 1996). However, it is not clear how the sensory integration works and when one would dominate over the other. Sellen et al. (1992) presented an experiment which demonstrated that kinesthetic feedback was more effective than visual feedback in reducing mode errors and could help to reduce cognitive load. Others suggest that when vision and kinesthesia are in conflict, visual feedback is more dominant (van Beers et al., 1999). Task objective could also influence the outcome of a bimanual task (Hinckley et al., 1997). In cooperative bimanual experiment of Kazennikov et al. (2002), when asked to pick an object from a drawer either unimanually or bimanually, subjects made longer curved trajectory with the pick-hand during bimanual task. This was to enable the
hand to arrive after the drawer was opened whereas in the unimanual task, no temporal and goal synchronization was required, therefore subjects could make the shortest possible route to the target, giving a much straighter trajectory showing that the objective of the task would influence the path taken.

An experimental condition close to micromanipulation, such as the micro-surgery procedure where surgeons have to move their hands back into the viewing range, would be the goal-directed reaching task. To perform reaching movement towards an object requires a trade-off between the speed of the limb and accuracy at the end-point (Riek et al., 2003). Several investigations have been carried out to determine how proprioception and vision can affect arm reaching movements (Gordon et al., 1995; Ghez et al., 1995; Sarlegna et al., 2006; Scheidt et al., 2005; Bernier et al., 2006). It was well-established that in planning for goal-directed reaching movements, the position of the arm is estimated by integrating visual and proprioceptive signals. Theories have surfaced suggesting that proprioceptive input are critical for updating motor memories and internal models to compute joint-based motor commands while visual information provides position estimate for planning and perhaps only adjust the motor commands (Hepp-Reymond et al., 2009; Sober and Sabes, 2003). Other studies have shown that visual input at the onset of movement further improved accuracy (Desmurget et al., 1997; Rossetti et al., 1994) suggesting that the internal mapping was formed even before the movement began. These studies investigated the vision and proprioception associated with the working hand and how information about the position of this hand could affect movement but did not look at the effect of the contralateral hand in assisting motion of the working hand.

The aim of the experiment described here was to investigate how the left hand affects small scale reaching movement of right hand under virtual reality environment. The VR gives indirect vision, similar to micromanipulation under the microscope, and can be difficult due to depth perception. All trials were performed without subjects looking at their limbs, but movement of the limbs were fed back to the subject via a moving cursor in a virtual reality setting.
under visual amplification, where errors could already be minimized. The task
designed was asymmetric-asynchronous, where subjects were allowed to move
their right hand directly to the target without having to synchronize with the
left hand. By varying visual feedback and motion, contributions of the left hand
when the right hand had to perform the reaching task can be identified. The
experiment compared two conditions, trials with initial vision of the reaching
hand and without initial vision, to ascertain the effects of initial vision during
motion planning stage. By moving the left hand at the beginning of trials, the
dynamic effect was compared to static vision. Trials conducted unimanually
acted as a baseline to identify the effects of the bimanual strategy. This work
focused on manipulation of stylus with finger and wrist, similar to movements
and workspace during micromanipulation.

Figure 3.1: The 2D screenshot of visual feedback during the experiment (left)
and the experimental setup (right). Using the PHANTom Omni for
position feedback, subjects were required to move the cursor from
start point at the furthest right to every green target points, pre-
sented one at a time in random order. Orange point representing left
finger position was displayed only during relevant sessions when both
hands were used.
3.2 Experiment

3.2.1 Subjects

Nine subjects without known pathology, aged between 20-30 years, participated in this study. The subjects were all right-hand dominant (1 female) and gave informed consent prior to starting with the test.

3.2.2 Setup

The PHANToM Omni haptic device developed by Sensable Technologies was used for position measurement and to provide forces to guide the hand at the start of trials. It allows six degree-of-freedom position and orientation sensing using digital encoders with nominal accuracy of 0.055 mm. Three-dimensional force feedback can be provided, with continuous force of 0.88 N and maximum force of 3.3 N within a 160x120x70 mm³ workspace. Visual display was provided through a stereoscopic visor, the eMagin z800 3DVisor (Fig. 3.1, right). This model provides 3D view through two organic light emitting displays (OLED) of 800 x 600 resolution. While the OLED displays are only 15 mm in the diagonal, the picture is the equivalent of a 2.67-meter screen viewed at 3.66 meter. The graphics card used together with this visor is the nVidia QuadroFX 1500.

3.2.3 Protocol

The subjects were seated at a table with their eyes looking into the stereoscopic visor, which was affixed on a metal stand. Height of the visor was adjusted to suit subject’s height and distance between OLED displays was adjusted to match individual interocular distance. Subjects had their wrists rested on a platform and were asked to take a comfortable seating position. They had to hold the stylus with their right hand between their index finger and thumb, which ensured that all subjects have similar grip across trials.

For this trial, the visual display (Fig. 3.1, left) showed the purple-colored start point at the right and an orange point as left hand indicator on the left
Table 3.1: Distance of targets from start point

<table>
<thead>
<tr>
<th>Target</th>
<th>Distance [mm]</th>
<th>Start point within view</th>
<th>Start point out-of-view</th>
</tr>
</thead>
<tbody>
<tr>
<td>target 1</td>
<td>30.0</td>
<td></td>
<td>52.5</td>
</tr>
<tr>
<td>target 2</td>
<td>26.6</td>
<td></td>
<td>48.0</td>
</tr>
<tr>
<td>target 3</td>
<td>20.0</td>
<td></td>
<td>42.5</td>
</tr>
<tr>
<td>target 4</td>
<td>26.6</td>
<td></td>
<td>48.0</td>
</tr>
<tr>
<td>target 5</td>
<td>10.0</td>
<td></td>
<td>32.5</td>
</tr>
<tr>
<td>target 6</td>
<td>26.6</td>
<td></td>
<td>48.0</td>
</tr>
<tr>
<td>target 7</td>
<td>26.6</td>
<td></td>
<td>48.0</td>
</tr>
</tbody>
</table>

of the screen. A pink dot which moved according to the stylus tip position was also displayed on the screen. In the middle region, there were 7 green points representing the target subjects had to aim for. These targets were presented one at a time, in random order, to the subjects when they were ready at the start point. Two start points were used in the experiment, one within view as shown in Fig. 3.1 and another slightly to the right of this point but out of viewing range. The distances of these targets from the start points are presented in Table 3.1.

Subjects were required to move from the purple start point to the green end-point “as fast and as accurately as possible”. A speed threshold of 0.02m/s was required and if subject’s speed fell below the threshold, a feedback of “too slow” will be displayed. Subject was required to complete a successful movement before moving on to the next target. Each movement was considered a success if all the following conditions were fulfilled together:

1. Subject’s mean trajectory was faster than a speed threshold of 0.02m/s
2. Subject stopped for at least 1s within 40% the trajectory distance from end-point.
3. Whole trajectory movement was within a pre-defined zone, for safety reasons.

In each session, subject repeated the reaching movement ten times for each target, where five times were with start point within view and the remaining five
times with start point out of view. For the case where start point was out of view, the purple dot was further to the right and no visual display was provided to indicate the position of the start point in the visual screen. The subjects were unable to see where their pink cursor started from at the beginning of each trial. They had their right hand positioned at the start point automatically using forces from the haptic device. The sequential order of tests in one session was as follow:

i. One random order series of Target 1 to 7 with start point within view

ii. One random order series of Target 1 to 7 with start point out-of-view.

iii. Intermittent repetitions of first and second series to total five times each.

Actual distance between visible start point and Target 1 (the furthest end point) was 30\text{mm} while the distance between start point out of view and Target 1 was 52.5\text{mm}. The distance in the case of start point out of view was much further than that of a typical microsurgical workspace to emulate movements during suturing when surgeons would take a tool out of the microscopic viewing range. A visual magnification of 6.0x was used to amplify movement error throughout the trial. When the subject was prepared to begin the session, a keyboard press set the cursor to overlap the start point and data collection commenced. Cursor will be held in position with haptic force for 1 s, after which a buzz will indicate that the force was switched off and the word “GO” displayed to prompt subject to move towards the target. At this point, subject was free to start their trajectory towards the end point.
3.2.4 Session Settings

The subjects completed 6 sessions to cover three sets of test conditions (Fig. 3.2): one set of conditions per session, repeated once.

Figure 3.2: Setups for three different experimental settings: unimanual, bimanual-static and bimanual-dynamic.

UNIMANUAL

In the unimanual session, subjects were asked to use only their right-hand to complete the task. Using the stylus held in their right hand the subjects were asked to move towards the target as soon as the “GO” indicator appeared on screen. Their movement was represented by movement of the pink cursor. The left hand was placed comfortably on the table. No orange cursor was displayed on screen.

BIMANUAL-STATIC

Two variants of bimanual conditions were tested. In the first bimanual-static settings, subjects were asked to place their left finger on a stationary object of which the actual position relative to the start point was virtually represented on screen as an orange dot at the left (Fig. 3.1). Before the session began, subjects were asked to move their stylus from start point to the orange indicator, touching their left index finger for habituation. This movement was repeated ten times before the trial commenced, and the movements could be seen on the stereoscopic
display in the form of the pink cursor. The left index finger remained in the same position throughout the trial.

**BIMANUAL-DYNAMIC**

In the second set of bimanual settings, from now on referred as the bimanual-dynamic settings, two PHANTOM Omni haptic devices were used - one for the left hand, and one for the right. Subjects were asked to hold the stylus in each hand, as comfortably as possible. At the start of the session, both stylus would be pointing at the same point on an actual object and represented by an overlapping point on display screen. At a key press, the left hand would be moved automatically by haptic forces and positioned until the stylus tip was $2 \text{mm}$ to the left of the next target. Position of the left hand tool was represented by an orange cursor on screen. The right hand will be moved in a similar way to be positioned on the start point at the right. Movement of the right hand was represented by a pink cursor. When the right cursor was in place, the visual display of the next target appeared in the form of a green dot and after $2 \text{s}$ delay, the haptic force holding the right cursor was switched off. At this time, subject was free to move towards the target. The left hand was held in place with haptic forces from beginning of the trial until subject reached the target. When the next trial was to begin, the left stylus will be moved again towards the next target and the process was repeated for all the targets.
3.2.5 Data analysis

Data processing and statistical analysis were computed using Matlab software (The Mathworks, USA). A few parameters were checked to determine the influence of bimanual compared to unimanual tasks.

**Trial Time**

The *trial time* was the mean movement duration over all trials in a session. The movement duration was calculated from the time subject moved 2 mm away from the start point until subject stopped near the target point. Conditions to determine a stop was a velocity of less than 0.02 m/s for at least 1 s and stopping point from the target was within a radius of 40% of start-end points distance.

**Trajectory Error**

Figure 3.3: Calculation of trajectory error, where white shaded area denotes trajectory error in one sampling interval.

The *trajectory error* measured the magnitude of the error made throughout the trajectory. Based on Fig. 3.3, the trajectory error was the total area between the trajectory and the straight line joining the start and end points and was computed as:

\[ e = \int_{0}^{1} d \times dl, \]  

(3.1)

where \( dl \) was the distance traveled along the straight line within one sampling
interval and $d$ was the instantaneous distance of cursor from the target straight line.

To avoid different path lengths to influence this computation, the $x$ component was normalized to the length between start point and target point. The normalized length made comparison possible between target points.

Motion Smoothness

One common measure of motion smoothness is by computing the number of peaks in a velocity profile. To get the amount, the number of zero crossings from the first derivation of a velocity profile (acceleration) is calculated (Fig. 3.4). A smoother trajectory contains lower number of peaks, or lower amount of zero crossings in the acceleration profile.

End-point Accuracy

The measurement used to evaluate end-point accuracy was the average Euclidean distance of cursor point from the target point when subject stopped moving. Ten last readings during the “stop” were averaged to get one value representing end-point accuracy for the particular trial. Lower value indicates higher accuracy because subject managed to stop very near to the target point.

To allow all subjects’ data to be grouped together, each set of data underwent some pre-processing steps. The process to obtain normalized trial error is
described below:

i. Each subject underwent 6 sessions which required 70 successful trials per session (7 targets x 2 start points x 5 repetitions).

ii. Trial error from beginning till end of trajectory was calculated for each trial.

iii. For each subject, the trial error from the subject’s six sessions were grouped together and the outliers were removed from this data. The outliers were tested using the generalized ESD (extreme studentized deviate) test set at 95% confidence level.

iv. Next, the trial error without outliers were individually divided with subject’s own largest error across all trials. This is the normalization step. In this way, all subjects’ data could be grouped in spite of any subject differences.

v. When the data has been processed by subject, all subjects’ normalized trial error was grouped by session. For every session, the grouped data was further divided into two based on the start point locations, either within or out of view, for comparison.

vi. The same steps were used to process motion smoothness, end-point accuracy and trial time.

vii. In the case of trial time, the normalization step was omitted and actual time was presented instead because a fixed time limit and speed threshold had been set as condition throughout the trial, making the trial time comparable across subjects and across experiments.

For every parameter investigated, results are represented by four graphs to compare effects of target characteristics on experimental data:

1. Mean of normalized data from all targets

2. Target distance from start point: All targets were plotted, but targets 2, 4, 6 and 7 were averaged as one point because they share the same distance from start point.
3. **Target distance from reference point**: Targets 2, 3, 4, 6 and 7 had the same 15 mm distance from reference point in bimanual-static task, and were chosen to be compared against the five targets in bimanual-dynamic tasks, which was given a reference point 2 mm from target.

4. **Target direction from start point**: Five targets were chosen to be compared here, namely Target 2 (RIGHT), Target 4 (LEFT), Target 1 (CENTER), Target 6 (TOP) and Target 7 (BOTTOM).

Statistical tests were performed on all data patterns using paired t-test at 5% significance level.

### 3.3 Results

**Trial Time**

![Graph showing trial times for different settings](image)

Figure 3.5: Trial time when start point was visible (left) and start point not visible (right) for the three task settings.

Subjects were restricted to complete every trial within a stipulated time, otherwise the subject would be asked to perform the trial again. The maximum time given for each trial was linearly dependent on the distance between start
and target points. The longest distance in the whole experiment was 52.5 mm, between start point out of view and Target 1, and for this distance a total time of 2.50 s was allocated to complete the trial.

Results from experiment showed that when start point was within view subjects needed more time to complete the bimanual-dynamic movement trials compared to unimanual and bimanual-static trials (Fig. 3.5). This difference was highly significant (p < 0.001). Mean trial time for bimanual-static tests was similar to unimanual tests (p > 0.2). When start point was out-of-view, trial time was again longer for bimanual-dynamic settings compared to unimanual and bimanual-static (p < 0.006) while no significant difference was detected between unimanual and bimanual-static. All trial time was longer for start point out-of-view compared to within view because the distance was further.

Trial time increased with distance from start point (Fig. 3.6, top), as expected, because subjects were given longer duration with increasing distance. As shown in Fig. 3.6 (middle), having a reference point closer to the target did not improve trial time. The bimanual-dynamic task that had reference point nearer to the targets required significantly more reaching time compared to bimanual-static task which had the hand at fixed position (p < 0.021). Targets at upper and lower planes from the start-end points needed the most reaching time compared to other targets (Fig. 3.6, bottom). Targets on the same plane but to the left and right of the center axis also require more time than target which was located along the center axis.
Figure 3.6: Trial time based on distance from start point (top), distance from reference point (middle) and direction from start point (bottom). The left panels show results for start point within view, while the right panels are results for start point out-of-view.
Trajectory Error

As shown in Fig. 3.7, when start point was within view, bimanual-static tasks recorded lowest error among the three conditions and the difference was significant ($p < 0.03$). However, when vision of the start hand was removed, the bimanual-dynamic settings had the lowest error. The unimanual error was statistically different from both bimanual-static and bimanual-dynamic tasks under this condition ($p < 0.004$), while the error between bimanual-static and bimanual-dynamic tasks was similar ($p > 0.53$).

Trajectory error increased with target distance from start point (Fig. 3.8, top) but other factors also contributed as can be seen by the non-linearity at some targets, for example, the plots at location 26.6 mm from start point were averaged from four targets located at directions right (target 2), left (target 4), top (target 6) and bottom (target 7). Error at these points were higher than the value expected from a linear increment.

In Fig. 3.8 (middle), five targets with same distance from reference point were grouped to compare how trajectory error was influenced by the distance of the
Figure 3.8: Normalized trajectory error based on distance from start point (top), distance from reference point (middle) and direction from start point (bottom).
reference point. Contrary to initial assumption, error was not lower for points
with nearer reference. The bimanual-dynamic task which had reference point
nearer to the target recorded higher mean error when start point was visible
\((p<0.04)\). However, no significant difference in error between the two bimanual
settings were detected when start point was not visible \((p>0.33)\).

Fig. 3.8 (bottom) compared the error of four targets which had different
directions from start point. Overall, targets on the same horizontal plane as the
start and end points recorded lower error than targets at different planes (top and
bottom targets) and the difference was highly significant \((p<0.001)\) regardless
of start points. Bimanual-static settings and unimanual settings recorded very
similar trend, but with better accuracy in bimanual-static tasks. Bimanual-
dynamic settings had a different accuracy than the two where error was relatively
lower for the bottom target when the other two settings recorded highest error
for this particular target.

**Motion Smoothness**

![Figure 3.9: Normalized motion smoothness when start point was visible (left)
and start point not visible (right) for the three task settings.](image)
Motion smoothness was clearly affected by the presence of the second hand. The three test conditions recorded distinctly different results with the best smoothness in bimanual-dynamic tasks, followed by bimanual-static and worst smoothness during unimanual tasks (Fig. 3.9) for both start points. The difference among the settings was statistically significant, with p<0.05 for start point within view, and p<0.0002 for start point out-of-view.

Trend lines for unimanual and bimanual-static tasks displayed close similarities for both start points (Fig. 3.10, top). With visible start point, the number of peaks increased with travel distance for these two settings, but when start point was not visible, motion smoothness no longer showed this tendency. The amount of peaks in velocity profile was higher when start point was not visible compared to when start point was within view. Bimanual-dynamic setting showed the same level of motion smoothness regardless of start point visibility and travel distance. The bimanual-dynamic results had trend lines that were different from unimanual and bimanual-static for both start points. Results indicated that subjects performed smoother motion when start point was within view for unimanual and bimanual-static tasks, but for bimanual-dynamic movement tasks, they performed smooth paths in both conditions.

Bimanual-dynamic movement gave smoother reaching trajectories than bimanual-static movement for all points with same distance from the reference (Fig. 3.10, middle). Targets at different planes recorded statistically different motion smoothness (p< 0.01). Bimanual-dynamic settings had the smoothest motion for target at the lower plane (Fig. 3.10, bottom) and this was again contrary to unimanual and bimanual-static settings.
Figure 3.10: Normalized motion smoothness based on distance from start point (top), distance from reference point (middle) and direction from start point (bottom).
End-point Accuracy

Figure 3.11: Normalized end-point accuracy when start point was visible (left) and start point not visible (right) for the three task settings.

The end point accuracy was based on the cursor’s Euclidean distance from the target point. Results showed that bimanual-static settings gave the best end-point accuracy compared to the other two settings for both start points (Fig. 3.11). The accuracy during bimanual-static settings were statistically lower than unimanual during visible start condition ($p<0.03$) and statistically lower than bimanual-dynamic for non-visible start point ($p<0.005$). Accuracy of unimanual and bimanual-dynamic settings were similar ($p>0.28$).

Start point distance did not influence the end-point accuracy (Fig. 3.12, top). All three settings showed similar trend among them for the two start points, but the trend was different between start points. Error was consistently lower for bimanual-static tasks compared to unimanual tasks.

Bimanual-static and bimanual-dynamic setting errors were statistically different ($p<0.032$) for the five points which had same distance from reference (Fig. 3.12, middle), with bimanual-static recording lower error than bimanual-dynamic. End point accuracy of different planes (Fig. 3.12, bottom) were statis-
Figure 3.12: Normalized end-point accuracy based on distance from start point (top), distance from reference point (middle) and direction from start point (bottom).
3.4 Discussion

This experiment investigated how visual information and the presence of a contralateral hand affect a right-handed small range reaching movement. The trial time limit and speed threshold gave subjects just enough time to reach the respective targets without spending too much time adjusting for their accuracy or changing their planned trajectory.

Studies on bimanual experiments that compared response time reported that longer time was needed to complete a task in bilateral conditions than in unilateral conditions (Westenberg et al., 2004; Li et al., 2000; Vidal et al., 2001). This result was seen in the bimanual-dynamic settings where the mean trial time was significantly longer because subjects were getting position feedback from two cursors at the same time. Subjects had to maintain the left stylus position while giving attention to the right hand to perform the task accurately. Such tasks require more attention and effort than the unimanual task. However, the presence of the second hand during a task could be providing information for goal-targeted reaching that could make tasks easier and reducing time needed to complete the trials. The bimanual-static trials in our study provided this guidance but did not demand much attention from subject due to the fixed finger position, therefore did not require significantly more time than the unimanual tests.

What is the effect of initial vision of reaching hand? Recent studies have shown that planning of goal-directed movements is dependent on visual information of the hand and target (Elliott et al., 1999). Visual information of hand position at the onset of a pointing movement improved movement accuracy due to better encoding of initial state of the motor (Prablanc et al., 1979; Desmurget et al., 1997; Rossetti et al., 1995). In the present experiment, reaching movements to various targets at different locations were completed with initial vision of the start point, and without initial vision. With initial vision, the subjects’ accuracy at end points recorded similar trend for all three settings because sub-
jects could pre-plan their trajectory well in advance, therefore showing similar outcome at each target. Without initial vision, error increased but at different degree depending on availability of feedbacks from the contralateral hand.

How does the contralateral hand affects accuracy and movement? In this experiment, the increase in error can be attributed to two factors. First, travel distance was longer for start point out-of-view compared to visible start point, and as shown by the results, error was affected by path distance. The second reason could be related to sensory information. Studies have reported that error was larger when only proprioception was available than when vision and proprioception were available simultaneously because the two are integrated to improve determination of the initial hand condition (van Beers et al., 1996). The variability in position estimate would be significantly smaller than an additive or exclusive model from each sensory representation (Meredith and Stein, 1986). The effect from the additional sensory information can be seen by the smaller increase of error for bimanual-dynamic tasks from visible start point to non-visible start point because in the bimanual-dynamic settings, the location of the contralateral hand could provide more information for initial estimate of location and path planning. In a virtual scene when no other body parts were visible, this extra information can be used as additional sensory input to update the internal sensory map (Desmurget et al., 1997). Error in unimanual task, where feedback of the left hand was not available, showed the largest increase when initial vision was removed from trials.

Is there a difference between static and dynamic approach? Previous studies have claimed that static proprioceptive receptors are partially ineffective for accurate estimation of limb locations (Desmurget et al., 1997; Ghilardi et al., 1995) based on experiments comparing accuracy from a proprioceptive start to a proprioceptive target. In this experiment, movement towards the target immediately before the start of trials was compared to the bimanual-static task to see if dynamic motion provided better outcome. Results show that the dynamic input did not make the movement more straight, nor did it improve end-point accuracy.
at the target, but significantly helped to perform smooth motion. With the other hand moving and staying near to the target, a combination of factors such as memory of path, knowledge of the current location and dynamic proprioception may have helped the reaching hand to go more surely with less correction along the way. This trend was present with or without visual information of start point. This finding suggests that the presence of the left finger near the target helped in the path planning of trajectory well before subject had visual feedback of the reaching right hand.

The bimanual-static setting was closely similar to the unimanual task, except that the subjects had visual feedback of their hand position, and the hand was placed nearer to the targets. With such setting, the bimanual-static consistently outperformed the unimanual settings in all measures of accuracy and motion smoothness. This gave a strong indication of the use of the contralateral hand in improving accuracy. The bimanual-dynamic task was less consistent, with some targets having lower accuracy than unimanual but always better smoothness. This can perhaps be explained by the unsupported hand during bimanual-dynamic task as compared to the fixed position of unimanual and bimanual-static task. The lack of postural support demands effort to keep the hand in position, therefore performance was less consistent compared to the bimanual-static but still better than the unimanual overall.

In summary, testing with full visual information and incomplete vision showed how the visual and proprioceptive inputs from the contralateral hand could help improve accuracy and motion smoothness. With or without vision of the start point, the bimanual tests gave better results compared to the unimanual tests, except in trial time where additional attention to the movement of the second hand during bimanual-dynamic tasks caused the anticipated longer duration to complete trials.
4 Learning of Micromotion in Unstable Dynamics

4.1 Introduction

Humans have the capability to learn multitude of tasks and skills, by actually performing the task and deliberately practising frequently on areas that need improvement (Rosenbaum, 2010). Experiments investigating learning have found many effective ways to train. Given the same amount of training duration, distributed learning, where learners practiced with spaced breaks, was found to be better than massed practice where learners have to practise for hours without a break (Moulton et al., 2006). Other methods, such as using motor imagery to visualize a task (Hall, 2002; Sanders et al., 2008), have been recommended for learning complex procedures for better transfer of skills. Learning may also depend on the sensory feedbacks available during practice. When both visual and haptic feedbacks were present, students were able to describe and reconstruct an object more accurately than if only one sensory feedback was available, helping to promote 3-dimensional understanding in learning science (Jones et al., 2003). This study aims to investigate the effect of using force cues amplifying motion error in learning accurate motion.

Force cues enable humans to explore geometry and texture (Robles-De-La-Torre and Hayward, 2001). Using haptic devices, studies have been conducted to investigate the use of force feedback for exploration of environment (Robles-De-La-Torre and Hayward, 2001; Wagner et al., 2002) and perception of objects (Tholey et al., 2005; Wagner et al., 2002; Ström et al., 2006). In recent years,
robots and haptic devices were used to provide force-field for training motor tasks based on computerized sensing of ongoing movements (Mussa-Ivaldi and Patton, 2000; Reinkensmeyer and Patton, 2009). Convergent force-field creates a stable environment for learning motor functions by guiding the limbs along a desired path but constant guidance or error attenuation may hamper motor learning because of the limited experience in learning to deal with error (Marchal-Crespo and Reinkensmeyer, 2008). Conversely, divergent force-field generating unstable dynamics environment (Burdet et al., 2001) as shown in Fig. 4.1 may provide more experience to the subject in handling error compared to the limited experience as guided by a robot, therefore forcing the motor to adapt faster (Emken and Reinkensmeyer, 2005) and more completely (Patton et al., 2006). In real life, an example of unstable dynamics movement would be the act of chiseling at a rounded edge where a slight deviation may cause the tool to glide far off, leading to a huge deviation from the original path. Unstable tasks are particularly difficult to learn and take longer time compared to stable tasks (Franklin et al., 2003).

Figure 4.1: Figure representing movement adaptation in unstable dynamics of Burdet et al. (2001).

In the study of Patton et al. (2006), it was found that a divergent force field tends to decrease lateral deviation in movement more than a convergent or a null
force field for stroke patients. When investigating learning in unstable dynamics at macro-scale (Burdet et al., 2001; Franklin et al., 2003, 2007), it was found that subjects were able to adapt to the environment, eventually reducing deviation of free movements after training in a divergent force field (DF), suggesting a possibility of using a DF to train motion accuracy. Motor learning theories suggest that subjects learn by forming an internal model to predict forces that will be experienced in the next movement or through impedance control (Thoroughman and Shadmehr, 2000; Burdet et al., 2001; Franklin et al., 2003).

However, these studies involved only large arm movements on a flat 2-dimensional plane with arms supported against gravity. This limited the subjects’ movements to a horizontal plane but many common tasks in daily life are essentially 3-dimensional. In a micromanipulation task, a person has to counteract gravity and still make precise trajectory. Study by Peral-Gutierrez et al. (2004) on micromanipulation error in fact showed a large proportion of error in the depth plane. Furthermore, in the arm movement studies, accuracy was not a major concern because tremor does not affect macro-movement as much as it affects micro-movement. In micromanipulation, visual feedback is magnified and subject could already consciously try to reduce their error. Under this circumstances, the benefits of training with divergent force-field may be masked. Conversely, with magnification, perception of their own tremor may adversely affect the subjects’ movement and disturb their control rather than help it. Therefore, it would be interesting to investigate how DF influences the learning and performance of a 3D movement and for small-scale manipulation.

In this study, the contribution of divergent force field (DF) in micromanipulation learning was examined. Unlike previous studies using DF only in the lateral direction, two-dimensional DF was applied in the training of small scale reaching movements of the fingers. Visual feedback in 3D was provided through a stereoscopic visor to enable depth perception of movements. In the depth plane where visual feedback is non-dominant, the effect force feedback has on deviations can be quantified.
4.2 Experiment

4.2.1 Subjects

10 subjects without known pathology, aged between 20-30 years, participated in this study. The subjects were divided into two groups - one test group of 5 subjects (1 female, 1 left-handed), and a control group of 5 right-handed subjects (all right-handed, 1 female). The subjects gave informed consent prior to starting with the test. All subjects used their right-hand for the experiments, including the left-handed subject.

4.2.2 Setup

Similar setup as described in previous chapter was used for this experiment. The PHANTom Omni haptic device developed by Sensable Technologies was used for position measurement and to provide forces during movement. Visual display was provided through a stereoscopic visor, the eMagin z800 3DVisor (Fig. 4.2), used together with the nVidia QuadroFX 1500 graphics card.
4.2.3 Protocol

The subjects were seated at a table with their eyes looking into the stereoscopic visor, which was affixed on a metal stand. Height of the visor was adjusted to suit subject’s height and distance between OLED displays was adjusted to match individual interocular distance. Subjects had their wrists rested on a platform and were asked to take a comfortable seating position. They had to hold the stylus with their right hand between their index finger and thumb, and it was ensured that all subjects have similar grip across trials (Fig. 4.2, left panel).

To perform a trial, two green dots were displayed (Fig. 4.2, right panel): one start point near the left of the screen and an end point in a box near the right of the screen. A third pink cursor which moved according to the stylus tip position was also displayed on the screen. Subject was required to move the pink cursor from start point to the end point “as fast and as accurately as possible” in a straight line within 1 s. If subject exceeded the time limit, a feedback of “too slow” would be displayed. A session ended when subject completed 30 successful trials. A trial was considered successful if it was completed within one second, stopped within 2 mm radius of end target, and the movement was within a pre-defined zone, with boundaries indicated by the visual walls to avoid too large a deviation.

Actual distance between start and end points was 20 mm but a visual magnification of 7.5x was given throughout the trial. This magnification level was close to levels typically used during microsurgery, and a previous study had shown this magnification level to be suitable for computer-based experiments (Safwat et al., 2009). When the subject was prepared to begin the session, a keyboard press set the cursor to overlap the start point and data collection commenced. The cursor was held in position with haptic force for 1 s, after which a buzz indicated that the force was switched off. At this point, the subject was free to start the trajectory towards the end point. Subjects performed three sessions with approximately one minute break in between sessions.

For the control group, subjects completed three sessions in NF, without force
field programmed in the haptic interface. For the test group, their first and third sessions were in NF, similar to that of the control group. However, in the second session, they were subjected to divergent field (DF) during their trials. This divergent force aligned to the straight line was switched on when a subject moved a distance of 4 \( \text{mm} \) from the start point.

![Diagram showing two-dimensional divergent force field during experiment.](image)

Figure 4.3: Two-dimensional divergent force field during experiment escalates deviation from the target line.

Preliminary tests used a force increasing proportionally to the displacement from the target line. However, this force field provided too small force to the subjects, thus the magnitude of the force field \( F(r) \) was changed to a sigmoid (hyperbolic tangent) function of the deviation from the straight line between start and end points (Fig. 4.3):

\[
F(r) = \frac{e^{6r} - e^{-6r}}{e^{6r} + e^{-6r}},
\]

where \( r \) is the distance of cursor to the straight line in \( \text{mm} \). This function gave a greater instability at short distance and a limited force magnitude at maximum 1\( \text{N} \).

### 4.2.4 Data analysis

Data processing and statistical analysis were computed using Matlab software (The Mathworks, USA).

The *trial time* was computed as the mean movement duration over all trials in
Figure 4.4: Calculation of trajectory error.

a session. The movement duration was calculated from the time subject moved 2 mm away from the start point until subject reached the 20 mm distant target and stopped on it, as was checked using a 0.02 m/s velocity threshold.

The success rate, i.e. the percentage of successful trials in a session was calculated for all sessions.

The trial error, the area between the trajectory curve and the straight line joining start to end points (Fig. 4.4) was computed as:

$$e = \int_0^1 r |dx|,$$

(4.2)

where $dx$ was the change in distance along the straight line and $r = \sqrt{y^2 + z^2}$. Trial error was calculated for the part of trajectory 2 mm away from start point till end of trajectory when subjects stopped near the end point. As subjects were given a tolerance of 2 mm radius from the end point to stop, the total path lengths differed for each trajectory. To avoid the different path lengths to influence this computation, the $x$ component was normalized to the $x$ position of the cursor end point. Each subject’s trial errors were also normalized with the individual’s maximum trial error over the sessions before being grouped with other subjects’ data.

The standard deviation of trial error in a session was computed as the standard deviation of the session’s trial errors evaluated at 5000 equidistant increments along the target line (Fig. 4.5). The standard deviation parameter represented the variability in subject’s trajectory during sessions. Similar to trial error,
Figure 4.5: Trajectories in 3D view (top), planar view (middle) and side view (bottom) from one subject during a null-field (NF) session. Broken red line showed the target line joining start-end points and green double-ended arrow showed deviation from the target line. Standard deviation of trial error was calculated from this deviation.
each subject’s standard deviation values were normalized with the individual maximum value before being grouped into test or control group data.

Statistical tests were performed on all data patterns using paired t-test at 5% significance level.

4.3 Results

Raw data

![Graph showing trajectory changes](image)

Figure 4.6: A sample trajectory by a subject in the test group. Subject adapts to the divergent force field (DF) at the end of session as shown by smaller deviation in the last five trials compared to initial trials in DF. Subject could perform straight line in null field (NF).

Fig. 4.6 shows the trajectory of a subject performing in divergent force field (DF) and in null force field (NF). During initial trials in DF, the two-dimensional divergent force field deviated subject’s trajectories in Y and Z directions from the straight line joining start and end points. It was difficult to reduce the error during DF as even a slight disturbance of the hand would translate to much larger deviation due to the exponential force field applied. Both Y and Z deviations were large initially but after some training, the subject was able to adapt to the
force field and reduce the deviations as seen by the much smaller variations in last few trials of DF training. Post-training NF showed even lower errors.

Fig. 4.7 shows the evolution of errors in horizontal plane (deviation Y) and depth plane (deviation Z) for a subject from test group and a subject from control group. For the test subject, the largest deviations occurred in the first 10 trials of DF training but with further practice, the deviation was shown to gradually decrease. The post-training NF trials (session 3) showed further reduction of error compared to the initial NF trials before training, similar to results obtained in studies with arm movement. In the depth plane where visual perception was difficult, the subject could show a reduction of in deviation Z after training with DF. For the control subject, the horizontal deviation Y remained small throughout the trials, but larger depth errors in deviation Z were recorded in the post-training session compared to pre-training.

**Success Rate**

Subjects’ mean trial time was not different before and after training for both groups (p > 0.20). All subjects were able to complete a majority of trials within 1s. Fig. 4.8 shows the percentage of successful attempts for pre- and post-training sessions. Before training, the two groups have similar success rate over 80% (p > 0.224), indicating comparable populations. After training, subjects in the test group recorded a significant increase in success rate in Session 3 (p < 0.033). No significant change in performance was detected in the control group (p > 0.510). Only two out of five subjects from the control group had improved their success rate in the trials after learning. Results after training showed a near significant difference (p < 0.089) between the groups, with test group having much higher success rate than control. The test group had 92.56% success rate after DF training while the control group had only 85.34% success rate with NF training. During the training sessions, subjects in the test group made on average 43.0 ± 5.96 trials in DF while the control group made 34.6 ± 3.58 trials in NF.
Figure 4.7: Evolution of deviations in Y and Z directions for (A) a test group subject and (B) a control group subject.
Figure 4.8: Mean success rate before (blue) and after (red) training for test (left panel) and control groups (right panel).

**Trial Error**

Fig. 4.9 shows the grouped trial error of all subjects, normalized with individual maximum error. For the test group, the overall error \( \text{err}_R \) showed a reduction of error that tended to significance \( (p<0.088) \). Interestingly, in the \( z \) direction, where depth perception was limited, the error \( \text{err}_Z \) tended to be reduced significantly \( (p<0.082) \) by using haptic amplification during training. For comparison, in the horizontal plane where vision was more efficient, the error \( \text{err}_Y \) remained similar with learning, but was anyway small. In contrast, the error in the control group was not modified by learning in any direction \( (p>0.367 \) in all cases), though the error was also small in the horizontal plane, and showing a larger proportion of error from the depth plane where vision was limited.
Figure 4.9: Normalized overall trajectory error ($errR$), error in Y direction ($errY$) and Z direction ($errZ$) of test and control groups before (blue) and after (red) training.
Figure 4.10: Normalized standard deviation of trajectories over all subjects. Standard deviation in a session was evaluated for the distribution of the session’s trajectory errors at 5000 equidistant points along the target line. The subjects’ series of point-by-point standard deviation values were then averaged to get this plot. The top row shows standard deviation of overall trajectory error, the middle row shows standard deviation in Y direction and bottom panel shows the standard deviation in Z direction. Left column is for test group and right for control group.
Standard Deviation of Trial Error

The graphs in Fig. 4.10 were computed from standard deviation of the trial error at 5000 equidistant points along the target line and normalized by individual subject’s maximum value. This standard deviation shows the variability of overall path deviation (top row), horizontal deviation Y (middle row) and vertical deviation Z in depth plane (bottom row). The overall standard deviation of trial error decreased significantly between before and after learning in the test group ($p<0.038$), but no significant reduction in standard deviation was detected for the control group ($p>0.701$). In the test group, normalized mean standard deviation decreased by more than 21%. In contrast, for the control group, an increment of 11.24% was detected in the standard deviation, but this increment was not statistically significant ($p>0.5$). Subjects reduced their movement variability with training in DF, but were unable to do so without haptic amplification.

4.4 Discussion

This study investigated the effect of using unstable dynamics environment to train for accurate reaching in small range manipulation. The idea was conceived following studies of arm-reaching movement (Burdet et al., 2001; Franklin et al., 2003) which showed a potential of learning accurate motion after training with divergent force field in macro movement. Thus, this experiment was conducted to determine if similar form of training would work with the smaller finger movements, and be expanded into some form of psychomotor training just as weight or resistance training has been used as supplement to sports training.

The current experiment was different from the previous investigations of arm reaching because of the small range of movement, the additional dimension of force field, and the visual amplification during movements. With smaller range motion as in this study, it was unclear whether the same adaptation and learning can take place and what magnitude of force field would be appropriate. The pre-
vious studies used force field diverted only laterally (Burdet et al., 2001; Franklin et al., 2003), but in this study, vertical dimension of force field aligned to the line of motion was added. Visual amplification in micromanipulation could already help reduce error and under this circumstances, it may be difficult to observe any changes due to the divergent force field. Nevertheless, the results from this study have shown that even within small range and with visual magnification, the effects of unstable dynamics training can be detected.

Prior to this experiment, few types of force field training were attempted in preliminary tests. Initially, a constant gain was used to set the magnitude of force as a function of error, similar to the force field used in the arm studies. This force field was ineffective because the force was too low at small deviation. It would be risky to set high gain because this may result in too high force when subjects made large deviations. An exponential force field which increased largely with small error, but saturated at a fixed magnitude was found to be suitable for the task. Once the force field equation had been identified, this force field was put to test in a series of experiment sessions.

Earlier, an intermittent-force training was investigated using this force field, i.e. 5 trials with DF followed by 5 trials without DF, continuously until the session ended. Subjects were not informed of the intermittent pattern, and in fact, did not notice the intermittent pattern during trials. The experiment with intermittent force was carried out with seven training sessions. Subjects were asked to achieve a total of 80 successful trials for a session to complete. This was found to exhaust participants as was shown by gradual decrease of error indicating learning but followed by a gradual increase of error towards the end of their experiment, indicating an element of fatigue. Fatigue could mask the benefits of such training therefore, further investigations were conducted by reducing the number of sessions and relaxing the test condition.

Preliminary sessions also tested different paths. Initially, subjects were asked to make movements along a helix path, and during training the subjects would be diverted with forces. The helix path was chosen because this type of path
will show contributions of force field in many directions within one trajectory. However, this path proved too difficult to achieve as subjects ended up tracing the helix very slowly to keep within the boundary and took very long time to complete one session. The helix pattern was therefore shelved for a much simpler pattern of reaching in a straight line. The simple straight line path enabled the investigation of haptic cues without worrying about whether the subject’s skill level would interfere outcome (Franklin et al., 2003). This time subjects were not provided with a line to trace to avoid the dominance of visual effect and a straight reaching movement should be simple enough to achieve without explicit visual guidance.

The final experiment which generated the results presented here, used the exponential force field, required 30 successful trials and 3 experimental sessions. The test group were given training in the divergent force field (DF). The initial trajectories of the five test subjects’ deviated in a large margin. The deviations were recorded in two dimensions: the horizontal plane deviation Y and the depth plane deviation Z. The error in depth plane was larger compared to the horizontal plane for all subjects because of the difficulty in depth perception. After several trials, subjects were able to adapt to the force field and reduce their error, indicating learning occurred even within short distance, as was shown with arm movement studies. Subjects from the control group had null field sessions throughout their experiment and generally showed a decline in error at the end of session, compared to beginning of each session.

Success rate in the test group showed a significant improvement, in contrast to the control group. With practice, it is generally assumed that human tend to become more accurate but learning can saturate such that error does not decrease below a certain threshold. However, the results of this experiment shows that learning is dependent on available feedbacks. Improvements in trajectory error was observed when haptic amplification of error through the DF was provided. This shows in particular that magnified haptic feedback can be used for training accuracy in movement. The repetitive practice by control group is insufficient to
increase the success rate. The results indicate that visual feedback alone is not sufficient to improve accuracy, or that with only vision, learning is slower.

Error in the horizontal plane can be reduced visually but not in vertical direction, probably due to the limited depth perception. This was demonstrated in the larger error recorded in vertical direction for all subjects and the much smaller error in the horizontal plane, where subjects could use visual information to correct their error. Learning and subsequently accuracy, can be further improved if, besides vision, additional haptic feedback is also present.

One major observation of this study was the significant drop of standard deviation in free trials after training in the unstable force field. This meant subjects could make more consistent movements after than before training. A smaller standard deviation indicates better control of movement during the trial. This significant decrease was not found in the control group, thus, the improvement in motion control can be attributed to the training in unstable dynamics.

Findings from motor learning studies can shed some light on how the subjects learn to be more accurate. Certainly, a combination of factors contribute concurrently to learning better motion. One factor could be the additional trials during DF training by the test group who made more errors in their DF session and thus, required more trials in order to complete the session. This longer experience in correcting their trial errors may have contributed to better learning and control of their movement compared to the control group who generally had less trials during their NF training session.

Optimal impedance control could be another factor that causes the reduction of movement deviation. Motor learning theories formulated from investigations of stiffness, torque and force of arm movements (Burdet et al., 2001; Franklin et al., 2003; KadiAllah, 2008) proposed that the central nervous system (CNS) employed mechanical impedance of the arm to counter instability. Franklin et al. (2007) and KadiAllah et al. (2010) showed that CNS could tune arm stiffness in the direction of instability, then activate specific pairs of muscles to optimize impedance in a particular direction. When subjects become more success-
ful in counteracting instability, the stiffness geometry becomes more optimized (Franklin et al., 2004), reducing superfluous co-contraction (KadiAllah, 2008). Optimal co-contraction possibly leads to the reduction of variability in motor output, however, EMG or stiffness measurement would be necessary to test this hypothesis.

As interaction forces are generally negligible in micromanipulation, intuitively haptic training seems irrelevant to the microworld. However, the above results show an example where haptic feedback improved performance of motion controlled under magnification of visual feedback typical of work under the microscope. While it is true that tactile sensation is negligible during actual micromanipulation task, however the use of haptic feedback was shown to be efficient at acquiring more consistency in motion behavior. Subjects become more consistent while training with haptic cues as they did when training in the macroworld. Further, learning and adaptation patterns similar to observed in arm-movement were observed for the small hand movements, suggesting that some training strategies efficient for large movements may be used to train fine hand movements as well.
5 Virtual Reality Training

5.1 Introduction

Virtual reality has revamped the way training and learning can be conducted. Computer simulations that generate three-dimensional scenarios offer the opportunity of experiencing broad range of environments, materials and phenomena within the confines of a room. Successful use of simulators for training pilots in the aviation industry has motivated the research into virtual reality as an alternative mode of surgical skills training. This new surgical training method has several possible advantages over conventional training methods.

Figure 5.1: Training workshop for microsurgery. Images from Jiga and Ionac (2005)

Currently, basic skills and techniques are normally taught at microsurgical courses where trainees have the opportunity to work on animal tissues. Fig. 5.1 shows a training workshop for microsurgery. These courses typically last a few days (Power and Tan, 2007; Abreo and Sivathasan, 2009), therefore laboratory practice with supervision is extremely limited. Microsurgeons require a lot of practice to obtain sufficient manual dexterity and to adapt their hand-eye coordination to manipulate objects skilfully under the microscope (Yaargil, 1996).
Due to the complexity of the procedures, extensive and on-going practice is crucial to maintain proficiency in microsurgical techniques. In addition to improving educational opportunities, VR training may help reduce the steep learning curve, shorten residency programs and lower educational expenses. Trainees can learn basic steps and practice on them prior to attending formal training workshops so that focus of coaching would be on techniques rather than basic skills. Perhaps the most important advantage is the potential to avoid the detrimental consequences associated with the early phase of the surgical learning curve. With the VR system, a safe training environment can be provided where risk-free mistakes can be made, making it possible to pinpoint specific causes of failure during the learning process (Marescaux and Rubino, 2003). Training with computer simulation offer the possibility of distributed practice for effective motor skill learning with replication of cases difficult to emulate using real materials. The learner can train at individual learning pace, at a level of difficulty adapted to the learner’s capability.

Surgeons have formal examinations to gauge surgical knowledge but currently in the UK, there is no requirement to undergo psychomotor testing before starting a surgical training programme (Grantcharov, 2006). An awareness of trainees’ psychomotor abilities may help instructors to plan training programmes more suited for the individual and this information could also help to identify one’s strengths and weaknesses for optimizing training (Bann and Darzi, 2005). If simulators are designed to reflect surgical practise more closely, the assessment may be a valid tool (Darzi et al., 1999) and training using the simulator would be more relevant to actual operation.

A few commercial systems for virtual reality medical simulators are now available for training and studies on using these simulator systems in learning tasks have shown favorable outcome (Spiteri et al., 2010; Rossi et al., 2004; Aggarwal et al., 2004). Early simulators were for minimally-invasive surgery, such as MIST-VR, LapSim and LapMentor (Grantcharov, 2006). Another commercially available version of simulators is for eye surgery. The Eyesi from VRMagic, Ger-
many (Fig. 5.2) provides basic training step for cataract removal to vitreoretinal surgeries. It has an objective assessment of surgical performance and records parameters including handling of instrument, surgical efficiency and tissue treatment during training.

Figure 5.2: Figure shows user training with the Eyesi. Middle and right pictures show graphics from the simulator. Images from www.vrmagic.com

There were very few groups of researchers developing simulator for vascular anastomosis in open surgery. One of the earliest simulator was from Boston Dynamics Inc. which used real surgical tools with force feedback provided by a pair of PHANToM devices (O’Toole et al., 1999). The large tools and the bulky system corresponded to general surgery rather than microsurgery. Brown et al. (2001) developed a microsurgery simulator with tools tracked electromagnetically but it was not possible to provide haptic feedback using the system if it is required for training. Similar to Brown’s work, Holbrey (2005) developed a suturing simulator for vascular surgery with a pair of ratcheted needle holder attached to a PHANToM Desktop (Sensible Technologies) to provide haptic feedback to the dominant hand while tissue manipulation in the subordinate hand was achieved using Spacemouse (3dConnexion). He proposed that training should perhaps begin with sub-tasks and in random order. Therefore, in the project of this thesis, much simpler tasks were designed to train very basic movements and to investigate the benefit of cueing signals during microsurgery training.
This chapter presents the design and development of two virtual reality modules for training two basic tasks of microsurgery, needle grasping and needle insertion. The focus of the modules was not to replicate actual microsurgery scenario, but to provide a basic platform to train primitive movements in microsurgery and investigate some aspects of learning. Using PHANToM Omni made it possible to provide haptic feedback if required as part of training strategy, as force field have been shown to help improve accuracy (Burdet et al., 2001; Su et al., 2010). The force field training was not investigated using these training modules, but the force generation of PHANToM unit was used to provide gravity compensation to reduce the weight of the stylus. Experiments were conducted with healthy subjects to evaluate their performance when visual cues of object orientation were provided during training.

5.2 Development of Virtual Reality Trainer

5.2.1 Hardware

Measurement Device

Figure 5.3: Setup for the virtual reality modules.
Fig. 5.3 shows a subject using the virtual reality trainer. The position measurement device used for the virtual reality training system is the PHANToM Omni from Sensable Inc, which had been explained in previous chapters.

**Stereoscopic Visor**

The stereoscopic visor was the eMagin Z800, fixed on a metal stand as shown in Fig. 5.3. This visor was particularly suited for the training simulator because it provided viewing experience similar to a microscope. The visor had a pair of adjustable lenses which subjects had to peer into. Furthermore, with the eMagin Z800 visor fixed on a metal stand, users were required to maintain proper head position for the clearest view, similar to what trainees need to learn when using a microscope. This was a feature not available with other stereoscopic systems which used shutter glasses, such as the Immersive Workbench from Sensegraphics or the Reachin Display from Reachin Technologies.

**Needle Holder and Sensor**

![Figure 5.4: Typical way of holding microsurgical tool.](image)

In this thesis, the representation of the needle holder, both in characterization and graphics, was based on a pair of standard jewelers’ forceps due to the great availability and much lower cost. In real microsurgery, it should be noted that the right tool to use for grasping a needle would be a needle holder, although the
forceps could occasionally be used to hold the needle during needle retrieval stage. As for terminology, the term needle holder will continue to be used throughout this thesis to indicate the tool for driving the needle.

For dexterous manipulation of microsurgical tool such as forceps or needle holder, the rotating axis of the tool should lie between the thumb and index finger (Burdet et al., 2004). Fig 5.4 shows typical way of grasping a microsurgical tool.

Initially, a pair of instrumented forceps was constructed to represent the needle holder, and to electronically detect grasping action. The instrumented forceps’ opening or closing angle was determined by flexible bend sensor attached to both ends of the forceps, as shown in Fig. 5.5A. Closing or opening the forceps would deform the sensor, thus changing the resistance of the sensor leading to a change in measured voltage. The measured voltage was then calibrated to compute forceps opening angle. An aluminium fixture was fabricated to mount the instrumented forceps to the PHANToM stylus. A force sensor was added to measure thumb grip force.

Figure 5.5: (A) First tool prototype using a pair of instrumented forceps with flex-bend sensor (inset) to measure angle opening. (B) Current prototype using a force sensor to simulate tool opening angle.

However, due to the structure of the PHANToM measurement device, it was difficult to attach this fixture onto the stylus and still kept the tool rotation axis
between the thumb and index finger. To counter this problem, instead of using a real pair of forceps, only simulation of the forceps was implemented. Firstly, a force sensor was attached on the PHANToM stylus to capture grip force (Fig. 5.5B), which was fed into the software algorithm to simulate opening and closing of the jaws graphically. The width of the stylus was maintained to be similar to that of needle holder when opened. This design allowed a more comfortable gripping position as well as more realistic gripping movement compared to the instrumented forceps. Gravity compensation in the vertical direction was added to counter the weight of the stylus, leaving a much lighter load on the hand, as manipulating real tool. As the hand movement was small and slow, the inertia of the stylus was assumed to be negligible.

![Graph of force versus voltage for the force sensor.](image)

The force sensing resistor Model 402 (Interlink Electronics) was used to measure grip force in this system. To get force measurement, a calibration was first conducted to convert voltage readings into force. The force versus voltage graph is shown in Fig. 5.6. An exponential fit was used to predict the force level based on voltage readings from the sensor as follow:

\[
\text{force} = 3.767 \times 10^{-11} e^{5.516x} + 0.07872 e^{0.8894x}
\]  

(5.1)
where $x = \text{voltage}$.

The opening and closing of the virtual needle holder was based on the characteristics of a pair of standard forceps. Measurement of grip force versus tool jaws opening angle was made, and then the equation relating the two was used in the program to simulate the opening angle of the virtual needle holder based on applied force. Fig. 5.7 shows graph of forceps opening angle versus grip force. The minimum force required to close the gripping jaws of the actual pair of forceps was measured to be 0.75 N, and this was the force magnitude used to represent full closing of the virtual needle holder in the simulator. A different tool or tools from different manufacturers may require varying levels of force, which could be measured and applied to the program as appropriate to model the behavior of the chosen tool. For example, in microsurgery, the needle holder is commonly used to drive the needle instead of the forceps, therefore, the characteristics of a pair of micro needle holder can be modeled in the same way.

\[
\text{angle} = 4.5x^2 - 7.2x - 2.8 \quad (5.2)
\]
where $x = \text{force}$.

Figure 5.7: Graph of forceps opening angle versus grip force.
5.2.2 Software

The training modules were developed on a Viglen 2.66 GHz dual-processor PC with 3.25GB RAM and nVidia FX1500 graphics card. The operating platform was WindowsXP SP3. Basic framework of the training modules was developed using VisualC++ (Microsoft Corporation). Integration with the PHANToM haptic device was enabled by OpenHaptics Academic Edition drivers from SensAble. Graphics of environment and objects were developed using OpenGL. The collision detection algorithm and structure of object classes were from Wang et al. (2008).

Two virtual reality modules were developed to train for needle grasping and needle insertion, sub-tasks of a suture procedure (Payandeh et al., 2002). These two modules were rendered in 3D, allowing depth perception using stereoscopic visor. In the needle grasping and needle insertion modules, only rigid bodies were modeled. The needle grasping module had two main objects, the needle holder and the needle while needle insertion module had an additional torus target, used to indicate insertion point and to determine quality of insertion in the training exercises. An assessment function was added to each of the modules to calculate grasping angles, grasping point, insertion and exit angles, grip force and to record movement trajectories of the objects.
Needle

Figure 5.8: Suture needle description. Image from www.ethicon.com.

Suture needle is described by its length, curvature and point type (Fig. 5.8). For vascular applications, the suture needle is usually the 9-0 type, between 4mm-6mm and with 3/8 curvature (135° arc). The 3/8 suture needle is also used for applications related to eye, sub-cuticular, fascia, plastic and skin. For the two training modules, the needle was drawn as 3/8 with needle length 6.0mm.

Due to the simple environment, the dynamics of the simulated needle only depended on forces applied by the tool, either through touching or grasping. When touched by the tool, movement of the needle depended on the magnitude and direction of force applied to the needle. When in grasped mode, the needle moved together with the tool, adopting the transformation matrix of the tool. This needle arc was segmented into 32 separate portions, each portion represented by its own spatial coordinates [x,y,z]. These portions were used at later stage for detecting contact with another object, and for calculating reference vectors for assessment.

Needle Holder

In this training module, the graphical representation of the needle holder (Fig. 5.9) used a standard forceps object file from Wang et al. (2008) because the modeling of the tool was based on a pair of forceps. However, the object file can be changed depending on the choice of tool, its characteristics and specification.
The movement and orientation of the virtual tool was calibrated based on movements of the PHANToM Omni stylus. The transformation matrix of the stylus was obtained using OpenHaptics library. The movement translation was also magnified 10x on screen to give an effect of magnified motion under microscope.

![Tool reference vectors](image)

**Figure 5.9: Tool reference vectors.**

**Torus Targets**

The torus targets used for needle insertion module were abstract objects in the modules, used to indicate target positions, therefore would not move when touched. The torus was segmented into 128 segments along its curvature, each segment’s x-y-z coordinates was stored for collision detection algorithms. When a needle was inserted into the torus, the needle would stay in the torus until the needle was grasped and pulled out of the torus, to simulate suturing a membrane. Any needle contact with the torus circumference during insertion was recorded as inaccuracy. The radius of the torus can be adjusted bigger or smaller to train for different precision level. Position and orientation can also be varied to train tool manoeuvring.
Collision Detection

Collision detection is a very important component in a virtual reality simulation. It detects any contact between objects so that appropriate reaction forces can be applied to make the visual display mimic real physics. The method for collision detection used in these modules was the bounding-volume hierarchy method (BVH) which constructs a hierarchical bounding representation based on primitives (Ericson, 2005), e.g. spheres and boxes. During collision testing, the BVH method employs a simple search routine that queries for an overlap of bounding volumes and ignores most pairs of components without intersection. To choose the shape of bounding volumes in the hierarchy is one of the main design criteria of BVH. For fast application, simple shapes such as spheres and Axis-Aligned Bounding Boxes (AABB) (van den Bergen, 1998) are more favorable.

In these training modules, the bounding volume for the needle holder was using AABB bounding box method because the straight axis of the needle holder fitted into a boxed volume. The bounding volume chosen for needle and torus was sphere-based because spheres gave tighter fitting to curved regions. The lowest level BVH spheres on the needles were applied manually on each of the 32-segments along the needle arc. The next higher level spheres were built by bounding pairs of adjoining low-level spheres. The torus was given 128 BVH spheres in the lowest level and had a total of 8 levels. Fig. 5.10 shows the

![Figure 5.10: Needle bounding spheres.](image-url)
bounding spheres on a needle.

**3D rendering and workspace**

All objects were drawn in a workspace of 20mm x 18mm x 15mm, typical of microsurgery (Burdet et al., 2004). Movements on screen were amplified 10x from actual movement as measured by the PHANToM unit to illustrate views as seen through a microscope.

The objects were rendered in 3D to give depth perception of objects within the visual display. A boxed background was drawn to give an added depth perception to the workspace. The 3D effect was achieved by rendering two different views of the workspace based on two camera positions, separated by a distance of 60mm. The separation distance represented the typical distance between left and right eye and could be tuned longer or shorter with a keyboard press to suit the individual inter-ocular distance. This capability was in addition to the sliding of eye-pieces on the visor. Other graphical illustrations were added onto the workspace as required by each training modules, e.g. colored lines as visual cues.

**5.2.3 Assessment**

In the training modules, positions of needle and torus were varied to train manoeuvring and accuracy. Positions and orientations of objects were calculated based on direction vectors derived from a few points on the object.

**Grasp Angle**

Main performance metrics in these modules were the needle grasping angles (yaw, pitch and roll) and the needle grasping position. Optimal placement of the needle within the needle holder will facilitate the puncturing of tissues and make it easier to rotate the needle along the curvature in one smooth movement, minimizing damage. During initial stage of learning, the grasp angle should be perpendicular to the jaws of the needle holder although at later stage, in certain
anatomical situations such as in deep structures, an angled vector of the needle may be required (Macdonald, 2005).

To calculate the needle grasping angles in the training module, the reference vectors for the needle and virtual needle holder were compared. Reference vectors were obtained using several points on the objects. Similarly for the needle holder, using the transformation matrix obtained from the PHANToM unit, various points on the needle holder were identified. Using those points, the side, frontal and normal vectors of the needle holder were computed. The dot product of matching pairs of vectors from needle and needle holder gave the grasping angle errors for yaw, pitch and roll. Fig. 5.11 shows optimal grasping angles and calculation of angle errors.

![Figure 5.11: Optimal grasping angles (top) and how individual pitch, yaw and roll angles are calculated (bottom).](image)

**Grip Position**

The grasp location on the needle was determined from the lowest-level bounding spheres. The sphere on the needle which collided with the bounding box of the needle holder was recorded as the needle grasping point. The diameter of each bounding sphere was 0.19 mm, and this was the minimum resolution of position measurement on the needle arc.
The grasp position recommended is usually between the midway and 2/3 from needle point (Fig. 5.12). If the needle is grabbed too close to the tip, the tip will point downward and suturing range would be restricted. Conversely, if it is grabbed too close to the shank, the tip will point too far upward, and the needle would be prone to bending and breakage (Macdonald, 2005; Hughey, Hughey; Gi, 2010).

Figure 5.12: Recommended grasp position on a suture needle. Image from Gi (2010)

**Grip Force**

Grip force was recorded from the calibrated pressure sensor attached on the PHANToM stylus. Although the previous experiment had shown no effect of grip force in end-point accuracy, grip is still an important factor in needle grasping because over-exertion may bend the tiny needle, cause premature fatigue during an operation and grasping at the wrong angle using a large force may flick the needle out of the viewing range. The training simulator could record grip force data and if beneficial, could display this to the users for them to practise good grip.
**Insertion and Exit Angles**

Optimal needle insertion is at a right angle to the tissue surface to allow a smooth curving motion through the tissue during suturing. In the needle insertion modules, the torus object was used to calculate quality of insertion. Precision was calculated from the number of times a user touches the side of the torus with a needle. The insertion and exit angles were calculated using needle reference vectors and the normal vector to the torus plane. To get yaw and pitch angles, the needle side and normal vectors were used to compare against the torus’ normal vector as shown in Fig. 5.13. Other factors such as needle trajectory, hand movements and procedure time were also recorded for analysis.

![Insertion and Exit Angles Diagram](image)

Figure 5.13: Optimal insertion angles (top row) and tilted insertion with yaw and pitch angles (bottom row).
5.2.4 Training Modules

Needle Grasping Module

Figure 5.14: Screenshot of needle grasping module without visual cues (left) and with visual cues (right).

The virtual environment of the needle grasp was as shown in Fig. 5.14. Five needles with different orientations were prepared. At a key press, a needle would appear on the screen and user had to grasp the needle in the best orientation and position based on the user’s judgement. Once grasped, the user had to place the needle in the large wired sphere at the bottom left of the screen (dumping bin) and the next needle with a different orientation would appear. The training would stop after all five needles were collected, and a user could repeat the training by replaying the program.

In a special training session mode, visual cues of the needle reference frame and the needle holder reference frame were displayed to guide the user to the best orientation of grasp. The user could use the color-coordinated reference axis to orientate their tool to get a good grasping angle. The numerical angle errors were also displayed on screen. To help naive subjects who had no knowledge of proper grasping technique, two videos showing good grip orientation and good grip position were prepared and users could look at the training videos before embarking on their VR exercises.
**Needle Insertion Module**

The needle insertion module used the torus to indicate insertion points. The torus position and orientation can be randomized to train manoeuvring of needle (Fig. 5.15), or set to mimic a real training scenario such as suturing on a tube (Fig. 5.16). The screenshots show a pair of tori used for experimental purposes to compare training feedback, but the actual number of torus can be increased depending on training requirements. A series of torus pairs can also be pre-programmed and then fed to the user as in the needle grasping trials.

![Figure 5.15: Screenshot of needle insertion module with various torus orientations.](image1)

![Figure 5.16: Screenshot of needle insertion module with torus pair on tube, and needle fixed within the torus during insertion (inset).](image2)
5.3 Experiment

A simple experiment was conducted using the needle grasp VR module to investigate how visual cues can be used to train grasping angles.

5.3.1 Materials And Methods

Subjects

10 subjects without known pathology, aged between 25-35 years, participated in this study. The subjects were divided into two groups - one test group of 5 subjects (1 female), and a control group of 5 subjects (1 female). The subjects gave informed consent prior to starting with the test. All subjects were right-handed and used their right-hand for the experiments.

Protocols

All subjects were shown two videos before commencing the experiment trials (Fig. 5.17). The first video showed the simulator at work, and proper needle grasping position and orientation. The second video showed similar needle grasping procedure but had additional color-coordinated reference frames on the tool tip and on the needle to give subjects a better perception of an object’s planes. In that video, the tool reference frame was matched by color to the reference frame of the needle. Both groups were shown the two videos and once the subject understood the procedure and the expected outcome of their movement, they proceeded to start the experiment.

Each training session had 5 needles in different orientations which the user had to grasp and place in the wire sphere (dumping bin). Only one needle appeared on the screen at a time, and when subject released the needle in the wire frame, a new needle immediately appeared. If the needle was released out of the wire frame, the trial was considered incomplete, and subject had to grasp the needle again properly and place it in the bin. Subjects were allowed to rotate, grasp and release the needle as many times as they wanted until they were satisfied
with the grasp before placing the needle in the bin. When needle was within the bin boundary, the color changed from green to purple, indicating to the users that they could release the grip.

Subjects had to perform 7 training sessions, grasping a total of 35 needles. Sessions 1 and 2 were pre-training sessions, session 3 to 5 were training sessions and session 6 and 7 were post-training sessions. The control group used the same modules throughout all the seven sessions but the test group used a different training module with visual cues in their three training sessions. The visual cues indicated the correct orientation of the grasp with matching color axis on the tool and needle.

**Data Analysis**

The grasping angle and the grasping point were two important performance metrics to measure the quality of the grasp. Other parameters such as number of attempts, trial time, hand movement and grip force were also compared although these values should weight less in the evaluation of good grasping.
5.3.2 Results

Evolution overall angle - raw data

Figure 5.18: Evolution of angle errors over the 7 sessions.

Fig. 5.18 showed the evolution of overall mean error in contact angles between needle and needle holder for all seven sessions. Initial angle error showed similar magnitude between test and control group, indicating comparable populations. Results showed a gradual and small decline in error from initial trials to end of trial for the control group. For the test group, their angle errors dropped significantly when presented with visual cues in training session 3, 4 and 5. However, when visual cues were removed in sessions 6 and 7, this error increased but was still lower than pre-training error.

Angle performance before and after training

As shown in Fig. 5.19 (top), the test group showed significantly lower angle error after training (p<0.003) compared to the control group who had similar error before and after training (p>0.07). The error in the test group decreased by 27.53% from initial error while the control group reduced their error by only 9.62%. The assessment in the VR system allows separate calculation of yaw, pitch and roll angles which helped to identify contributions from each of these
angles towards overall angle error. The individual yaw, pitch and roll angle errors are represented in Fig. 5.19 (bottom). The yaw angle error was reduced in the test group by 24.24% or $9.15^\circ$ ($p<0.037$) while in the control group, the yaw error remained similar to before training ($p>0.36$). The pitch angle recorded the highest error compared to the other two angles for both groups in pre and post-training sessions. This was the vertical tilt of the needle holder relative to the needle. The test group reduced post-training pitch error by $12.44^\circ$ ($p=0.051$) while the control group reduced the error by $6.92^\circ$ ($p>0.12$). Similarly in roll angle error, the test group had large decrease of $14.29^\circ$ after training ($p=0.052$) but the reduction was small in the control group, only $4.55^\circ$ ($p>0.22$).
Grip Position

Figure 5.20: Absolute error (left) and signed error (right) of grip position.

Test group increased the grip distance (Fig. 5.20) from the recommended range by 0.12 mm compared to before training, while in the control group, subjects maintained similar grip position as before training. The recommended range used in this analysis was midway and 2/3 from the needle point although grasping point as far back as 3/4 from the needle point may also be acceptable (Moakeem, 2010). Subjects in the test group tended to grip upwards nearer to the swage area after training.

Trial time

Figure 5.21: Trial time for needle grasp.
Fig. 5.21 shows needle time in test group increased by 7.24 seconds after training, while in the control group the time was reduced by 0.5 second. However, these differences in trial time before and after training were not statistically significant in both groups (p>0.43).

**Tool movement**

![Figure 5.22: Movement of tool (left) and total gimbal rotations (right) as recorded from the PHANToM unit.](image)

The tool movement can be quantified by translation distance and total rotation angles (Fig. 5.22). In translation distance (left), total distance traveled increased for test group from 168.56 mm to about 279.43 mm, but this increment was not significant (p>0.24). In the control group, the distance traveled remained similar before and after training with a slight increment of 4.35 mm from 185.94 mm before training (p>0.95). Rotation angles in post-training data of the test group was recorded from the three gimbal encoders of the PHANToM unit. The total rotation angles showed an increase, similar to the translation data, but in rotation angles, the difference was found to be statistically significant (p<0.013). Total rotation angles in all three gimbals increased by 80% in the test group after training, while the rotation angles in the control group remained similar (p>0.92).
Ratio of Needle Tip to Tool Tip

Despite the increased distance traveled by the stylus, the ratio between distance traveled by the needle and tool did not change significantly in both groups (Fig. 5.23). The ratio was between the range of 0.42 and 0.44.

Normalized motion smoothness

Due to the difference in path lengths, the number of zero crossings which
measured smoothness of motion was normalized with the total distance traveled in individual trials. Fig. 5.24 shows that normalized motion smoothness improved in both groups but the improvement was only statistically significant in the control group (p<0.0023 for control, p>0.19 for test group).

**Number of attempts**

![Number of Attempts](image)

Figure 5.25: Number of attempts before needle was successfully grasped.

Both group in control and test showed an increase in number of attempts to complete the task (Fig. 5.25). Test group attempted on average 2.3 grasps per needle in pre-training sessions and increased the average to 3.6 after training (p<0.03). As for control group, user increased the number of attempts from 1.8 attempts to 2.3 but this increment was not statistically significant (p>0.45).

**Grip Force**

Fig. 5.26 shows that subjects from both groups maintained their force level during grasping with very low deviation (p>0.38). The test group had higher standard deviation before training but reduced after training to a level similar to control group. The force used to close the gripper set for this simulator was 0.75 N and subjects were able to maintain this.
5.3.3 Discussion

In this experiment, visual cues were shown to help in training tool orientation. Test group subjects changed their grasping behavior after the visual cues training although the initial instructions given to the two groups were the same. Subjects who were given visual cues during training voluntarily spent more time and more effort adjusting their grasping angle to get better grasp at the end of training. Their post-training angle errors were significantly lower as a result of this. Interestingly, one subject in the test group complained about the visual cues being a distraction during her training but results indicate that despite her dislike of the extra information, her performance did improve. This may correspond to the difficulty in actually learning the task. In contrast, overall angle error showed no significant improvement in the control group.

The overall angle error was the average of yaw, pitch and roll angles. Test group performed better in each individual angle compared to the control group, whose performance remained similar. The improvements could be attributed to the individual reference cue given to each of the angle instead of an overall representation of averaged angles. From the individual angles, it was noted that both groups had highest error in pitch angle, followed by roll angle and finally least amount of error in yaw angle. In the lowest group of error (yaw), the test
group could still improve significantly. The yaw angle was also the angle given most attention by surgeons during training because the pitch and roll angles could be improved by having a flattened area on the needle body for grasping.

As grip position was not specifically trained using visual cues in this experiment, no significant change in position was observed in the two groups. The average grip position of the test group shifted slightly nearer to the swage end after training but this difference was anyway small and insignificant. The reference frame shown to the user initially lie within the recommended range, which was mid-point and 2/3 of the needle length measured from needle point. When subject grasped the needle, this reference frame would shift position to their new grasping point, calculating and displaying a reference frame specific to the grasp point. Overall, both groups grasped nearer to the swage end than the point end.

In the experiment, the test group recorded higher values in number of attempts, trial time, distance traveled and rotation angles after training. The increments did not necessarily mean worse performance after training; instead it implied that precision may require more effort. A good surgeon is not necessarily a fast surgeon (Darzi et al., 1999). The test group had put in more effort in exchange for more precise angle while the control group were not shown to make the changes in movements to improve their precision. To reach a particular orientation required a certain amount of movements, which the subjects in the test group learned. After training, they made the effort to orientate their tool to get better grasping angles. Although a good surgeon is also perceived as having a greater economy in movements (Datta et al., 2001), if less movement yielded poor results, that would also be unacceptable. Conversely, too much hand movement causes fatigue and too long an operation could negatively influence the outcome of surgery. A balance between hand movement, duration and quality of the movements has to be identified. Currently, the optimal amount of movement and duration spent for the needle grasping tasks were not known, therefore it was inappropriate to grade the performance based on those measures. Performance of experienced surgeons using the trainer on the same task
can perhaps be used as a benchmark to determine an acceptable duration and movements for objective assessment of these tasks.

An interesting observation was seen from the motion smoothness results of the control group. The group maintained similar trial behavior before and after training as shown by the same level of rotation angles, distance traveled and time spent on each needle. However, their motion smoothness improved by a significant margin. With repetitive training on the same module and not altering their paths much, subjects learned to improve their motion smoothness. In contrast, the test group’s improvement on the normalized motion smoothness did not show a significant difference although the number of peaks also reduced. This could be attributed to the new information obtained during training phase, which subjects used to plan for new trajectories and therefore, practise on these trajectories began much later.

Previous studies of objective assessment of surgical skills which measured economy of movements only looked at translation distance of the hand but did not compare rotation angles (Grober et al., 2003; Judkins et al., 2008; Kazemi et al., 2010). Grober et al. (2003) used the Imperial College surgical assessment device (ICSAD) which sensed hand motion using electromagnetic trackers placed on the dorsal surfaces of the microsurgeons hands. The computer software then computed the number of hand movements, hand travel distance and direction, and acceleration while the surgeons performed a microsurgical drill. The microsurgical test required each subject to pass two interrupted sutures through synthetic tissue, and tie a square surgeons knot, followed by two additional square knots. Judkins et al. (2008) compared performance of one surgeon while training with the da Vinci surgical system and when the surgeon performed similar task during a real human operation. The metrics used was time to task completion, total distance traveled, speed, curvature and grip force. In Kazemi et al. (2010), instead of working with tangible materials, subjects worked on virtual objects using PHANToM Desktop. The metrics calculated were tool travel distance, insert and exit angles, ratio of needle to tool movement, damage area and number
of attempts. Similar to Kazemi’s insertion task, the needle insertion module developed here calculated all the parameters, but with additional computation of grip force, grip position and individual grip angles. Total rotation angle was also computed from the sum of gimbal rotations as measured with the PHANToM device. Microsurgical procedures involve much rotation of tools; therefore total rotation could possibly be used as a performance measure in parallel to total translation.

In conclusion, with appropriate feedbacks on a training simulator, user can be conditioned to learn particular skill. The cues can provide corrective promptings during actual activity, allowing meticulous coaching. Visual cues in this experiment have been shown to help with grasping angles, while haptic cues in earlier experiment was shown to reduce deviation but how and when to apply these cues during simulated surgical training require careful consideration. The VR should train for proper movements by giving useful cues at suitable time, and ideally should be reduced gradually as a user progresses through the levels. Feedbacks of their performance must be available in order to learn from previous performance and identifying their strong or weak points.
6 Conclusion

This chapter summarizes and analyzes the contributions of the work in this thesis. Certain limitations are discussed, followed by some recommendations as extension of these studies.

Continuous miniaturization in the medical, life science and electronics industry has made it necessary for humans to perform procedures on more minute objects using micromanipulation techniques. Micromanipulation requires a high degree of accuracy because a slight deviation may lead to unsuccessful operations or cause a product defect. Due to the highly unique nature of the tasks requiring decision-making capability and high dexterity, humans are still preferred over automated systems. Humans are limited in their precision due to many factors. It is important to understand the factors that influence accuracy in micromanipulation in order to propose ways to improve accuracy and learning of micromanipulation, thus I performed experiments to identify these parameters.

Contributions

A first experiment was carried out to investigate the factors of magnification and grip force affecting accuracy of static and dynamic micromanipulation tasks. Three groups of subjects from different skill levels in micromanipulation helped to identify how expertise influence accuracy. The results showed that, for all groups of subjects, accuracy increases with magnification until 10x, but larger magnification did not improve it further. Expertise led to reduced error and grip force did not affect accuracy in the magnified condition, indicating that
controlling grip force may not be the most important factor to train.

The second experiment compared bimanual versus unimanual strategies for small range reaching movement to several targets presented randomly. Overall, results showed that performance was much better with bimanual strategy compared to unimanual. With static left hand within view, subjects moved straighter and stopped more accurately on a target whereas additional dynamic movement from the left hand further helped the right hand make a smoother trajectory. Postural support of the reference left hand provided more consistent outcome. These results outlined the importance of the left hand, and its visual feedback, in assisting the right hand perform more accurate reaching movement, even within small travel range. Movement of the left hand should therefore be trained together with the right hand, to form coordinated, accurate motions.

The third experiment studied the effects of learning 3D micromanipulation in an unstable dynamic environment. The test group subjects were given training of small range reaching movement in an divergent force field, providing unstable dynamics, while the control group had training in a stable environment with null force. Results showed that subjects in the test group increased the success rate, in contrast to the control group which had similar rate after training. The error and its standard deviation decreased more in the test group than in the control group. In summary, training with haptic cues, i.e. amplification of proprioceptive error, enabled subjects to become more accurate, in contrast to training using only visual magnification.

Virtual reality simulator is anticipated to be an important training and assessment gadget in the near future, but this project did not aim to develop such sophisticated training simulator as part of the thesis. Instead, this project aimed to develop simple training modules to investigate some factors that affect micromanipulation accuracy because a better understanding of micromanipulation will hopefully help in the design of better training methodology. Two virtual reality training modules were developed with 3D stereoscopic view and assessment capability to provide basic training, and to enable investigations related to
primitive tasks of a microsurgery procedure that have not been addressed in previous simulator efforts. The tasks to be trained were needle grasping and needle insertion. The assessment included computation of individual angle errors, grip position, grip force, trial time, travel distance of tools and needle.

Using the VR training module, a fourth experiment was conducted to study how visual cues helped in learning orientation of the tool. Results showed subjects who trained with the visual cues showed less angle error after training compared to the group who did not receive visual cues, but needed longer trial time and more motion to achieve better angles. Results from this experiment imply that visual cues, if applied appropriately during training, could help facilitate learning and improve performance.

**Limitations and suggestions for future work**

There are several limitations with this work, ranging from human factors, equipment limitations and the movements studied in the experiments. Firstly, the experiment with visual magnification and grip force was investigated with visual feedback only in two dimensions, displayed on a monitor screen. Only 2D view was used in this experiment because the visual feedback of the horizontal view is expected to have a greater influence on error reduction since depth perception is difficult with micromanipulation. However, if a stereoscopic setup had been used, measurements from the depth plane could provide some other insights relating to micromanipulation accuracy. In subsequent experiments where the aim was to control movements along a path in 3D space, subjects were provided with stereoscopic view.

Another limitation of this work relates to movements studied. Simple reaching movements was investigated in the learning of unstable dynamics tasks. This certainly did not reflect the full learning of actual micromanipulation task, and there is a possibility that other movement paths will generate a different outcome, though studies with arm movements have shown that human do generalize learning to other directions (KadiAllah et al., 2010). Pilot tests were carried out
and it was found that subjects had difficulty when a complex path was presented, i.e. helix path, because this would impose long experimental sessions on subjects (nearly one hour per session) and much effort from subjects to complete a session, leading to fatigue. It is important to find a suitable amount of trials and fairly easy task so that the effect of learning from the experimental paradigms can be observed within short experimental sessions. Now that the experimental results have identified some benefits of haptic amplification training, other tests in the future could use similar experimental paradigm to test more movements, i.e. short cursive or straight movements in multiple directions, to identify how learning can generalize to different visual depths and motion. EMG recordings of muscles related to precision grip can help the understanding of how muscle groups work together in various training conditions to generate the end-point accuracy for a micromanipulation task. Some muscles that can be studied would be the adductor pollicis, flexor pollicis brevis, first palmar interosseous, extensor digitorum and flexor digitorum profundus, which affect grip (Harwell and Ferguson, 1983).

As instability was shown to help in learning accurate reaching motion, this learning strategy using unstable dynamics can perhaps be implemented as a form of psychomotor training for fine manipulation. This can be easily implemented on a training simulator, as a basic training module prior to practising on sophisticated tasks.

The VR training simulator that had been developed for the study here was a simple one with basic training modules for needle grasping and needle insertion. This is definitely insufficient to provide surgical skills training, therefore the ultimate long term goal should be to develop a simulator with progressive modules, providing training of complex skills in multiple stages. A user should have the possibility to progress from primitive training, such as the needle grasping, insertion or knot-tying to more complex task once the basic level of psychomotor skills have been achieved. The highest level training should provide a platform with tissue and fluid modeling to give users more realistic response to their ac-
tion. With accurate fluid modeling, the blood flow rate after suturing can be calculated as a measure of competence for the higher level training modules.

Many different procedures can be modeled with a virtual reality system but for effective training, appropriate segmentation of tasks and timing and type of cues must be given careful consideration. As a next step, the performance of training a full complex task will be compared to training on sub-tasks before embarking on the whole complex task. This is to examine the effect of modular learning and how to best segregate the learning of tasks using a surgical simulator. Findings from the task decomposition study of Frederiksen and White (1989) indicate the necessity of constraining task in a way that will develop particular concepts needed for expert performance, especially the cognitive aspects of expertise. A well designed task decomposition would help learning not only of the task itself, but on other dynamic control tasks.

In order to get a simulator to be widely accepted as an assessment tool, there must be evidence to show the transfer of learning from simulator to actual microsurgical task. Currently, there is no consensus on quantitative assessments of trainees using a simulator. Various parameters like speed, grip force, economy of movements, suture placement, suture tension and quality of knots from experts during an actual operation and when they use the simulator can be compared to make a suitable assessment checklist for new trainees. This in itself is a difficult study because judging a trainee’s actual performance in surgery from their performance on a trainer is very dependent on what parameters are being used for the assessment, and how closely the simulator can emulate real operation. Transferability of skills from simulation to operating theater and retention of skills are areas that should be carefully studied.
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