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Effects of Varying the Force Levels and Direction of Force Change on Accuracy and Force Variability in a Cyclic Isometric Pinch Force Tracking Task

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by

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Abstract

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Abstract: This study investigated how varying the required force level and the direction of force change produced by the thumb and index finger affect the accuracy and variability of a cyclic isometric pinch force-tracking task. Accuracy was examined by both absolute error and relative error for the minimum and maximum force levels and by root mean square error (RMSE) and normalized root mean square error (normalized RMSE) for the force direction reversals. Variability was represented by coefficient of variation of error (CVE). In this study, 'maximum force' was defined as the highest force level of a given target force range, and 'minimum force' was defined as the minimum force level of the target range. In addition, 'force increasing to decreasing' indicated that the track ball motion changed from increasing to decreasing, requiring the performer to exert increasing force up to the maximum force level and then decreasing force to follow the track ball moving toward the minimum force level. The phrase ‘force decreasing to increasing’ indicated the opposite force direction reversal. Eighteen healthy right handed adult volunteers (nine men and nine women; mean age ± SD, 28.3 ± 1.22 and 26.4 ± 1.74) participated in this study. The participants performed a cyclic isometric pinch force tracking task over three different force ranges. Force range 1 was from a minimum force of 3% of maximal voluntary contraction force (MVC) to a maximum force of 6% MVC. In force range 2, the range was from 6% to 12% MVC, and force range 3 was from 12% to 24% MVC. For each force range, five practice trials and ten actual test trials were performed. Rest periods of twenty seconds between trials and one minute between sets of trials (including between practice and actual test trials) were provided to minimize fatigue effects. Absolute error uniformly increased as a function of increasing force. However, the 3% target force level showed larger relative error compared to the 12% target force level ($p < 0.05$). Another finding of this study was that producing forces positioned at the minimum target level in a range yielded higher absolute error and relative error compared to the same forces when placed at the maximum target level of a different force range. In terms of the reversals, RMSE values were higher at the change from force deceasing to increasing than the opposite, as well as at higher force levels, while normalized RMSE values were greater at lower force levels. CVE was not significantly different between the two reversals in this study. This might indicate that poorer performance during the change from force decreasing to increasing could originate from the effort to maintain consistent performance and additional effort was not beneficial to increase accuracy for the change from force decreasing to increasing.

Table of Contents

List of Figures

Chapter 1: Introduction

Many daily tasks, such as writing, eating, and buttoning a shirt, demand continuous coordination and regulation of increasing and decreasing fingertip forces using sub-maximal force levels to accomplish the task goals. Thus, force control in a task requiring force manipulation of thumb and fingers at sub-maximal force levels is relevant to activities of daily living and has been studied by many investigators. This study was designed to extend understanding of factors affecting accurate low-level force manipulation by the thumb and index finger.

Previous research has shown that errors and variability in isometric force control are greater at low force levels than at high force levels. Several researchers, using similar protocols, have examined the relationship between performance and force level as well as the one between the direction of force change and force variability (Harbst, Lazarus, & Whitall, 2000; Masumoto, & Inui, 2010). In comparing the production of cyclical increases and decreases of force, Harbst et al. (2000) and Masumoto and Inui (2010) found that increasing force to match an upper target force was less variable than decreasing force to arrive at the lower target force in these cyclical tasks. Harbst et al. (2000) analyzed self-paced isometric bimanual pinch performance of adults and children at two target force ranges: 10% maximal voluntary contraction force (MVC) as minimum force and 30% MVC as maximum force and 20% MVC as minimum force and 40% MVC as maximum force. They found that a larger constant error occurred at the minimum target force than at the maximum target force. Masumoto and Inui (2010) studied repeated isometric contractions of the right index finger at force levels of 5~40% of MVC. The results revealed more force variability when the target force was the minimum force. However, Harbst et al. (2000) measured only the total combined force of both fingers exerted during the bimanual pinch task. Measuring total force precludes understanding how each digit affects force variability. In Masumoto and Inui's (2010) study only the index finger force was analyzed, which limits generalization to most daily life tasks, because most daily tasks require the coordinated use of more than one digit simultaneously. Obtaining and analyzing the forces of individual fingers separately during coordinated action should provide a better understanding of how each digit affects force variability.

In addition, Harbst et al. (2000) used visual feedback only for practice trials, but not for the actual test trials, to measure rhythmical inter-limb coordination in their bimanual pinch task. Inui (2005) and Masumoto and Inui (2010) followed this same experimental procedure, though the second study only measured the dominant hand. In this paradigm, the task places great demands on memory to reach the maximum and minimum force levels. In the present study, visual information was provided to individuals throughout both practice and actual test trials in order to focus on examining control of force and force variability, independent of memory constraints.

In addition to these studies of tasks requiring production of specified levels of isometric force, other researchers have adopted isometric tasks requiring continuously changing levels of isometric force production, which could be called 'dynamic isometric tasks'. The most representative of these tasks were to track a sine wave shape plotting force over time (Knight and Kamen 2007; Moerchen, Lazarus, & Gruben, 2007; Vaillancourt and Newell, 2003) and to track a diagonal straight line plotting one force against another (Francis, MacRae, Spirduso, & Eakin, 2012; Spirduso, Eakin, Francis, & Stanford, 2005; Kamen and Du, 2000). These tasks require subjects to continuously adjust applied force to track the target line during performance of the task.

In terms of force production levels, many investigators have examined the effects on force variability in different experimental settings. The most common finding is that high force variability has been found for tasks requiring production of low force levels. It has also been reported that force variability follows a U-shape relationship between force levels and force variability for the thumb (Danion and Gallea, 2004) and for the index finger (Taylor, Christou, & Enoka, 2003). These studies used the coefficient of variation (CV) to compare variability across force levels because of issues related to force level normalization. The results indicated somewhat different points where the lowest CV occurred: 22.5% MVC (Danion et al., 2004) and 30% MVC (Taylor et al., 2003). It is possible these different observations were related to the range of actual levels used. For example, if the first study had used force levels between 22.5% MVC and 35% MVC, it would have been possible to see a lower CV than the one at 22.5% MVC.

Studies exist that present entirely different results. For example, Galganski, Fuglevand, and Enoka (1993) reported finding a plateau for the index finger between 35% MVC and 50% MVC in the CV in which the force range showed less variability compared to lower force levels. Even though these studies found the lowest CV at different force levels, the highest CV usually occurred at the lowest force levels. Contrarily, a few studies didn’t find this relationship. In one study the CV values were almost the same across a range of force levels for young subjects (Ranganathan, Siemionov, Sahqal, & Yue, 2001).

These diverse results derive from subjects who had different motor skill levels. Therefore, additional experimental procedures are needed to control for this variable, such as questionnaires to control for previous experience playing instruments or video games. However, it seems obvious that force production tasks in a middle range of force (20~50% MVC) are less difficult compared to tasks performed at higher or lower force levels and that tasks performed at low force levels are the most demanding (Galganski et al., 1993; Laidlaw, Bilodeau, & Enoka, 2000; Burnett, Laidlaw, & Enoka, 2000; Lindberg, Ody, Feydy, & Maier, 2009; Griffin, Painter, Wadhwa, & Spirduso, 2009).

Still, there have been only a few previous studies of the effect of dynamically changing force levels on force variability during isometric pinch tasks. Thus, the aims of this study were to:

1. Compare force accuracy of the individual digits (thumb and index finger) at three different minimum force levels (3% vs 6% vs 12%) and peak force levels (6% vs 12% vs 24%) during dynamic isometric pinch force production. We hypothesized there would be no differences in accuracy of task performance among force levels.

2. Compare force accuracy of the thumb and index finger when the target force was positioned as the minimum force to the accuracy when the same target force was positioned as the peak force. We hypothesized there would be no differences in end-point force accuracy when the target force was positioned as the minimum force in a range compared to when the same target force was positioned as the maximum force in a range.

3. Compare accuracy and steadiness during reversals of force direction at maximum and minimum force levels: a) reversing from the application of increasing force to decreasing force, and b) reversing from decreasing force to increasing force. We hypothesized that force variability and accuracy would not be different in these two reversal conditions, when the absolute force level was the same.

Chapter 2: Methods

2.1 PARTICIPANTS

Eighteen adult volunteers (nine men and nine women; mean age ± SD, 28.3±1.22 and 26.4±1.74) participated in this study. To be eligible for participation in this study, individuals must have been between the ages of 18-30 years, been right-handed, and reported normal vision (with or without correction). They reported that they had never had a medical diagnosis and treatment of neurological disability, injury, or neurological complications in their right hand or arm. They also reported that they had not consumed within the previous week any prescription or over-the-counter medications known to affect the central nervous system (CNS Depressants, CNS Stimulants, hallucinogens, Phencyclidine [PCP] and its analogs, narcotic analgesics, inhalants, marijuana, and any allergy medications). An additional questionnaire was given related to these issues, and the participant was excluded if he or she answered 'Yes' to at least one of the questions. Potential participants were asked to arrive at the laboratory without any caffeine intake within the previous two hours to control caffeine effect (Bovim, Næss, Helle, & Sand, 1995). Finally, individuals had to have had no previous experience with the experimental apparatus used in this study.

2.2 TASKS AND PROCEDURES

This study used the manual force quantification system (MFQS) apparatus to measure forces from both the index finger and thumb in a precision pinching task through two force transducers (Spirduso et al, 2005). A computer monitor provided visual display of the task as participants performed by manipulating the individual fingertip flexion forces of the right hand thumb and index finger. There were two balls on the screen, one was a target ball showing the prescribed forces, and the other one was a cursor manipulated by participants. The X- and Y-axis values of the cursor position were determined by the thumb force and the index finger force respectively. A strap was used for immobilization of the participants' right forearms and elbows, and the right arm, i.e., that of the hand whose digits were being tested, was kept flexed at 135 degree at the elbow. The participants were seated in a chair facing the computer monitor. The width between the two transducers was constant (2 inches) while the height of the chair and the location of the force transducers could be adjusted based on the height and arm-hand geometry of the participants. The orientation of the force transducers was also adjusted to encourage the subjects to touch the respective transducer pads while the three unused digits were flexed to the palm. Immobilization of the force transducer block was achieved by a magnetic clamp. Therefore, this equipment allowed measurements of independent isometric flexion or pinch force of each digit without any motion of the participants' hands and arms.

Three maximal voluntary isometric pinch forces (MVCs) were measured initially using a 20-pound maximum pinch transducer. The largest MVC among these three trials was employed to determine the absolute values of the three ranges of force used in this study. The subsequent test trials were measured using a 10-pound maximum transducer, and they required precise increases and decreases of isometric force to keep the cursor on the target track ball while the track ball cycled four times between the minimum and maximum levels of force prescribed by the task (see Figure 1). In each task, the combinations of force increases and decreases were presented first with both thumb and index finger forces increasing, followed by both thumb and index finger forces decreasing. This process was repeated continuously four times during each trial. The participants manipulated the cursor with the objective of continuously matching the moving position of the target ball up and down a 45 degree line segment for a total time of 24 seconds. The force scaling displayed on the monitor was in %MVC in both dimensions so that the 45 degree diagonal line represented equal force production changes by each digit in terms of their respective %MVC. The experimental conditions included performing this task repeatedly and at three different force ranges. Force range 1 was from a minimum force of 3% MVC to a maximum force of 6% MVC. In force range 2, the range was from 6% to 12% MVC, and force range 3 was from 12% to 24% MVC.

An explanation of the procedure, a consent form, and an additional questionnaire were provided to participants, consent was obtained, and then the initial MVC test protocol was performed, to establish the target force levels for both practice and actual test trials. After MVC was determined, the individual was tested at 3-6%, 6-12%, and 12%-24 MVC. Testing at each force range was preceded by practice trials over that same range. For each force range, five practice trials and ten actual test trials were performed for a total of 45 trials. The order of force levels tested was “randomly” assigned to every individual among the eighteen participants within the constraint that three participants were tested in each of the six possible task orders. After all trials were finished, three MVC tests were performed again to determine whether fatigue developed during the trials.

Rest periods of twenty seconds between trials and one minute between sets of trials (including between practice and actual test trials) were provided to minimize fatigue effects. Data to be analyzed were collected only from the actual test trials.

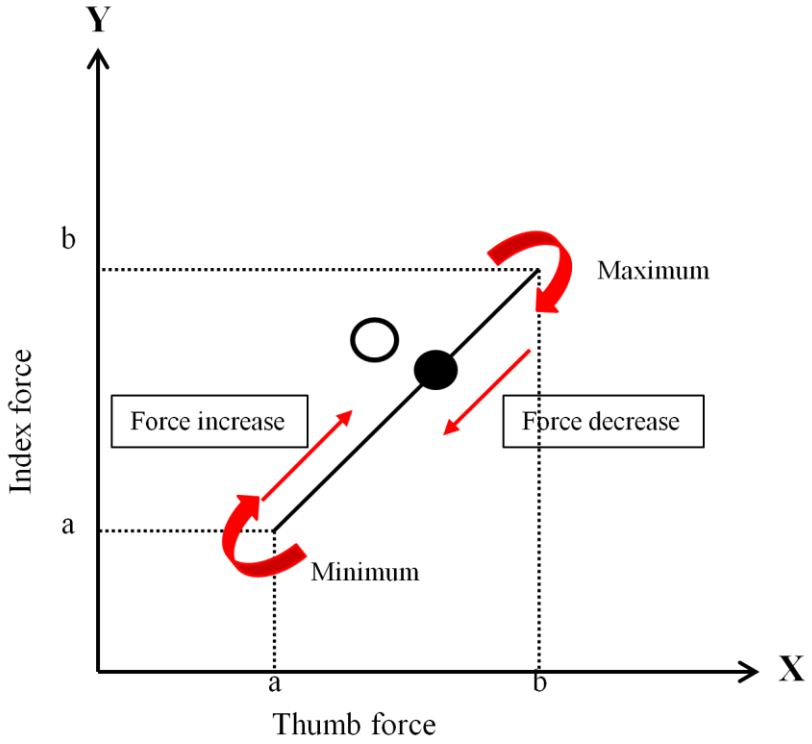

Figure 1: Tracking template in which the thumb manipulates the x position of the cursor (the white ball) and the index finger manipulates the position of cursor in the *y* direction on the reference frame. The black ball is the target ball, which moved alternately up and down the diagonal solid line. The position of cursor reflects the combined force exerted by the individual fingers. There were three different ranges of force: 1) a=3% and b=6%, 2) a=6% and b=12%, and 3) a=12% and b=24%.

2.3 DATA AQUISITION

The MFQS system consisted of a Dell computer, a 14 inch LCD monitor, custom-designed LabVIEW software, and a pair of isometric force transducers with an A/D converter. A LabVIEW software application was used to display the task on the screen as well as to collect and store all data from experiments. Two pairs of strain-gauge sensors were used to measure the individual finger-tip forces in grams. One (that was calibrated up to 20 lb of force) was used for measuring maximal voluntary pinch force. Another (that was calibrated up to l0 lb of force) was used to measure the actual performance during trials for higher precision. Force data were first sampled at 1000 Hz with LabVIEW, then reduced by averaging every 5 samples so force data were stored at 200Hz.

2.4 DATA ANALYSIS

The target path analyzed was divided into eight directional force change segments, four each for force increase and force decrease. The first segment data were not analyzed and functioned as a "warm-up" phase for each trial. Likewise data from the last portion of the eighth segment were not analyzed. This left three minima and three maxima in each trial to be analyzed, each of which was preceded and followed by a segment of force change toward and away from that force level, respectively.

Absolute error and relative error were calculated to assess the accuracy of the performance across the three force ranges, to test the first and second hypotheses. Absolute error and relative error values for the individual digits were calculated at the moment when the target ball arrived at the maximum and at the minimum. Absolute error was determined by the shortest distance between the x position of the cursor and of the track ball for the thumb and by the shortest distance between the y position of the cursor and of the track ball for the index finger. Relative error was determined as a percentage of the absolute error relative to the required force. These values were used not only to compare force accuracy of the individual digits at the different minimum force levels (3% vs 6% vs 12%) with maximum force levels (6% vs 12% vs 24%) but also to compare force accuracy of the individual digits when a particular target force was located at the minimum of a range with force accuracy when that same target force was located at the maximum of a range (6% and 12% MVC).

To analyze data relative to reversal of cursor direction, each force change segment was divided into four sub-segments for force range 1, eight sub-segments for force range 2, and sixteen sub-segments for force range 3 (see Figure 2). This resulted in all sub-segments being 0.75% MVC in magnitude in each of the two orthogonal directions. Thus, comparison of the forces produced during reversals was made in comparable windows of force magnitude when a designated force was positioned as maximum and when that force was a minimum. Only the first and last sub-segments from segments were used for measuring the reversal periods. Data were collected from three occurrences of each reversal in each actual trial (see Figure 2).

The accuracy of the performance for the reversals was represented by both root mean square error (RMSE) for individual digits and normalized root mean square error (normalized RMSE) values. Root mean square error (RMSE) for the reversals was calculated as the square root of the mean of the squared distance between the cursor and the track ball of each digit. Normalized RMSE was also calculated in percentage for the digits by multiplying by100 after calculating RMSE and dividing each distance by the target force at each sampling. Consistency of the performance was measured as the coefficient of variation in the magnitude of force error (CVE).

RMSE, normalized RMSE, and CVE values were used to compare force accuracy and consistency during reversals of force direction at the maximum and minimum: a) reversing from the application of increasing force to decreasing force, and b) reversing from decreasing force to increasing force.

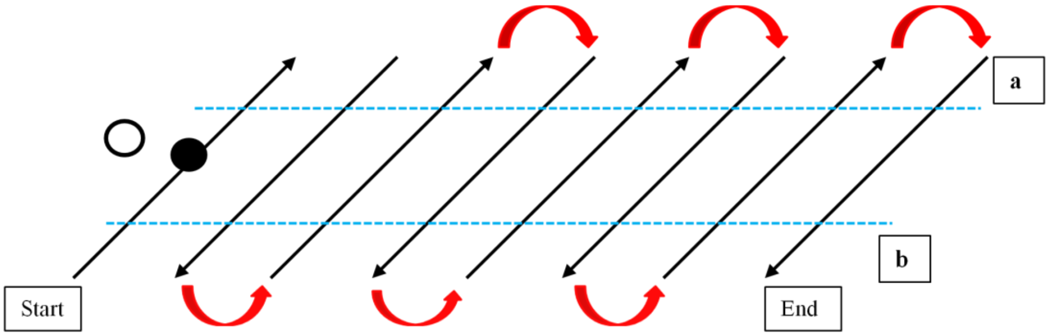

Figure 2: Sub-segments for the reversals. Each black line indicates a segment so that there are eight segments. Accomplishment of each segment took 6 seconds. A segment was divided into sub-segments depending on the force level. The 'a' and 'b' indicate the edges of the sub-segments for each 'force increasing to decreasing' and 'force decreasing to increasing'.

The data collected from each trial were analyzed with MATLAB and Excel programs to determine absolute error, relative error, RMSE, normalized RMSE, and CVE for each digit. A coding system was used on all participant records for confidentiality regarding the identity and performance of the participants.

Four different statistical methods were used for testing the three hypotheses. For the first hypothesis, two 2 (digits) × 3 (force levels) between-subject analysis of variance (ANOVA) tests were performed, one for minimum force levels (3% vs 6% vs 12%) and one for maximum force levels (6% vs 12% vs 24%) for the individual digits. Additional 2 (digits) × 2 (force levels) × 2 (positions) ANOVAs were performed to compare force accuracy of the individual digits when a particular target force was at the minimum of a force range and when that same target force was at the maximum of a different force range (6% and 12%), to test the second hypothesis. The dependent variables analyzed with these ANOVAs were absolute error and relative error. To test the third hypothesis, a 2 (digits) × 2 (force levels: 6% and 12% MVC) × 2 (reversals: force increasing to decreasing and force decreasing to increasing) multivariate analysis of variance

(MANOVA) test, was used to analyze three dependent variables (RMSE, normalized RMSE, and CVE) to determine the main effects of changes in digit, force magnitude, and reversal. Whenever significant main effects or interactions were found, post-hoc tests were used to examine the significance of differences between conditions and the contributions to any significant interactions. A 2 (digits) × 2 (times: pre and post testing) repeated measures ANOVA was performed to compare pre and post testing MVC values to determine whether fatigue may have been an alternative explanation for any differences observed. SPSS was used for all statistical comparisons and the level of significance was set to $p < 0.05$.

Chapter 3: Results

The main effect of force levels on absolute error was significant, both at the minimum force values ($F(2, 36) = 43.693$, $p < 0.001$) and at the maximum force values ($F(2, 36) = 60.884$, $p < 0.001$). Figure 3 shows that the absolute error increased as a function of increasing target forces, at both the minimum and maximum points. Bonferroni post hoc analysis revealed that at the minimum target point the absolute error for the 12% MVC was greater compared to the absolute error for the 3% ($p < 0.001$) and 6% MVC ($p < 0.001$) while 6% MVC also showed larger absolute error than 3% MVC ($p < 0.001$). At the maximum, the same tendency was found. The 24% MVC target led to greater absolute error than the 6% ($p < 0.001$) and 12% ($p < 0.001$) targets, while the 12% MVC target resulted in larger absolute error than the 6% MVC target ($p < 0.001$).

However, scaling the error score to the magnitude of the target force revealed different results. There were no significant differences in the relative error between the maximum target force levels ($p > 0.05$, See Figure 4B). Moreover, a significant main effect of force level at the minimum target force level was found for relative error ($F(2, 36) = 5.225$, $p < 0.001$). Post-hoc tests revealed that the 3% target force level showed larger relative error compared to the 12% target force level ($p < 0.05$) although there were no significant differences between 3% and 6% or 6% and 12% target force levels (See Figure 4A).

No significant interaction between digits and forces and no main effect of digits on absolute error were found, at both the minimum and maximum target force levels ($p > 0.05$).

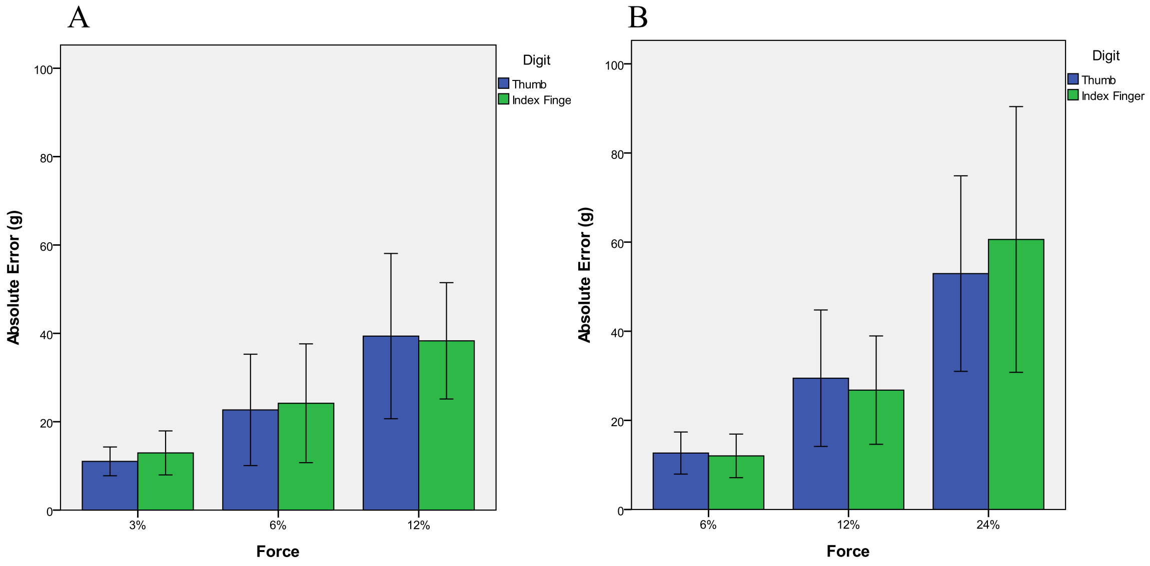

Figure 3: The absolute error at the minimum (A) and maximum (B)

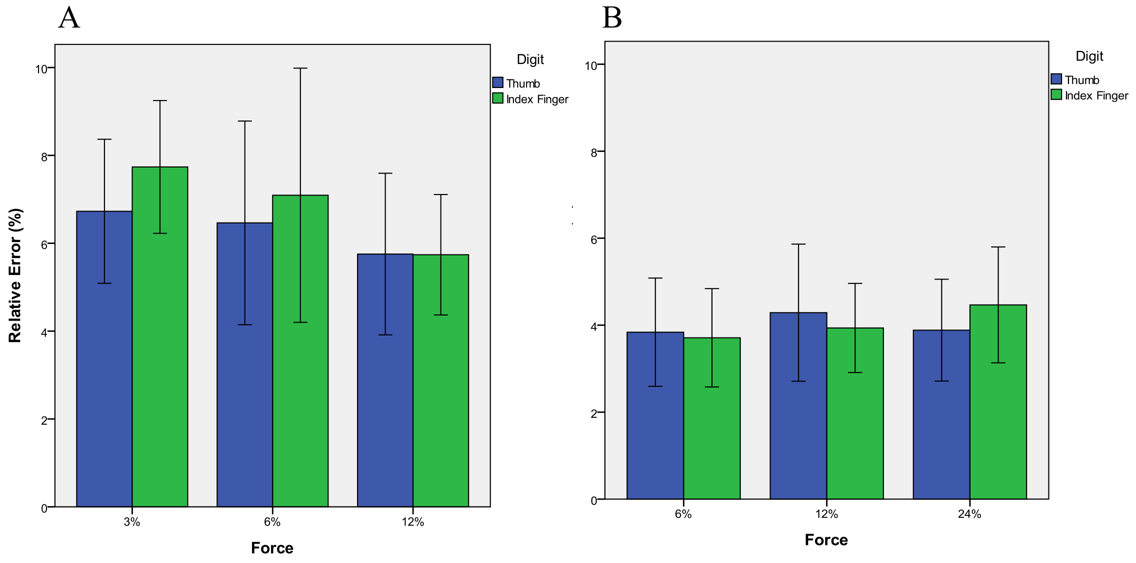

Figure 4: The relative error at the minimum (A) and maximum (B)

When comparing the 6% and 12% MVC force absolute error between minimum and maximum target positions, significant main effects of target force level (F(1, 72) = 54.252, $p < 0.001$) and position (F(1, 72) = 26.494, $p < 0.001$) were found. The absolute error was less at the maximum compared to the minimum, and less at 6% MVC than at 12% MVC (See *Figure 5*). No interaction among forces and positions was found for absolute error at these force levels.

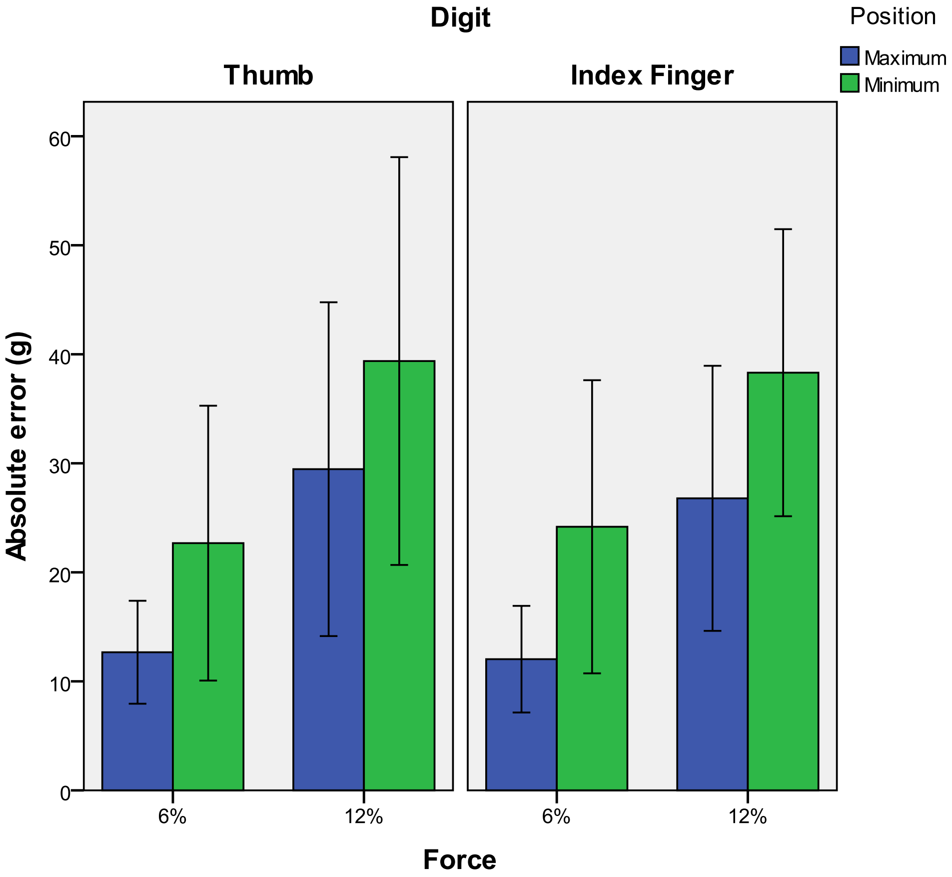

Figure 5: The absolute error at the two positions tested as both minimum and maximum.

A significant effect of target position was only found for relative error (F(1, 72) = 61.086, $p < 0.001$). When the forces were positioned as the minimum, the relative error was greater (See *Figure 6*). However, although force level did not affect the error significantly, an interaction of the forces and positions was found (F(1, 72) = 5.322, $p < 0.05$). Post hoc analysis showed that the difference in the error between the minimum and maximum positions decreased when the force levels increased.

No significant interaction related to digits or main effect of digits on either the absolute error or relative error was found.

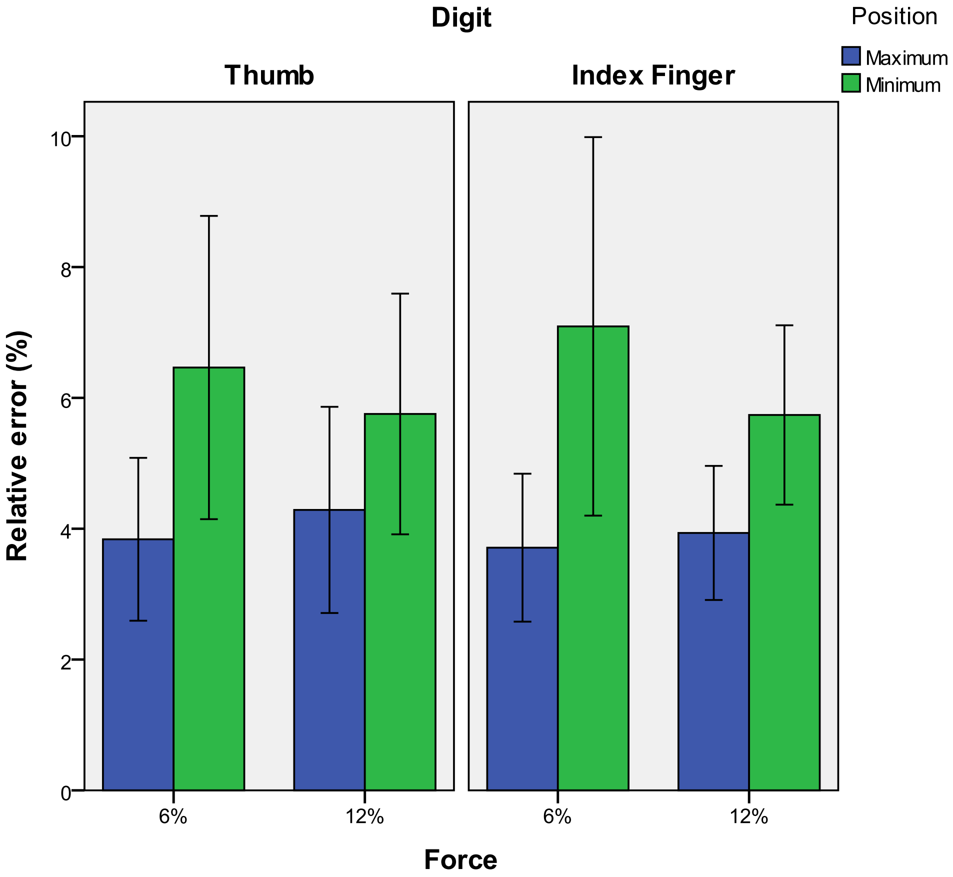

Figure 6: The relative error at the positions, minimum and maximum.

There was a significant main effect of force level for RMSE (F(1, 72) = 58.115, $p < 0.05$). Significant main effects of reversal direction on the normalized RMSE (F(1,

72) = 123.367, $p < 0.001$) and CVE (F(1, 72) = 35.516, $p < 0.001$) were also found. RMSE was greater when the required force was greater and larger RMSE was found when the reversal direction changed from force decreasing to increasing (See *Figure 7*). Normalized RMSE also was significantly greater when force levels were smaller and was greater when the reversal direction changed from decreasing to increasing than when the reversal direction was from force increasing to decreasing (See *Figure 8*).

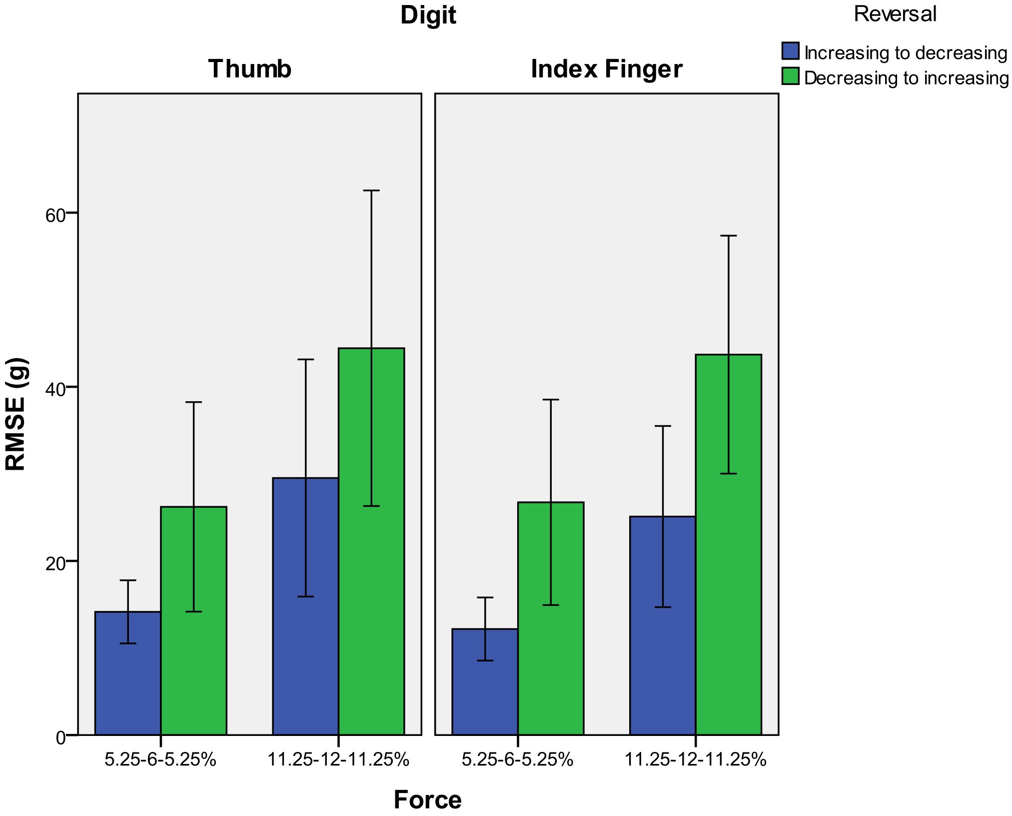

Figure 7: RMSE at the reversals

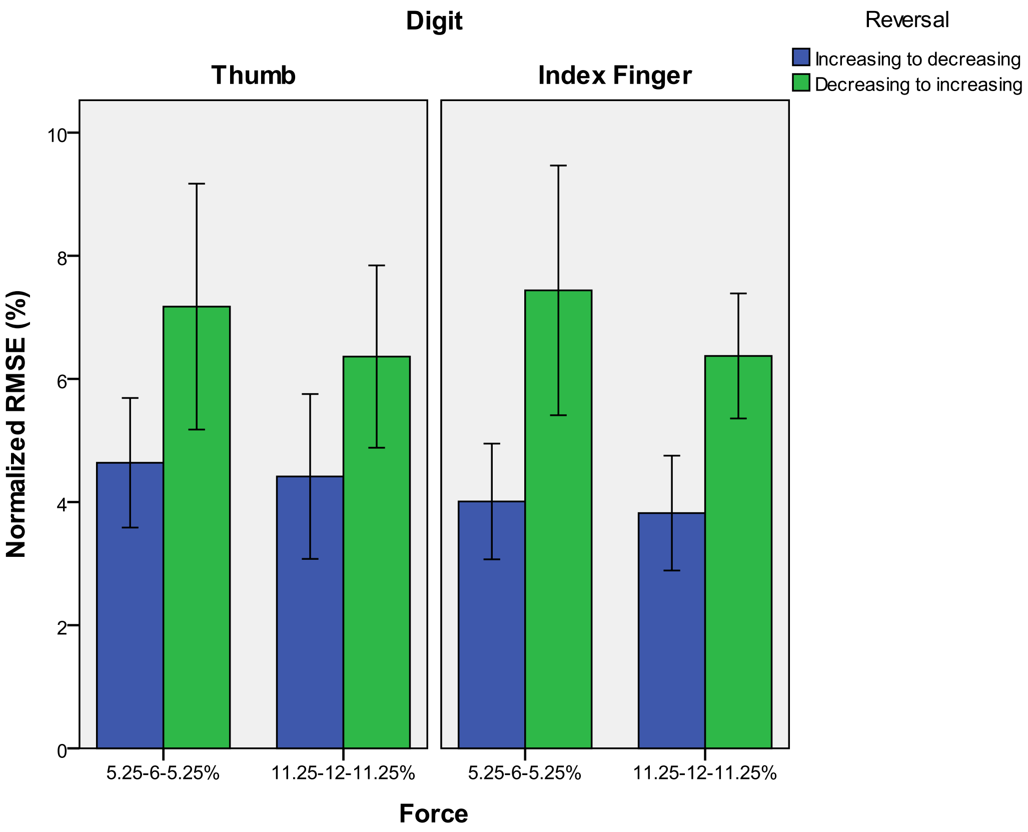

Figure 8: Normalized RMSE at the reversals

There were no significant differences in the CVE values between the force levels and the reversals (See *Figure 9*)

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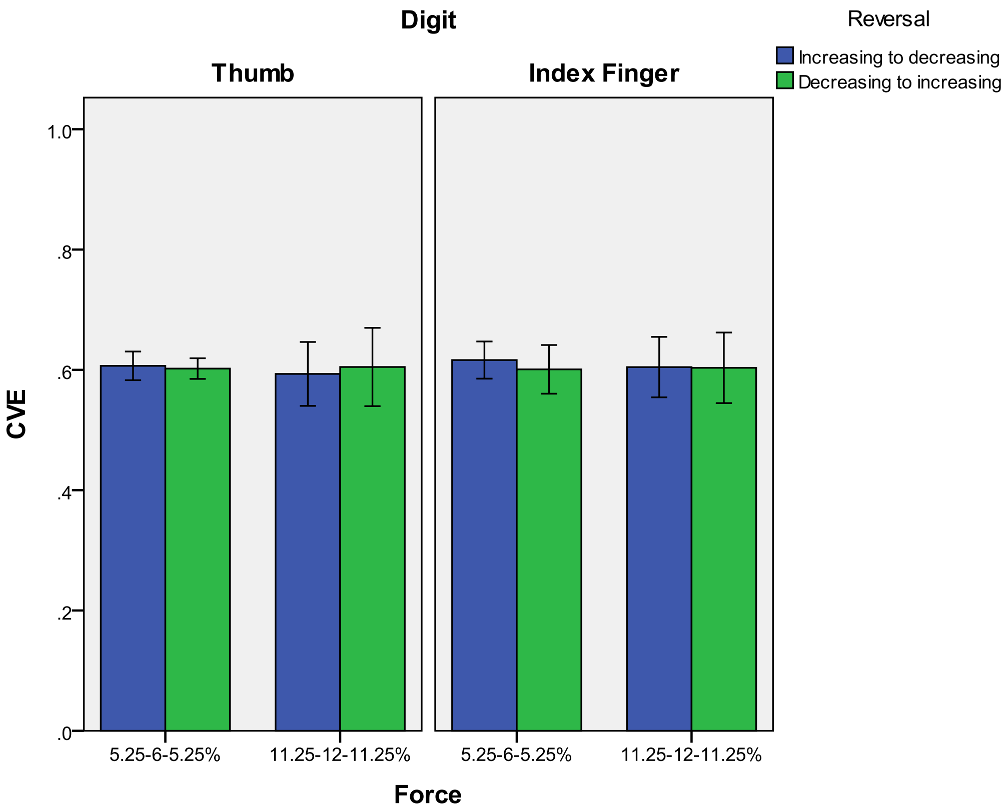

Figure 9: CVE at the reversals

MVC was measured for each digit (the thumb and the index finger) before and after the experiment. Comparison of these data indicated that there was no significant reduction in MVC of each digit after the experiment and also no difference in MVC between the digits (See *Figure 10*). No significant interaction between digits and time was found on MVC. Thus, fatigue did not appear to affect the results of this experiment.

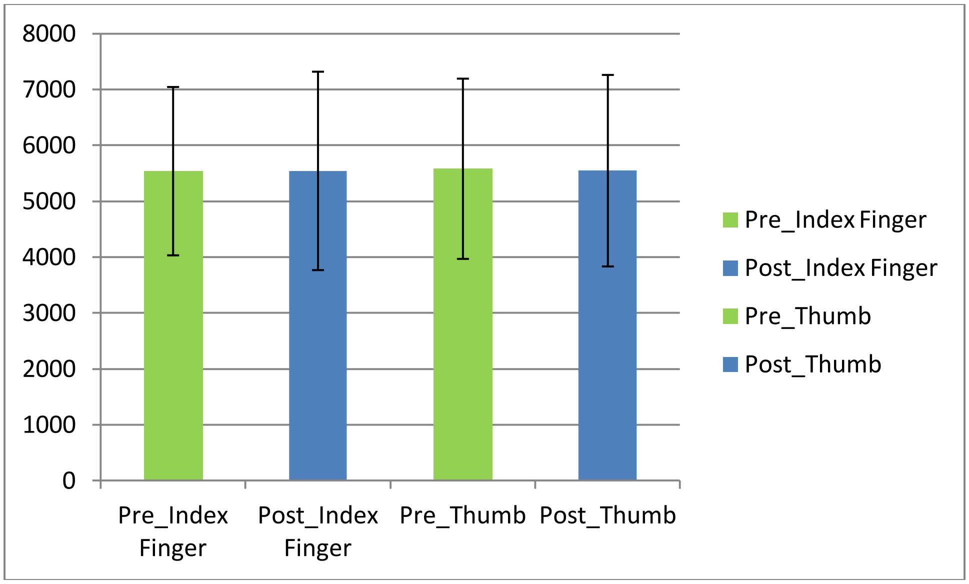

Figure 10: MVC comparison to examine whether fatigue had developed after completing all the trials

Chapter 4: Discussion

In order to more carefully examine the relationship between force level and force accuracy, this study used both absolute error and relative error for representing accuracy of the maximum and minimum target forces in each force range. Absolute error has been one of the most common dependent variables for accessing accuracy of performance. Absolute error has been shown to increase as a function of increasing force (Slobounov, Johnston, & Ray, 2002). This study showed the same tendency in the absolute error at the minimum and maximum target forces. On the other hand, relative error (normalized absolute error) was not significantly different across force levels when the target force was the maximum value in a repetitive oscillating force pattern. However, when the target force was the minimum value in a repetitive oscillating force pattern, there was a significant difference between the lowest and highest target force levels (3% and 12% MVC). This trend is similar to previous results and also supports previous evidence that low force production is more challenging (Lindberg et al., 2009).

Another main finding of this study was that when forces were positioned at the minimum target level of a force range there were higher absolute error and relative error scores compared to when the same forces were placed at the maximum target level in a different range. This finding is consistent with previous reports. (Harbst et al., 2000; Masumoto et al., 2010). The interaction between force levels and reversal positions indicated that the effect was larger at the lower force level, which is also consistent with previous evidence that producing lower force is more demanding.

There have been many previous electromyographic (EMG) studies examining why producing low forces accurately is more difficult than producing higher force. These studies have suggested several main contributing factors to this phenomenon: 1) motor unit firing rate variability and motor unit recruitment, 2) co-activation of agonist and antagonist muscles, and 3) motor unit synchronization.

The way motor units are recruited is widely known as the “size principle” (Henneman, Somjen, & Carpenter, 1965). According to this strategy, the smallest motor units are recruited first, and then orderly recruitment of progressively larger units will occur to increase force output. This principle has been demonstrated for intrinsic (Milner-Brown Stein, & Yemm, 1973) and extrinsic finger muscles (Monster and Chan, 1977). Rate coding of recruited motor units also plays an important role for exerting voluntary force. The importance of rate coding has been reported for the first dorsal interosseus compared to the deltoid (De Luca, LeFever, McCue, & Xenakis, 1982) and the biceps brachii (Seki and Narusawa, 1996). These results were also consistent with data from the adductor pollicis (Kukulka and Clamann, 1981). Thus, rate coding of motor units within the intrinsic hand muscles appears to be critical for precision of finger force production. Laidlaw et al. (2000) reported a positive correlation between force variability and relative motor unit firing variability at low force levels, 2.5% and 5% MVC. That study would support the notion that force variability may reflect increased motor unit firing variability at low force levels. This is supported further by the finding of an exponential decrease of relative discharge rate variability as force of the index finger increases above the recruitment threshold (Moritz, Barry, Pascoe, & Enoka, 2005). From these results, it appears that higher motor unit firing variability could result in higher force variability at low force levels.

Evidence of involvement of antagonist co-activations was found in a study that used an isometric abduction task for the left index finger and measured EMG of the first dorsal interosseus muscle (FDI) as an agonist and the second palmar interosseus muscle (SPI) as an antagonist. The activation amplitude of the antagonist increased while the relative activation amplitude in percent (100*antagonist activation/agonist activation) decreased (Burnett et al., 2000) as force levels increased. Thus, force variability at low force levels could be caused by a higher relative contribution of the antagonist to the resultant force output and less co-activation which might aid in force regulation.

There is also evidence of a higher probability of motor unit synchronization at low force levels, even when force increase was not related to level of motor unit synchronization (Huesler, Maier, & Hepp-Reymond, 2000). At low levels, with few motor units active, even small levels of synchronization could affect steady force production. This supports the idea that motor unit synchronization could be a factor that contributes to higher force variability at low force level.

Previously, standard deviation and coefficient of variation (CV = SD/mean force) have been used for measuring both absolute force variability (Keogh, Morrison, & Barrett, 2006) and relative force variability (Sosnoff, Jordan, & Newell, 2005; Keogh et al., 2006). Even though standard deviation was higher at higher force levels, higher values in the coefficient of variation were found in lower force levels during constant isometric force production task (Galganski et al., 1996; Sosnoff et al., 2005) and dynamic isometric force production task (Vaillancourt et al., 2003).

RMSE is also a dependent variable which has been used as a measure of absolute force variability of performance (Sosnoff et al., 2005) as well as of performance error (Kriz, Hermsdörfer, Marguardt, & Mai, 1995; Keogh et al., 2006; Knight et al., 2007; Singh, SKM, Zatsiorsky, & Latash, 2010; Francis, MacRae, Spirduso, & Eakin, 2012). Increase in RMSE values was found as a function of increased target force (Vaillancourt et al., 2003). In this study, RMSE values were higher at the change from force deceasing to increasing as well as at higher force levels while normalized RMSE values were greater at lower force levels. This result clearly indicates that normalizing error measures to the target level reveals different information about performance and can augment the information found using absolute error values.

CVE was calculated in this study to indicate the extent to which a subject was able to maintain steady performance during the reversals. Specifically, higher CVE represents less consistency in following the track ball during the reversals. This value is similar to the CV because both of these measures indicate relative force variability based on the participants' own performance (since the target track ball was moving steadily). However, while CV reveals variability in force output, CVE reveals variability in the error. The CVE was not significantly different between the two reversals in this study. In a sine wave force production task, the CV was not significantly different between force increasing and force decreasing phases for young adults (Voelcker-Rehage and Alberts, 2005). However, in that study the investigators did not investigate the difference between the two reversals. Higher values of SD and CV have been found in changing from force increasing and decreasing compared with change from force decreasing to increasing during a repetitive force production task (Masumoto et al., 2010). This inconsistency may originate from differences in task characteristics. The duration of each phase of the oscillating force pattern was 0.5s in Masumoto's study rather than the 6s in the current study. The shorter time in that study required the participants to produce rapid force changes while the longer time in our study allowed the subjects to make these shifts with more feedback and precision. The previous study also did not provide visual feedback, so that proprioceptive feedback also would play the largest role in producing the required forces (Masumoto et al., 2010). The visual feedback provided in this study was probably a much more powerful source for regulating fine force control compared to proprioceptive feedback (Henningsen, Knecht,

& Ende-Henningsen, 1997). Taken together, these differences are likely to have contributed to the differences between these two results.

The CVE was not significantly different between the two reversals, which is different from the results reported in the normalized RMSE and the RMSE results. This might indicate that the participants tried to maintain their own strategies throughout the task and did not try to make corrections to increase force accuracy, or perhaps they were able to increase consistency even though the RMSE values were different at the two extremes of each force range. That is, poorer performance during the change from force decreasing to increasing could originate from the effort to maintain consistent performance and additional effort was not beneficial to increase the accuracy for the change from force decreasing to increasing.

The results of this study offer some insights to practical application, as well as future research questions. Increasing and decreasing force properly is important for people in many daily life tasks. For example, grasping and manipulating a cup or buttoning a shirt requires appropriate force control form the digits. Clinical conditions are often accompanied by specific deficits in these skills. Children with hemiplegic cerebral palsy have been reported to have longer times to release an object and to have shown more unexpected force release compared to normal children during replacing the object on a table (Eliasson and Gordon, 2000). Longer time to release isotonic force was found in moderate Parkinson's disease patients (Kunesch, Schnitzler, Tyercha, Knecht, & Stelmach, 1995). These results demonstrated that damage from these clinical conditions affects force regulation. However, these studies only measured release time when visual or auditory cues were provided. Thus, it would be interesting to study differences in fine force control between patients and healthy people in terms of the reversals.

Even after people who have suffered from neurological disorders have demonstrated full recovery, they often still cannot manipulate digit forces as skillfully as they did before, so more work is needed to develop rehabilitation strategies. For example, improved capability to track a sine wave has been reported for patients with brain damage through training that consists of following a trapezoidal shape repetitively (Kriz et al., 1995).

In this context, this study may serve as a foundation, not only to examine differences in force control of the reversals between healthy people and clinical patients, but also to see learning effects of repetitive force manipulation at different force ranges. It will also be valuable to examine the extent to which practice transfers to daily performances.

There are a few limitations to applying the results of this study. Caffeine withdrawal has been recommended before neuropsychological and psychomotor testing because above 300 mg can affect hand steadiness (Bovim et al., 1995). In this study, two hours withdrawal before testing was required to prevent a significant caffeine effect on the results. However, no publications were found that have examined the effect of the time of withdrawal as well as the amount of caffeine intake before testing. Future studies are needed for better recommendations on controlling caffeine effects on psychomotor experiments.

The task in this study required the participants to increase and decrease pinch force of the index finger and the thumb with the same proportional amount of force relative to their individual digit MVCs. All statistical comparisons showed that there were no significant main effects between the index finger and thumb. This indicated high coupling between the two digits during the task, which was consistent with previous results (Moerchen et al., 2007). Even though there were no significant results with respect to digits in this study, the difference in relative error at the minima between the index finger and thumb was greater at the lowest force level compared to higher force level. This also is consistent with previous research that found a greater extent of digit coupling at higher force level (Sharp and Newell, 2000). Decoupling could be found through different tasks requiring different force levels for each finger, such as pivoting of the transducers (Moerchen et al., 2007). Thus, decoupling between the fingers may occur depending on task characteristics.

One of the limitations of this study was the fixed width between the two force transducers. Participants who had differing sizes of their right hand might have experienced the task differently, which could have affected the results (Jordon, Pataky, & Newell, 2005). However, all possible individual differences in hand geometry are not considered in the design of objects such as pencils or buttons, so this limitation is consistent with many daily activities.

Another limitation was the possibility of hand or wrist movement during the performance. Since the best performance was achieved by staying close to the track ball, subjects could try to change the angle of the wrist and finger joints to adjust the applied force. Change of angle of the wrist can affect finger joint motion (Su, Chou, Yang, Lin, & An, 2005). If such changes happened during the testing, it could have affected the results. However, we encouraged the subjects to maintain their posture as much as they could during the task and trials with observable motion of the fingers or the wrist were eliminated from the analysis. Also, each subject performed trials using all the force ranges so that the differences which we found were not attributable to individual differences.

Chapter 5: Conclusion

The results of this study showed that while absolute error increased as a function of increasing force relative error decreased (e.g. the 3% target force level showed larger relative error compared to the 12% target force level). This trend supports the hypothesis that low force production is more challenging. Forces positioned at the minimum target level in a range had higher absolute error and relative error compared to the same forces placed at the maximum target level in a range. In terms of the reversals, RMSE values were higher at the change from force decreasing to increasing as well as at higher force levels while normalized RMSE values were greater at lower force levels. However, CVE was not significantly different between the two reversals in this study. This might indicate that poorer performance during the change from force decreasing to increasing could originate from the effort to maintain consistent performance and additional effort was not beneficial to increase the accuracy for the change from force decreasing to increasing. Future work is needed to more clearly understand the full meanings of the different results with different dependent measures and experimental conditions.

Appendices

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
digit	16.563	1	16.563	.111	.740	.001
force	13081.353	2	6540.676	43.693	.000	.461
digit x force	47.042	2	23.521	.157	.855	.003

Appendix A. 2 (digits) × 3 (force levels) analysis of variance (ANOVA) test for the minimum force levels (absolute error)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
force	41.769	2	20.884	5.225	.007	.093
Digit	7.903	1	7.903	1.977	.163	.019
force x digit	4.831	2	2.416	.604	.548	.012

Appendix B. 2 (digits) × 3 (force levels) analysis of variance (ANOVA) test for the minimum force levels (relative error)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
force	36502.037	2	18251.019	60.884	.000	.544
Digit	56.687	1	56.687	.189	.665	.002
force x digit	539.042	2	269.521	.899	.410	.017

Appendix C. 2 (digits) × 3 (force levels) analysis of variance (ANOVA) test for the maximum force levels (absolute error)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
force	3.347	2	1.673	1.056	.352	.020
Digit	.030	1	.030	.019	.890	.000
force x digit	4.270	2	2.135	1.347	.265	.026

Appendix D. 2 (digits) × 3 (force levels) analysis of variance (ANOVA) test for the maximum force levels (relative error)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
force	8756.045	1	8756.045	54.252	.000	.285
digit	18.617	1	18.617	.115	.735	.001
position	4275.955	1	4275.955	26.494	.000	.163
force x digit	47.806	1	47.806	.296	.587	.002
force x position	1.142	1	1.142	.007	.933	.000
digit x position	31.541	1	31.541	.195	.659	.001
force x digit x position	.633	1	.633	.004	.950	.000

Appendix E. A 2 (digits) × 2 (force levels: 6% and 12% MVC) × 2 (positions: minimum and maximum) analysis of variance (ANOVA) (absolute error)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
force	4.347	1	4.347	1.371	.244	.010
digit	.040	1	.040	.013	.911	.000
position	193.739	1	193.739	61.086	.000	.310
force x digit	1.696	1	1.696	.535	.466	.004
force x position	16.880	1	16.880	5.322	.023	.038
digit x position	2.692	1	2.692	.849	.358	.006
force x digit x position	.398	1	.398	.126	.724	.001

Appendix F. A 2 (digits) × 2 (force levels: 6% and 12% MVC) × 2 (positions: minimum and maximum) analysis of variance (ANOVA) (relative error)

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
digit	RMSE	98.356	1	98.356	.703	.403	.005
	Normal_RMSE	2.028	1	2.028	1.015	.315	.007
	CVE	.001	1	.001	.370	.544	.003
force	RMSE	9064.539	1	9064.539	64.786	.000	.323
	Normal_RMSE	11.776	1	11.776	5.897	.016	.042
	CVE	.001	1	.001	.435	.511	.003
reversal	RMSE	8131.275	1	8131.275	58.115	.000	.299
	Normal_RMSE	246.348	1	246.348	123.367	.000	.476
	CVE	.000	1	.000	.101	.751	.001
digit x force	RMSE	30.941	1	30.941	.221	.639	.002
	Normal_RMSE	.109	1	.109	.054	.816	.000
	CVE	.000	1	.000	.003	.956	.000
digit x reversal	RMSE	86.232	1	86.232	.616	.434	.005
	Normal_RMSE	5.040	1	5.040	2.524	.114	.018
	CVE	.001	1	.001	.609	.437	.004
force x reversal	RMSE	106.923	1	106.923	.764	.384	.006
	Normal_RMSE	4.831	1	4.831	2.419	.122	.017
	CVE	.002	1	.002	1.010	.317	.007
digit x force x reversal	RMSE	3.234	1	3.234	.023	.879	.000
	Normal_RMSE	.186	1	.186	.093	.761	.001
	CVE	.000	1	.000	.004	.952	.000

Appendix G. A 2 (digits) × 2 (force levels: 6% and 12% MVC) × 2 (reversals: force increasing to decreasing and force decreasing to increasing) multivariate analysis of variance (MANOVA) test

Source		digit	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
time	Linear		3828.125	1	3828.125	.002	.962	.000
digit		Linear	9917.014	1	9917.014	.369	.551	.021
time * digit	Linear	Linear	6593.347	1	6593.347	.157	.696	.009

Appendix H. A 2 (digits) × 2 (times: pre and post testing) repeated analysis of variance (ANOVA) to compare pre and post testing MVC values to determine whether fatigue developed.

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