ABSTRACT

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The purpose of this study was to investigate central nervous system strategies for controlling multi-finger forces in three-dimensional (3-D) space during a circle-drawing task. In order to do this the Kinetic Pen, a pen capable of measuring the six-component force and moment of force that each of four individual contacts applies to the pen during writing, was developed. The synergistic actions of the contact forces, defined as kinetic synergy, were investigated in three orthogonal spaces: radial, tangential, and vertical to the circle edge during a circle drawing task. We employed varying directional (clockwise vs. counterclockwise) and pacing (self-paced vs. external-paced) conditions. Results showed that synergies between pen-hand contact forces existed in all components. Radial and tangential component synergies were greater than in the vertical component. Synergies in the clockwise direction were stronger than the counter-clockwise direction in the radial and vertical components. Pace was found to be insignificant in all conditions.

HANDWRITING KINETICS: A SEARCH FOR SYNERGIES

By

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Table of Contents

CHAPTER 1: INTRODUCTION

The seemingly simple act of handwriting is one of many marvels of the central nervous system. Whether writing a word or drawing a basic shape, we are able to generate a sort of code that is both universally recognizable, yet individually unique. The complex joint torques and rotations within the arm, wrist, and digits, working together to create a precise and singular output make any multi-digit coordination task, particularly handwriting, an excellent gateway to understand the central nervous system's (CNS) control of movements. Research in this area has historically been divided into two parties: kinematic investigations of handwriting and kinetic investigations of multi-digit force production tasks. Both of these fields have strengths and weaknesses. Handwriting kinematics allows the study of an actual writing task, but is limited to measurements of a single effector, the pen, not the interaction between the digits and the pen. Multi-digit force production tasks allow each digit's individual performance during a task to be measured as well as how all digits work together in a manner to attain a common output. However, physical limitations of mounting force sensors on a writing utensil while maintaining a normal and comfortable writing grip have prevented the extension of kinetics to an actual writing task. The recent design of a Kinetic Pen breaks down the barrier that has long separated these two fields, allowing the performance of individual digits during a writing task to be monitored for the first time.

The purpose of this study is to identify force stabilization synergies in a writing/drawing task. Synergies will be quantified using the Uncontrolled Manifold (UCM) analysis. Systematic variation of circle-drawing direction and pace will be analyzed with respect to pen tip force control along three components of the movement:

1) normal to the writing surface, 2) tangential to the writing surface in the radial direction, and 3) tangential to the writing surface in the direction tangential to the circle edge. The importance of these synergies from a neural control perspective is discussed.

The thesis is divided into five chapters. The first chapter is an introduction. The second chapter provides a literature review on different perspectives on the degrees of freedom problem, motor synergies, and handwriting motor control patterns. The third chapter describes the development of the Kinetic Pen and its capabilities. The fourth chapter explains describes an investigation of kinetic synergies of circle drawing in three-dimensional space and the final chapter discusses implications of and draws conclusions from this work and suggests possible future research.

CHAPTER 2: LITERTURE REVIEW

Motor Redundancy

In order for a person to control a movement, several factors come into play. These include basic mechanical properties of muscles and segments, the neuronal connections carrying signals to the segments, the coordination of the mechanics and neuronal connections, and the influence of feedback from the external environment by the central nervous system's chosen response. A task as seemingly simple as reaching for an object becomes very complex given all of these factors. An object's position has six components: three describing its location and three describing its orientation. As each of these components is free to change independently, an object in space is considered to have six degrees of freedom. In comparison, the joints of the human body yield a total 244 degrees of freedom (Vladimir M. Zatsiorsky, 1998). Extend this to the kinetic domain, where various combinations of muscle forces can produce the same output and the kinetic degrees of freedom increases exponentially. The excessive degrees of freedom of the human body relative to the environment with which it interacts is a fundamental problem in motor control known as the motor redundancy problem or the degrees of freedom problem, as introduced by Bernstein (Bernstein, 1967).

Anatomy and Motor Redundancy of the Human Hand

The extensive network of bones, muscles, ligaments, tendons, and other tissues working seamlessly together make the human hand make it an extensively redundant system and as such an excellent gateway to understanding the CNS's method for dealing with motor redundancy.

Each hand has 27 bones and three different types of bones: carpals, metacarpals, and phalanges. The most proximal are the eight carpal bones. These irregular bones comprise the wrist and connect to the arm at the distal end of the ulna and radius. Distal to the carpal bones are five metacarpal bones. These are short bones and comprise the hand. Distal to the metacarpals are the 14 phalanges. Each finger has three phalanges: the proximal, medial, and distal phalanges, all of which are short bones. The thumb only has two phalanges, one proximal and one distal. The "finger mover" muscles are broken into two categories, intrinsic and extrinsic muscles. Intrinsic muscles originate in the hand, such as the thenar, hypothenar and midpalmar muscles. Extrinsic muscles originate in the forearm, such as the flexor digitorum profundus, flexor digitorum superficialis, extensor digitorum communis, extensor carpi radialis, and extensor carpi ulnaris.

The numerous degrees of freedom created by the muscles and bones described above are constrained by both anatomical and neuronal factors. The anatomical factors include multitendinous tendons, in which a single muscle is connected to multiple tendons within the digits, intertendinous connections, in which tendons branch off and connect one muscle to multiple digits, and simple inter-digit webbing of soft tissues. The neuronal factors are when a single cortical motor neuron spreads to multiple spinal motor neuron groups and their corresponding muscles. In other words, while one part of the brain is activated, the signal spreads to multiple muscles which in turn pull multiple tendons (Schieber & Santello, 2004). This combination of excessive degrees of freedom and complex constraints makes the control of hand movement an excellent tool for CNS control strategy investigations.

Motor Redundancy Resolution Techniques

While it is a mathematical fact that the human body contains more DOF than necessary to perform most motor tasks, there are widely varying approaches in understanding the relationship between the CNS and its control over these DOF. These range from elimination of excessive DOF to *solve* the DOF *problem*, to optimization of DOF, to the existence of motor synergies in which the CNS uses the excessive DOF to enhance the movement control (M. L. Latash, Scholz, & Schoner, 2007).

Bernstein first introduced the elimination approach in 1969. His experiments suggested that the excessive DOF pose a problem for the CNS and to overcome this problem the CNS locks the "unneeded" DOF during movement (Bernstein, 1967). This theory continues to be supported and furthered through varying experimental techniques. One such set of studies considered the idea of the CNS prioritizing the joints involved in a task by looking at each joint's variability during an isometric task (Newell & Carlton, 1988). Another approach theorizes that the CNS eases its computational demands by grouping DOF, rather than prioritizing them, lessening the effective DOF (Turvey, 1990). This grouping technique can be learned as new motor skills such as pistol shooting (J. P. Scholz, Schoner, & Latash, 2000). Critics of this approach argue that while the limitation of DOF make movement computationally simpler for the CNS, it reduces the efficiency of movement. That is, the elimination approach does not take into account that the distribution of muscular effort across many DOF and their corresponding muscles decreases the muscular effort required.

Another approach to understanding the DOF-CNS relationship looks to the optimization principles and their complex cost functions developed in engineering (Seif-Naraghi & Winters, 1990). Here it is thought that the CNS is choosing a complex cost function in which a unique solution optimizes the movement when the function approaches a maximum or minimum value. There are also more advanced approaches that intertwine with the synergistic approaches described throughout the remainder of this paper (Todorov, 2004). Arguments as to what variables and what cost function(s) the CNS recruits are wide ranging.

The third approach proposes the use of synergies by the CNS to control human movement by using the excessive DOF in the human body as an advantage rather than hindrance. This approach has been dominant in recent research and will be described and used throughout the duration of this paper.

Motor Synergies

The word "synergy" appears to be the magic solution to understanding the CNS's control of human movement as it shows up in research on quiet stance posture, locomotion, multi-joint reaching movements, force production tasks, and numerous others (Mark L. Latash, 2008). While its definition seems to vary slightly depending on the researcher, it is generally understood to be a correlation of outputs. The idea is most easily understood relating to muscle synergies. In this case multiple muscles are coupled such that with a single signal the CNS proportionally activates all muscles in the synergy. As the demands of the task vary, the control signal to the synergy changes, resulting in parallel changes in all muscles coupled in the synergy. By extending the notion of muscle synergies to groups of muscles that span multiple joints, the coordination of multiple DOF may be understood in a similar way as a motor synergy.

A review by Latash et al. states that, qualitatively, motor synergies consist of three parameters: sharing, error compensation, and task dependance (M. L. Latash et al., 2007). When multiple factors are involved in a task, sharing describes the amount of contribution of each individual factor. Tasks such as quiet stance, locomotion, reaching, grasping, and pressing have all been shown to have invariant sharing in which the same elements contribute the same amount every time the task is performed (Hsu, Scholz, Schoner, Jeka, & Kiemel, 2007; Kelso & Tuller, 1984; Santello, Flanders, & Soechting, 1998; J. P. Scholz, Danion, Latash, & Schoner, 2002). Error compensation in a synergy allows it to be both flexible and stable. It is often measured by comparing the variance of the individual factors in relation to the variance of the total (V. M. Zatsiorsky, Gao, & Latash, 2003). In other words, the sum of the factor variances remains low, creating stability, while individually the factors have high variance, enabling flexibility. Synergies also must be task dependent, meaning that synergies comprised of the same elements can change with the task being performed. A series of significant studies will be presented below in which kinematic, kinetic, and handwriting synergies are reviewed.

Kinematic Motor Synergies

When broken down into all of the elements the CNS must take into account for successful motor output, even the apparently simple tasks become highly sophisticated. One example of this is posture. Posture is an area of research in which kinematic synergies are widely used as the task goal is to maintain the position of the head and torso. Position stabilization, in this case, requires synergies to be dependent on numerous sensory systems, specifically the vision, auditory, vestibular, proprioceptive, and touch systems, in order to stabilize the head and torso position (Allison, Kiemel, & Jeka, 2006; Jeka & Lackner, 1994; J. P. Scholz et al., 2007). These posture studies point to synergistic control of muscles by the CNS to stabilize balance.

Another example of apparently simple, yet actually sophisticated task is that of reaching. A series of experiments in which subjects would reach for a target through a dynamic force field suggests the CNS employment of synergies. Subjects grasped a robotically controlled handle and where told to move it to a specified target. The system was redundant as three joints, the wrist, elbow and shoulder, were used in controlling a single effector in two dimensions. The robotic handle perturbed the subject's movement in a direction opposite the target trajectory. When the handle was perturbed, the endpoint variability increased and the movement trajectory became curved. After practice, the endpoint variability decreased and the trajectory straightened. These studies indicated that the CNS's pre-practice synergies were not adapt at moving in a force field, however after practicing the reduction of errors indicates that the synergies are flexible and task dependent, as they can change with the task (Shadmehr, Mussa-Ivaldi, & Bizzi, 1993; Yang, Scholz, & Latash, 2007).

Grasping tasks have also been shown to have kinematic synergies as the position of the hand and digits are controlled. It has been shown that hand postures for "mimed grasps" (grasps in which a subject reached for an object that had been as if they were to still be able to actually grasp it) can be described by a small number of postures (Mason, Gomez, & Ebner, 2001) Even in the case of an unconstrained haptic exploration task in which no specific task (or accompanying synergies) was demanded of the subjects, hand posture could be explained by seven basic postures (Thakur, Bastian, & Hsiao, 2008). Additionally, grasping synergies have been identified in the domain of metacarpophalangeal joint angular velocity in which three different synergies accounted for 28 different grasps (Vinjamuri, Mao, Sclabassi, & Sun, 2007). Kinematic synergies identified in handwriting will be discussed later in the literature review.

Kinetic Motor Synergies

In the case of kinetics, synergies related to force and torque production have been identified. Time and position dependent muscle synergies have been identified in a study by Mair and Hepp-Reymond in which EMG activity of both the intrinsic and extrinsic muscles was recorded during a grasping force production task (Maier & Hepp-Reymond, 1995). They found that the temporal synchronicity of muscle activation was significantly more common in sets of muscles innervated by a single nerve than sets of muscles innervated by separate nerves. This synergy only occurred on sets of intrinsic muscles. EMG amplitude synergies, however, were equally strong across the intrinsic, extrinsic, and intrinsic-extrinsic muscles sets.

Studies on multi-digit force production tasks also indicate the presence of kinetic synergies. In the case of a study by Li et al.(Z. M. Li, Latash, & Zatsiorsky, 1998), subjects performed a series of isometric finger flexions with each of the four fingers pressing on a force transducer performing ramp and maximum voluntary contraction (MVC) tasks. In the case of both tasks, a force synergy was identified by greater total output force variance than the summed individual finger force variance, indicating that the performance variable, in this case total force, was more stabilized than the individual effectors of the system. This is an example of a force synergy.

Force and moment synergies have also been identified in prehension grasping tasks. In one such study, subjects held a handle equipped with five, six-dimensional force transducers, one transducer for each digit, in a grip similar to holding a book in which the thumb opposed the four fingers. The inertial properties of the handle were systematically varied. The results indicated that both force and torque synergies were present across all conditions. That is, the sum of variability of the forces and torques of individual effectors was greater than the variability in the force and torque on the handle as a whole (V. M. Zatsiorsky et al., 2003). This prehension study, the pressing task study by Li, Latash and Zastiorsky mentioned above, as well as other recent studies in the field all took the effect of digit enslaving—the unintended force production by non-task fingers—into account, as described by Zatsiorsky, Li, and Latash (V. M. Zatsiorsky, Li, & Latash, 1998).

Object manipulation studies under both unimanual and bimanual circumstances have identified coordination of digit forces such that grasp stability is maintained while the individual digit forces are minimized. This pattern of results is supported by studies on grasping of both rectangular and circular objects (Shim *et al.*, 2004; Shim *et al.*, 2006). Shim's studies found that digit forces are split between two groups. The first group relates to grasp stability, i.e. ensuring the object is not dropped via normal force control. The second group relates to object orientation stability, i.e. ensuring you don't spill your water glass via tangential force control.

Handwriting Review

Handwriting studies encompass a very broad field, allowing researchers with varying interests to collaborate and interact at multiple levels with individual, yet complementary, objectives. These studies frequently consist of a two dimensional digitizing tablet with a sampling frequency of at least 100Hz capable of recording position and pressure changes of the pen tip on the tablet surface and range from modeling to neurological disorder quantification (Adi-Japha & Freeman, 2001; Dounskaia, Van Gemmert, & Stelmach, 2000; Mergl, Juckel et al., 2004; Mergl, Mavrogiorgou, Juckel, Zaudig, & Hegerl, 2004; Plamondon, 1993; Plamondon & Privitera, 1996)

The goal of handwriting modeling can broadly be described as to gain a better understanding of handwriting generation at the global neuromuscular level and gain insight into how the CNS generates precise, complex trajectories. Two complimentary approaches have been proposed to study these mechanisms: central and peripheral. The central approach focuses on the application of the task, how it is coded and controlled by the CNS, and how it is learned (Margolin, 1984). The peripheral approach focuses on the synthesis of biomechanical processes and how to mechanically generate handwriting-like movements. At the most basic level, these models consist of a single mass being acted on by a combination of muscle forces (MacDonald, 1984). Réjean Plamondon, one of the leaders in modeling, has found that the CNS tends to use its most basic properties and limitations to its advantage, rather than a hindrance, to produce complex tasks in a semi-automated fashion (Plamondon & Guerfali, 1998).

Handwriting kinematic analysis is also used to quantify countless neurological and psychological disorders, including Parkinson's disease, multiple sclerosis, stroke, schizophrenia, obsessive-compulsive disorder, depression and many more. (Caligiuri, Teulings, Filoteo, Song, & Lohr, 2006; Gallucci, Phillips, Bradshaw, Vaddadi, & Pantelis, 1997; Mavrogiorgou et al., 2001; Mergl, Mavrogiorgou et al., 2004; Schenk, Walther, & Mai, 2000; Van Gemmert, Teulings, & Stelmach, 2001). In a 1998 study, Van Gammert et al. designed an experiment to test whether Parkinson's disease patients had more difficulty producing specified stoke durations and stroke lengths in a writing task than a control group with no movement disorders. They found that the Parkinson's patients could alter the speed or size of their writing individually, but not simultaneously. Thus, if speed was increased, size was decreased, and vice-a-versa. While they attributed their results to the subjects' inability to control the synergistic release of digit forces on the pen, this conclusion could not be directly tested due to lack of an instrument capable of measuring digit forces on the writing instrument (Van Gemmert et al., 2001).

Studies using the handwriting of schizophrenic patients as a quantification of both the severity of the disease and effectiveness of treatments dates back to the 1950s (Breil, 1953; Muhl, 1953). More recently, a study by Tigges et al. (Tigges et al., 2000) identified differences between healthy controls' and schizophrenics' stroke duration and automation during a concentric circle drawing task. Handwriting studies have also identified micrographia and bradykinesia in obsessive-compulsive disorder patients (Mavrogiorgou et al., 2001) as well as irregular velocity control and bradykinesia in depressed patients (Mergl, Juckel et al., 2004).

Handwriting Synergies

As a task that inherently involves at least 10 degrees of freedom from the joints in the wrist and hand and results in highly specified shapes with unique size and shape, handwriting studies have indicated the presence of kinematic synergies. In one such study, subjects preformed one circle drawing task and a series of line-drawing tasks in which the coordination of the fingers and wrist were controlled in different ways (Dounskaia et al., 2000). The study found that subjects' performance was maximized when wrist and finger movements occurred simultaneously in low phase with one anther, indicating that synergy between these two control parameters exists. In a more recent study, subjects drew a series of ellipsoids of various eccentricities and orientations. Throughout the tasks, it was identified that subjects exhibited distinct coordination patterns during which the stability of the task was maximized. Again, this high level of coordination between the fingers and wrist indicate a kinematic synergy (Athenes, Sallagoity, Zanone, & Albaret, 2004).

UCM Analysis

In search of a more concrete explanation of what the CNS controls in creating a synergy, as well as a more formal definition between what does and does not constitute a synergy, Scholz and Schöner developed the uncontrolled manifold (UCM) hypothesis (J. P. Scholz & Schoner, 1999). The UCM hypothesis states that, “When a controller of a multi-element system wants to stabilize a particular value of a performance variable, it selects a subspace within that state space of elements such that, within the subspace, the desired value of the variable is constant” (M. L. Latash, Scholz, & Schoner, 2002). This selected subspace is known as the UCM. The controller places limitations on the variability inside the state space but not outside the UCM. Limitations on variability within the UCM are minimal, allowing the controller high effector variability so long as the desired value of the performance variable is unchanged (M. L. Latash et al., 2002). The UCM hypothesis differs from the method of synergy quantification described in the above pressing and grasping experiments in that UCM looks directly at the individual element relative to the performance variable, or whether the element is varying in a way that either does or does not affect the outcome of the performance variable. Numerically, this is quantified by the ratio DV, which is the difference between variance along the

UCM (V_{UCM}), “good variance,” and the variance orthogonal to the UCM (V_{ORT}), “bad variance,” normalized for dimensionality total variance. While DV values typically range from $-1 \leq DV \leq +1$, they are not mathematically constrained to this range. The more positive a DV value is, the stronger the synergy is along the chosen UCM, 0 indicates a lack of synergy along the chosen UCM, and negative values indicate a strong synergy orthogonal to the chosen UCM (Zhang, Zatsiorsky, & Latash, 2006).

An example of a basic experiment using UCM analysis can be seen in the work of Latash, Scholz, Danion, and Schöner (M. L. Latash, Scholz, Danion, & Schoner, 2001). Oscillating finger flexion forces during single, two, three, and four finger tasks in which all fingers were acting in parallel were investigated. Subjects followed an oscillating target total force on a computer screen projecting real time feedback of the subjects total force output. Two different UCM analyses were run, one with a total force UCM and another with a total torque UCM. The results computed V_{UCM} and V_{ORT} for each UCM and found a strong torque synergy during the bulk of each oscillation cycle with a force synergy being dominant at the beginning and end of each cycle (M. L. Latash et al., 2001). This same type of analysis is common in force and torque production studies including MVC, ramp, and oscillatory pressing tasks (M. L. Latash, Danion, Scholz, & Schoner, 2003; S. Li, Latash, Yue, Siemionow, & Sahgal, 2003; Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2007; Shim, Olafsdottir, Latash, & Zatsiorsky, 2005; Shim, Park, Zatsiorsky, & Latash, 2006; Zhang, Sainburg, Zatsiorsky, & Latash, 2006) as well as in prehension and grasping tasks (Gao, Latash, & Zatsiorsky, 2005; M. L. Latash, Shim, Gao, & Zatsiorsky, 2004; Shim, Latash, & Zatsiorsky, 2005b). These studies have not yet been extended to handwriting, not due to lack of desire, but lack of a kinetic pen, as illustrated by Latash's thoughts on the potential of UCM hypothesis to study handwriting: "Presently, the UCM-hypothesis offers a framework for such an analysis, and the only limitation is technological: instrumenting a 'pen' with a set of miniature six-dimensional force sensors that would provide information on the mechanical interaction between the pen and the hand" (M. L. Latash, Danion, Scholz, Zatsiorsky, & Schoner, 2003).

For this study, a kinetic pen has been designed and will be used to check for the existence of digit force synergies in a basic writing task. The directionality, clockwise versus counter-clockwise, and pacing, external versus self, will be compared across three different force control strategies: normal force, tangential force, and radial force. This will test four hypotheses. 1) Force synergies will exist across all control strategies (normal force, tangential force, and radial force) due to the aforementioned previous research and hypotheses. 2) Force synergies will be stronger in the counter-clockwise than the clockwise direction. While handwriting is comprised of loops in both directions, the explicit task of circle drawing is most similar to writing the letter 'o,' a counter-clockwise letter, indicating that the counter-clockwise strategies will likely be stronger. 3) The self-paced condition will yield consistently stronger synergies across the performance variables than the externally paced condition. This is due to the fact that timing is a consequence of well-tuned handwriting, not a requirement of it (Thomassen and Teulings 1985). Hence, making timing a requirement will alter what is likely an already well-developed control strategy. While the task is inherently mildly different than natural writing, the self-paced condition differs to a lesser extent; hence it will likely have a stronger force synergy and higher ΔV value. 4) The radial and tangential force performance variables will yield stronger synergies than the normal force control variable. This is due to the fact that when writing errors in the tangential and radial forces have more adverse effects on the writing than normal force. In other words, normal force has a wide range of acceptable values between the minimum of having the pen off the surface of the paper and the maximum of tearing through it. Errors in the radial and tangential forces, however, yield misshapen and possibly illegible script. This indicates that the central nervous system is more likely to have a more developed control strategy for the tangential and radial forces than the normal ones. The existence of these synergies will be determined by DV values in a force synergy UCM analysis.

CHAPTER 3: THE KINETIC PEN

This chapter consists of a technical note written by the author describing the development of the Kinetic Pen to be used in this study (Hooke, Park, & Shim, 2008).

The Forces Behind the Words: Development of the Kinetic Pen

Abstract

Studies in handwriting have historically focused on kinematic parameters of the pen tip rather than the grip forces between the pen and the user. This paper describes the creation of a "kinetic pen" capable of measuring the six-component force and moment of force that each of four individual contacts applies to the pen during writing. This was done by staggering the mounts the four sensors along the long axis of the pen and having an extended arm run from the sensor to the grip site, preventing a clustering of the sensors where the digit tips meet while grasping. The use of the extended arms required a series of coordinate system transformations to yield the forces and moments of force produced at the grip site.

Introduction

The ability to produce proficient and legible script is a skill necessary in everyday life for both children and adults. A lack of this skill leads to several undesirable effects such as misinterpretations due to illegibility, a negative influence of poor penmanship on a writer's perceived competence, and a lack of composition skills due to motor memory interference (Berninger, 1997; Graham, Harris, & Fink, 2000; Peverly, 2006). Scripting ability can be easily affected by neurological disorders such as Parkinson's disease (Caligiuri et al., 2006; Van Gemmert, Adler, & Stelmach, 2003; Van Gemmert et al., 2001), schizophrenia (Tigges et al., 2000), obsessive compulsive disorder (Mavrogiorgou et al., 2001), depression (Mergl, Mavrogiorgou et al., 2004), and others. Additionally, focal dystonias, such as writer's cramp, can have negative effects on writing ability and have a largely unknown pathogenesis (Cohen & Hallett, 1988; Sheehy & Marsden, 1982).

Previous research has primarily focused on the kinematic aspects of handwriting. However, this does not necessarily provide information on the unique kinetic relationships between the hand and pen. For example, when a system is kinetically redundant (Shim, Huang, Hooke, Latsh, & Zatsiorsky, 2007; Shim, Olafsdottir et al., 2005), as in the three-digit grasp often used in handwriting, different digit force and torque combinations can produce identical kinematic profiles. The inability to physically fit the necessary sensors into a natural grip setting has previously prevented this extension to kinetic handwriting research (M. L. Latash, Danion, Scholz, Zatsiorsky et al., 2003). Limited previous research on handwriting kinetics has focused on force relationships between the writing surface and pen-tip (van Den Heuvel, van Galen, Teulings, & van Gemmert, 1998; Wann & Nimmo-Smith, 1991), as well as one-dimensional grasping forces (Herrick & Otto, 1961). A more recent attempt at measuring pen grip forces investigated total grasping force as well as digit-force specificity via contour plots (Chau, Ji, Tam, & Schwellnus, 2006). Recording six-component signals (three force and torque components) from each contact during handwriting is critical in research on handwriting mechanics because handwriting occurs in three-dimensions and cannot be simplified to less dimensionality.

Instrumentation

The dimensions of the Kinetic Pen are similar to those of a typical writing utensil.

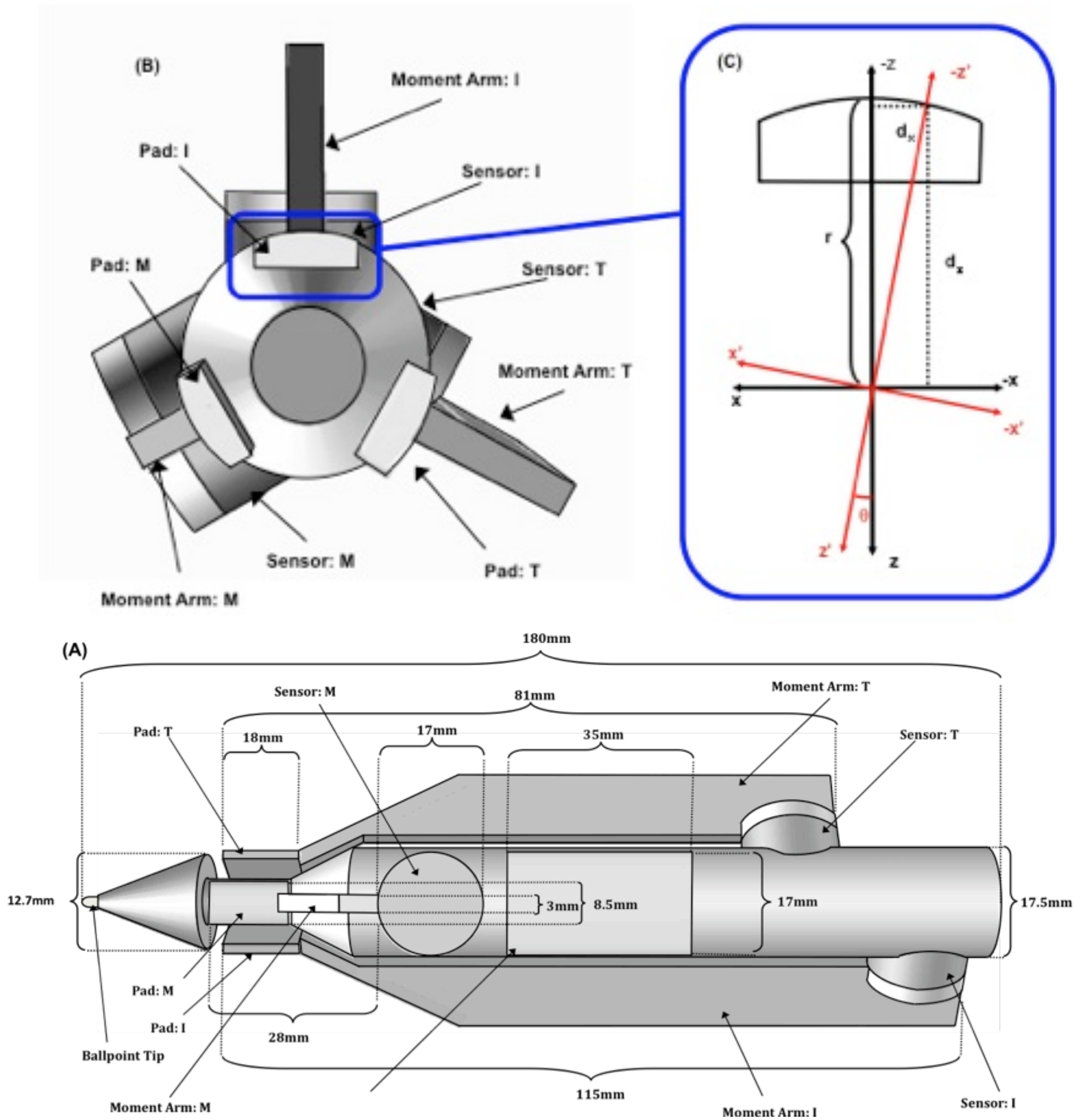


Figure 3.1. (A) Schematic of Kinetic Pen with sensors, moment arms, and grip pads labeled by contact point. Units are mm and T, I, M, and W represent, thumb, index, middle, and webbing area, respectively. (B) Schematic of Kinetic Pen viewed from writing end with tip removed. (C) Definition of original x_j-and z_j-axes, transformed x_j'- and z_j-'- axes, x_j- and z_j- moment arms (d_{xj} and d_{zj}), radius (r), and rotation angle (θ_j). y_j-axis is not shown in the figure, but it is orthogonal to x_j- and z_j-axes, and follows the right hand-thumb rule for its direction.

The pen is equipped with four, six-component sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA). The manufacturer provided a calibration matrix calculated from a set of loading scenarios designed to cover the entire six-axis calibration range. These procedures comply with the ISO 9001 standard. The measurement uncertainty for the calibration ranged between 0.01% and 0.96%. The independent measures of each of the three-dimensional force and torque components were achieved by multiplying the sensor-specific calibration matrix by the six-channel analog signals.

Each sensor is countersunk into the pen's body such that all but 2mm is encased and corresponds to an individual contact point with the hand in a typical, four contact-point writing grip: thumb, index finger, middle finger, and webbing between the thumb and index finger. Thumb, index and middle digits' sensors have extended arms mounted to the flat surface of their respective sensor and run parallel to the long axis of the pen ending at a rounded grip site. The extended arms contact the pen at exclusively their respective sensor mountings and nowhere else on the pen body. This "floating" design of the arms yields forces at the grip site to equivalent the sensor readings. The thumb and index finger's extended arms are titanium, eliminating arm bend. The shorter, middle finger arm is aluminum. The webbing sensor has an aluminum plate mounted to its surface as a resting pad that can be adjusted via translations along the pen's long axis to accommodate varying hand sizes. These attachments prevent temperature-sensitive signal distortions.

Reference System Transformation:

Each sensor uniquely corresponds to a specified contact point (*j*) with the pen and has its own original local reference system such that the y-axis runs parallel to the pen's long axis, the x-axis runs tangential to the curvature of the pen's body, and the z-axis passes through the pen's body, normal to the surface curvature (Fig. 3.1C). Each of the sensors has three component force ($\overrightarrow{F_j}$) and torque ($\overrightarrow{T_j}$) outputs. The total torque is comprised of force, moment arm ($\overrightarrow{d_j}$), and free torque ($\overrightarrow{\mu_j}$) elements (Eq. 3.1).

$$
\begin{aligned}
\overrightarrow{T_j} &= \overrightarrow{d_j} \times \overrightarrow{F_j} + \overrightarrow{\mu_j} \\
\overrightarrow{F_j} &= \left[F_{xj}, F_{yj}, F_{zj}\right] \\
\overrightarrow{T_j} &= \left[T_{xj}, T_{yj}, T_{zj}\right] \\
\overrightarrow{d_j} &= \left[d_{xj}, d_{yj}, d_{zj}\right] \\
\overrightarrow{\mu_j} &= \left[\mu_{xj}, \mu_{yj}, \mu_{zj}\right]
\end{aligned}
\tag{3.1}
$$

j =contact point of thumb index, middle or web area

The center of pressure (COP) of each digit on the grip pad fluctuates during a writing task. To increase the intuitiveness of analysis, the original local coordinate systems (i.e., x-y-z) of each sensor are transformed via a center of pressure-determined y-axis rotation such that the rotated x'- and z'-axes represent the tangential and normal axes, respectively (Fig 3.1C). The amount of rotation (q_j) is unique to each contact at each moment in time and is described by rotation matrix R_{qj} (Eq. 3.2).

$$
R_{\theta j}(t) = \begin{bmatrix} \cos(\theta_j(t)) & 0 & -\sin(\theta_j(t)) \\ 0 & 1 & 0 \\ \sin(\theta_j(t)) & 0 & \cos(\theta_j(t)) \end{bmatrix}
\tag{3.2}
$$

The forces ($\overrightarrow{F_j}'$), torques ($\overrightarrow{T_j}'$), moment arms ($\overrightarrow{d_j}'$), and free torques ($\overrightarrow{\mu_j}'$) in the transformed reference system (i.e., x'-y'-z') are calculated by multiplying the transformation matrix, R_{qj}, by each respective vector (Eq. 3.3).

$$\overrightarrow{F_j}' = R_{\theta j}\overrightarrow{F_j}$$
$$\overrightarrow{T_j}' = R_{\theta j}\overrightarrow{T_j}$$
$$\overrightarrow{d_j}' = R_{\theta j}\overrightarrow{d_j} \tag{3.3}$$
$$\overrightarrow{\mu_j}' = R_{\theta j}\overrightarrow{\mu_j}$$

The transformed force, torque, moment arm, and free torque values must be found as a function of the original force and torque components (as these are the sensor outputs) and distance *r*, representing the distance from the sensor origin to the surface of the grip pad (Fig. 3.1C).

The original moment arm values of d_{xj} and d_{zj} can be described in terms of the rotation angle q_j and distance *r*, as illustrated in figure 3.1 (Eq. 3.4).

$$\begin{aligned} d_{xj} &= -r\sin(\theta_j) \\ d_{zj} &= -r\cos(\theta_j) \end{aligned} \tag{3.4}$$

The original torque definition equation defined previously (Eq. 3.1) is expanded and the d_{xj} and d_{zj} values in Eq. 3.4 can be substituted into the y-component of the total torque (Eq. 3.5).

$$\begin{aligned} T_{yj} &= d_{zj}F_{xj} - d_{xj}F_{zj} + \mu_{yj} \\ T_{yj} &= r\sin(\theta_j)F_{zj} - r\cos(\theta_j)F_{xj} + \mu_{yj} \end{aligned} \tag{3.5}$$

No free torque about the y-axis exists because it has no normality with the grip site.

$$T_{yj} = r\sin(\theta_j)F_{zj} - r\cos(\theta_j)F_{xj} \tag{3.6}$$

The physical constraints of the grip pads dictate that range of possible θ_j values is -45° to 45° (Fig. 3.1C). By solving equation 3.6 for θ_j, the amount of y-axis rotation needed to define the x'- and z'-axes as instantaneously tangential and normal to the grip pad, respectively, is a function of all known values (Eq. 3.7).

$$\theta_j = \sin^{-1}\left(\frac{T_{yj}}{r\sqrt{F_{xj}^{\ 2} + F_{zj}^{\ 2}}}\right) + \tan^{-1}\left(\frac{F_{xj}}{F_{zj}}\right) \tag{3.7}$$

Using the above equation (Eq. 3.7), the transformed forces ($\overrightarrow{F_j}'$) and torques ($\overrightarrow{T_j}'$) can be calculated by substituting q_j into the rotation matrix R_{qj}.

As the z'-axis is the only axis normal to the grip site in the transformed system, free torques about the x'- and y'-axes cannot exist, the tangential displacement of the moment arm (d_{xj}') disappears, and the distance from the system origin to the grip site, -*r*, is equivalent to d_{zj}' (Eq. 3.8).

$$\begin{aligned} \mu_{xj}' &= \mu_{yj}' = 0 \\ d_{xj}' &= 0 \\ d_{zj}' &= -r \end{aligned} \tag{3.8}$$

By substituting the values defined above (Eq. 3.8) into the transformed component torque equations, the only remaining unknown values of d_{yj}' and m_{zj}' can be found (Eq. 3.9).

$$\begin{aligned} T_{xj}' &= d_{yj}'F_{zj}' + rF_{yj}' \\ T_{yj}' &= -rF_{zj}' \\ T_{zj}' &= -d_{yj}'F_{xj}' + \mu_{zj}' \end{aligned} \tag{3.9}$$

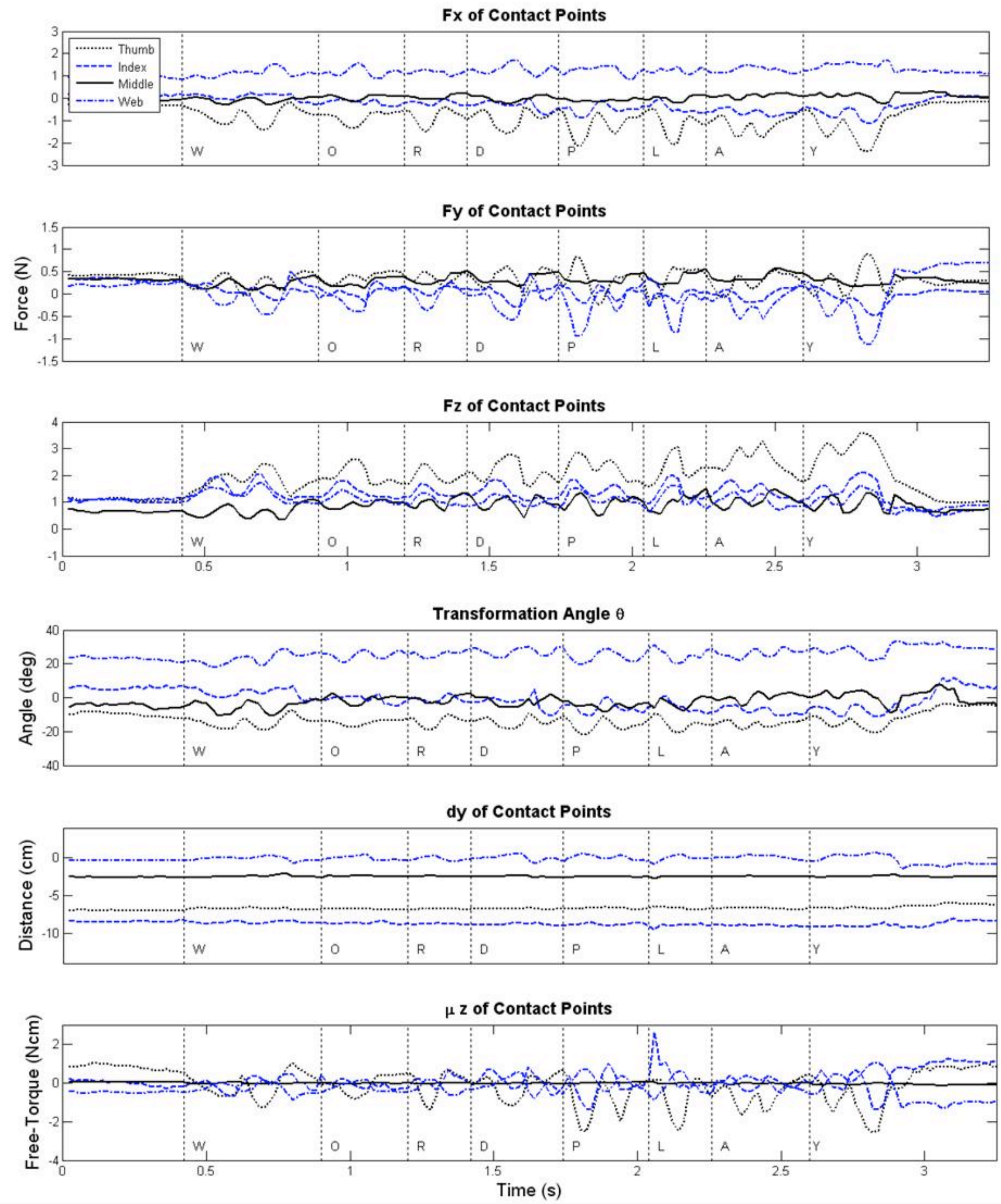


Figure 3.2. Time profiles of a single trial of transformed data of a subject writing "Wordplay". The vertical dashed lines indicate the initiation of the writing of the corresponding letter. The thumb, index, middle, and webbing components are shown. (A) F_x': forces tangential to the curvature of the pen. (B) F_y': forces running parallel to the pen's long axis. (C) F_z': forces normal to the curvature of the pen (D) q: transformation angle (E) d_y': distance along pen's long axis from sensor to grip site center of pressure (F) m_z': free torque about axis normal to curvature of pen.

The T_{xj}*'* and T_{zj}*'* equations are used to solve for final unknowns, d_{yj}*'* and m_{zj}*'* (Eq. 3.10).

$$d_y' = \frac{T_x' - rF_y'}{F_z'}$$
$$\mu_z' = T_z' + \left(\frac{T_x' - rF_y'}{F_z'}\right)F_x' \qquad (3.10)$$

The $\overrightarrow{F_j}'$, $\overrightarrow{T_j}'$, $\overrightarrow{d_j}'$, and $\overrightarrow{\mu_j}'$ values are then known for each contact point on the pen and the relationships between these values can be identified instantaneously over time.

Figure 3.2 shows a time profile of the transformed output of a single trial of a subject writing “Wordplay”. The initiation of each letter was determined by non-zero readings from a force plate writing surface and these points are indicated by vertical dashed lines. The transformations comply with the expectations based on the physical properties of the system as well as what specific forces are produced along each axis and how the orientation of the pen’s contact with the digits fluctuates during writing.

Implications

The Kinetic Pen provides three-dimensional forces and torques at each contact enabling researchers to quantify the finger joint torques from inverse dynamics during handwriting. This was not possible in previous studies (Chau et al., 2006; van Den Heuvel et al., 1998; Wann & Nimmo-Smith, 1991). This tool provides a novel set of measurement techniques in handwriting mechanics, shedding light on issues such as on the pathogenesis of writer’s cramp and other focal dystonias (Cohen & Hallett, 1988; Sheehy & Marsden, 1982). Previous investigations on this have been limited to EMG of forearm muscles and neural imaging techniques that do not provide a comprehensive understanding of specific tendon and muscles forces (Cohen & Hallett, 1988; Müller & Poewe, 2007; Tempel & Perlmutter, 1993). These forces may be identifiable via inverse dynamics using this instrument. Our future studies will investigate the force and torque synergies of the digits during writing and the inverse dynamics of these relationships, offering help in the diagnoses, quantification and treatment of movement and psychological disorders and dystonias connected to handwriting.

CHAPTER 4: KINETIC SYNERGIES INVESTIGATION

***Title**:* Handwriting: kinetic synergies of circle drawing movements in 3-D space.

Abstract

The purpose of this study was to investigate central nervous system strategies for controlling multi-finger forces in three-dimensional (3-D) space during a circle-drawing task. Subjects drew 30 concentric, discontinuous circles in the clockwise and counter clockwise directions at self and experimenter set paces. The 3-D forces and moments of force were recorded at each contact between the hand and the pen as well as the 3-D trajectory of the pen's center of mass. The synergistic actions of the contact forces, defined as kinetic synergy, were investigated in three orthogonal spaces: a radial component that dictates the pen's motion from the circle edge towards its center, a tangential component that dictates to the pen's motion tangent to the edge of the circle, and vertical component that dictates the pen's motion perpendicular the writing surface. We employed varying directional (clockwise vs. counterclockwise) and pacing (self-paced vs. external-paced) conditions for the circle drawing. Uncontrolled Manifold Analysis was used to quantify the synergies between pen-hand contact forces. Four hypotheses were tested. 1) Synergies between the pen-hand contact forces exist in all three components. 2) The radial and tangential components yield stronger synergies than the vertical component. 3) Synergies exist in both clockwise and counter-clockwise directions and the synergistic strengths do no differ between them. 4) The self-pacing yields stronger synergies than the external pacing. Results showed that synergies between pen-hand contact forces existed in all components. Synergies in the radial and tangential components were significantly stronger than in the vertical component. Synergies in the

clockwise direction were significantly stronger than the counter-clockwise direction in the radial and vertical components. Pace was found to be insignificant under any condition. Additionally, synergistic dependences on time and position are discussed.

Introduction

The seemingly simple act of handwriting is one of many marvels of the central nervous system. Whether writing a word or drawing a basic shape, we are able to generate a sort of code that is both universally recognizable, yet individually unique. The complex joint torques and rotations within the arm, wrist, and digits, working together to create a precise and singular output, make any multi-digit coordination task, particularly handwriting, an excellent gateway to understand the central nervous system's (CNS) control of human movements (Dounskaia et al. 2000).

An object in space, such as a pen in one's hand, has six degrees of freedom (DOF). Three of these describe its position and three others describe its orientation. These six DOF can be manipulated by actuators, a hand and fingers in the case of writing with a pen, working along six kinetic DOF, three corresponding to force and three corresponding to torque in thre dimensional space. When writing, the pen usually has contacts with five parts of the hand: the thumb, index, middle, interdigit webbing between the thumb and index. One can consider each of the contacts as an actuator with six kinetic DOF and when working simultaneously a total of 30 kinetic DOF must be synergistically controlled in order to attain the desired movement of the pen. Under these circumstances, an infinite number of actuator force combinations can create an identical pen trajectory. This is known as kinetic redundancy (Shim et al. 2005a; b). How the CNS handles these extra DOF is a fundamental question in human motor control that has varying proposed solutions. One such solution suggests that the CNS considers the extra DOF as abundant versus redundant (Gelfand and Latash 1998; Latash 2000). When confronted with a redundant system, the CNS does not employ a single solution by eliminating redundant DOF, but rather governs families of solutions that are each capable of accomplishing the desired task using all DOF available (Zatsiorsky and Latash 2004). That is, the CNS uses the excessive DOF as a task-specific tool for control via neural correlations of elemental variables that stabilize particular performance variables, and such a correlation of elements can be functionally defined as a synergy (Latash et al. 2008).

Recent experiments have found that complimentary multi-digit synergies can simultaneously exist in prehension grasping tasks (Shim et al. 2003; 2005b; Zatsiorsky and Latash 2004). One synergy relates to grasp stability, i.e. ensuring an object not to be dropped via normal force control in static grasping, and the other relates to object orientation stability, i.e. ensuring an object not to be rotated via both normal and tangential digit force control (Shim et al. 2004; Shim et al. 2006). These complimentary synergies follow the principle of superposition proposed in robotics which suggests that complex tasks performed by a multiple elements can be broken into independently controlled sub-tasks without interference between them (Arimoto and Nguyen 2001; Arimoto et al. 2001). The present study will extend this notion of the multi-digit force synergies to the realm of handwriting in three-dimensional space.

In the case of drawing circles, the dynamics of the pen motion can be logically broken down into three orthogonal components of control. First, there is a radial component causing the centripetal acceleration of the pen and the force of this component creates the curvature during circle drawing. Second, there is a tangential component causing deviations to a mathematically perfect circle via forces tangential to the circles edge. Third, there is a vertical component constituting the pen motion normal to the writing surface (i.e. often parallel to gravity). Given that handwriting is another form of grasping task requiring extremely high precision and accuracy, one can predict that the digit forces, while grasping the pen, will yield strong synergies between hand-pen contact forces across all three of these components. However, it is also likely that the radial and tangential components will yield stronger synergies than that of the vertical. Errors in the radial and tangential components will cause misshapen and possibly illegible script while errors in the vertical component can range from lifting the pen from the surface to tearing through the paper without having adverse effects on the writing's appearance, suggesting that the CNS would employ a strategy emphasizing radial and tangential components.

Other aspects of human movement control, specifically directionality during circle drawing and pacing of manual movements have been investigated in previous research. Recent studies investigating joint kinematics and control during circle drawing found no identifiable differences in control ability between the clockwise and counter clockwise direction (Bosga et al. 2003; Tseng and Scholz 2005). Additionally, from a handwriting perspective, writing is comprised of a series of loops in both the clockwise direction—such as 'b', 'm,' and 'p'—and counter-clockwise direction—such as 'd,' 'o,' and 'w'—as well as others that consist of both clockwise and counter-clockwise parts, suggesting that controls in both directions may be well developed through life-long handwriting experinece. The current study is designed to investigate this directional dependence of handwriting synergies at the kinetic level as synergy strength will be compared between the clockwise and counter clockwise directions.

Previous studies on pacing control, some of which use drawing as the task, indicate that rhythmic movements are generated by internal clocks originating in the cerebellum (Spencer and Zelaznik 2003; Welsh et al. 1995). Additionally, it has also been shown that the invariant relative timing of handwriting may be a self identifiable characteristic of one's handwriting (Knoblich and Flach 2003). This suggests internal rhythm is a component of handwriting and susceptible to perturbations to one's natural rhythm. The effect of external pacing on handwriting performance at a kinetic level will be investigated in this study. It is hypothesized that given the inherently internal nature of handwriting pacing, forcing one to match an external pace will adversely affect the handwriting performance indicated by lower synergy strength in the externally paced condition than the self paced condition.

While no prior work has been able to directly study kinetic digit synergies during writing, previous investigations have inspired four hypotheses. 1) Pen-hand contact synergies during circle drawing will exist across the radial, tangential, and vertical components. 2) Hand-pen contact force synergies will be stronger on the radial and tangential components than the vertical component. 3) There will be no significant difference in synergy strength between the clockwise and counter-clockwise directions. 4) Synergy strength will be greater in the self paced condition than in the externally paced condition.

Method

Twenty-four subjects, 12 male and 12 female, between ages 19 and 27 volunteered as unpaid subjects for this study. All subjects were right handed. Subjects' participation was also limited by the handwriting grip technique used. Due to the design of the testing instrument, only subjects using the common grip of 3 digit contacts—the tip of the thumb, the tip of the index finger, the lateral surface of the distal phalanx on the middle finger—and a 4^{th} contact at the metacarpophalangeal (MCP) webbing between the thumb and index finger were tested. Subjects were screened for neurological, psychological, and any other potentially confounding health conditions. The right hand length and width were measured from the middle finger tip to the lunate of the wrist and between the MCP joints of the index and little fingers, respectively. The average hand length of the subjects was 17.9 ± 3.2cm and the width was 8.0 ± 1.2cm. The Institutional Review Board (IRB) at the University of Maryland approved the procedures used in the experiment. All subjects received both written and verbal instructions for the test procedures. Informed written consent was obtained from all participants in the study.

Apparatus

The Kinetic Pen was used as the writing utensil for this study (Hooke et al. 2008). The Kinetic Pen was equipped with 4, six-dimensional sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA) and a plastic, non-inking tip (Figure 1A).

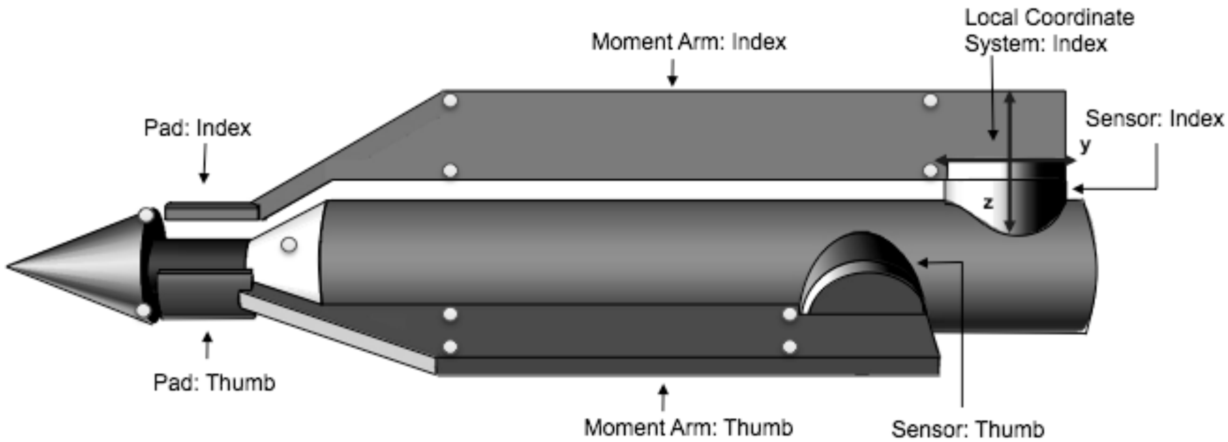
Participants wrote on a writing surface created by mounting 14 x 14 x 0.5cm square, transparent Plexiglas plate atop a six-component sensor (Nano-17, ATI Industrial Automation, Garner, NC, USA). The mounting of the plate was secure such that it had no movement during the writing task. A piece of white construction paper was affixed to the Plexiglas with a circular template printed on it in order to guide subjects for circle drawing tasks.

A four-camera motion capture system (Vicon Motion Systems Inc., CA, USA) was used to obtain kinematic data from the pen and the writing surface. Subjects were seated within a calibrated volume of 100 cm × 100 cm × 100 cm. An array of 9 reflective, markers (3 mm in diameter) was placed on the Kinetic Pen. Three markers were on the writing end, three defining the thumb sensor and extended arm, and three defining the index sensor and moment arm. An array of four reflective markers was mounted to the construction paper on the writing surface to define the global reference system.

Each of the force sensors, both for the writing surface and in Kinetic Pen, were calibrated by the vender to be accurate to the following resolutions: 1/640 N in F_x, F_y, and F_z and 1/128 Nmm in M_X, M_Y, M_Z. A total of 30 analogue signals from the sensors were sent to two synchronized 12-bit analogue-digital converters (PCI-6031 and PCI-6033; National Instrument, Austin, TX, USA) to be processed and saved by a customized LabVIEW program (LabVIEW 7.1; National Instruments). The force sensors sampled data at 50Hz. The time-varying three-dimensional coordinates of each reflective marker were sampled at 100Hz and recorded synchronously with the kinetic data from the force sensors.

The writing surface was orientated with one edge parallel to the table edge with approximately 30cm of table space between the two edges. A 30cm^2 wood block with a height of 4.5cm was placed on the table between the subject and force plate. Subjects were told to hold the pen with their natural handwriting grip and all subjects reported the pen gripping was comfortable. The wires from four sensors were bundled together and the bundle was taped to the posterior part of the subject's forearm with about 20cm of slack between the taped area and the pen (Figure 4.1B). This preparation was made to minimize the effect of the wires' weight putting unwanted forces and torques on the pen..

A



B

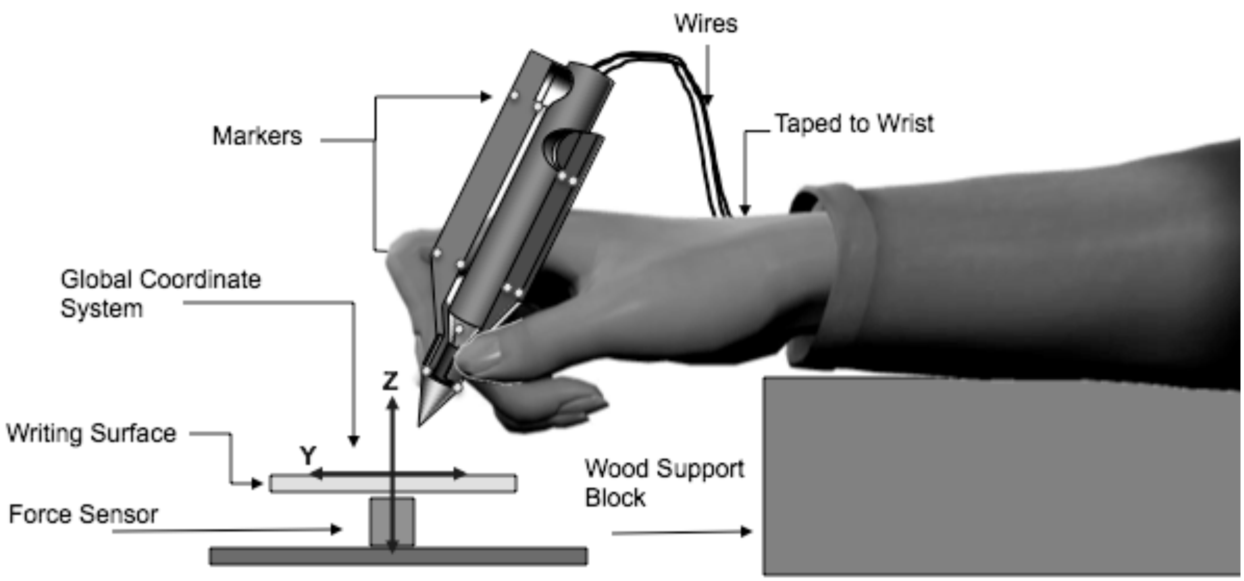


Figure 4.1. A) Schematic of Kinetic Pen. Pen contains four, six-component sensors, thumb and index shown above. Each sensor is equipped with a moment arm running along the long axis of the pen. Each moment arm has a rounded grip pad with each pad corresponding to a single, unique contact point with the hand: thumb, index, middle, and webbing at the thumb-index MCP joint. Nine reflective markers were mounted to the pen. Each sensor had a local coordinate system in which the y-axis runs parallel to the long axis of the pen, the z-axis normal to the sensor's surface and the x-axis orthogonal to the y- and z-axes. B) Schematic of experimental setting showing a subject holding the Kinetic Pen with reflective markers attached. The three-dimensional and contact forces and torques between the hand and the pen were recorded from the six DOF sensors implemented in the pen and pen tip force was recorded from the same type of force sensor underneath the writing surface with the surface sensor's coordinate system defining the global coordinate system. The writing surface was made of Plexiglas.

Experimental procedures

Participants were instructed to draw circles 3cm in diameter at whatever speed they felt most "comfortable" while maintaining as close to a geometrically accurate circle as possible, pausing briefly between concentric circles for approximately 0.5 sec. These practice trials were quickly analyzed to determine their pacing for the external pacing condition in the following drawing tasks.

For the drawing tasks, subjects were asked to draw circles 3cm in diameter on the writing surface with a template of the circle. Using this basic task, four conditions were tested. There were two different paces: self paced and externally paced. Each pace condition was done in both clockwise and counter-clockwise directions, yielding 4 total variations (2 paces x 2 directions). The order of the conditions was balanced across subjects. One trial was done for each condition and each trial consisted of drawing 30 concentric, but discontinuous circles. A target position 1.5 cm above the circle center was the starting point of the pen tip. Subjects placed pen tip on the target, drew a circle in the assigned direction, returned to the starting position, and began the next concentric circle. In the externally paced condition, subjects tried to match their circle drawing pace to an audible metronome omitting beeps at a frequency determined by the pacing in the self-paced practice trials. Subjects were told to begin a circle on a beep, complete that circle on the next beep, and begin the next circle on the third beep, repeating this pattern for 30 circles for each trial. Both pace conditions were run for the clockwise and counter clockwise conditions. The circles were centered about the center of the writing surface such that the force sensor beneath the surface was in the center of the circle.

The circle center on the writing surface was considered as the origin of the global reference system. The global Z-axis was normal to the writing surface, positive pointing upward. The global Y-axis was parallel to the writing surface and perpendicular to the Z-axis and table edge, positive pointing away from the subject. The global X-axis was orthogonal to the global Y- and Z-axes, following the right-hand-thumb rule. The local coordinate system was aligned local at each sensor such that the y-axis ran parallel to the pen's long axis, the x-axis ran tangential to the curvature of the pen's body, and the z-axis passed through the pen's body, normal to the surface curvature.

Data Processing

Identification of pen tip kinematics

The three dimensional coordinates of the pen tip were needed to identify the performance of subjects but could not be directly recorded as the writing surface was a force plate versus the digitizing tablets commonly used in kinematic handwriting studies. Prior to each participant's data collection, the experimenter recorded a 15 second, exclusively kinematic trial in which the pen tip remained stationary and the pen body was pivoted around it. This allowed the pen tip to be treated as an instantaneous joint joint center (Gamage and Lasenby 2002; Holzreiter 1991). The three-dimensional position whose coordinates were known relative to the other nine markers on the pen was determined as the pen tip coordinates.

Circle Separation

During each pace-direction condition, the kinetic and kinematic data for all 30 circles were saved as individual files. To separate these individual circles, the local minima of the magnitude of the pen-tip velocity were used as a cut points. The first 5 circles and the last 5 circles were disregarded for each condition to eliminate the effects initiating and finishing the trial.

Transformation of digit forces into global reference frame

Data collected in this study were considered in multiple reference frames. The kinematic data recorded by the motion capture system and the pen-tip force data was considered in the global reference frame, denoted [X, Y, Z]. The force data collected from each digit was in a reference frame local to each digit, denoted $[F(t)_{xi}, F(t)_{yi}, F(t)_{zi}]$ where i corresponds to the contact points: thumb, index, middle, and webbing. As the goal of this study was to investigate synergistic actions between each of the hand-pen contact forces, a direct, linear relationship between the digit forces, pen-tip force and the acceleration of the pen was necessary. To make this comparison, the digit force local reference frames underwent a rotation such that they were expressed in the global reference frame.

Using the three-dimensional coordinate data from the motion capture system, the orientation of the Kinetic Pen relative to the global reference frame was computed. From this orientation, the amount of rotation about the global X-, Y-, and Z-axes each local reference frame must undergo such that the digit forces are in the known relative to the global system was found. These Euler angle rotations about the X-, Y-, and Z-axes, denoted $\theta(t)$, $\phi(t)$, and $\psi(t)$, respectively (Eqs. 4.1 and 4.2). Rotation matrix R(t) denotes the necessary rotation about each of the global axes.

$$\mathrm{R}(t) = \mathrm{R_X}(\theta(t)) \bullet \mathrm{R_Y}(\phi(t)) \bullet \mathrm{R_Z}(\psi(t)) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta(t) & \sin\theta(t) \\ 0 & -\sin\theta(t) & \cos\theta(t) \end{bmatrix} \begin{bmatrix} \cos\phi(t) & 0 & -\sin\phi(t) \\ 0 & 1 & 0 \\ \sin\phi(t) & 0 & \cos\phi(t) \end{bmatrix} \begin{bmatrix} \cos\psi(t) & \sin\psi(t) & 0 \\ -\sin\psi(t) & \cos\psi(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4.1)$$

$$\begin{bmatrix} F(t)_{Xi} & F(t)_{Yi} & F(t)_{Zi} \end{bmatrix} = \begin{bmatrix} F(t)_{xi} & F(t)_{yi} & F(t)_{zi} \end{bmatrix} \bullet \mathrm{R}(t) \tag{4.2}$$

where i = (thumb, index, middle, and web). XYZ and xyz represent the global and local reference systems, respectively.

Transformation to radial and tangential components

Three different synergies were considered with regards to the motion of the pen: components along the radius of the circle, tangential to the curvature of the circle, and parallel to gravity (i.e. normal to the writing surface). In order to calculate these three components of motion, another transformation took place: the X and Y components of each digit and the pen-tip became components instantaneously radial and tangential to the curvature. The Z components did not change, as they were already vertical and orthogonal to the X-Y plane.

The Z-axis rotation was determined using the kinematics of the pen tip. A vector **r** was created pointing from the pen-tip to the circle center, indicating the radial direction. The $F(t)_{Xi}$ and $F(t)_{Yi}$ components were rotated such that one component of the rotated force was parallel to **r** becoming the radial force $F(t)_{ri}$. The magnitude of this rotation is denoted λ(t) (Eq. 4.3). The other component of the rotated force, by definition of being perpendicular to the radial and vertical forces, was the tangential force F_{ti}. In this case, each set of digit forces and the pen tip force were rotated as the rotation is global.

$$\begin{bmatrix} F(t)_{ri} & F(t)_{ti} & F(t)_{vi} \end{bmatrix} = \begin{bmatrix} F(t)_{Xi} & F(t)_{Yi} & F(t)_{Zi} \end{bmatrix} \begin{bmatrix} \cos\lambda(t) & \sin\lambda(t) & 0 \\ -\sin\lambda(t) & \cos\lambda(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.3}$$

$$F(t)_{ri} = F(t)_{Xi}\cos\lambda(t) + F(t)_{Yi}\sin\lambda(t) \tag{4.4}$$

$$F(t)_{ti} = -F(t)_{Xi}\sin\lambda(t) + F(t)_{Yi}\cos\lambda(t) \tag{4.5}$$

$$F(t)_{vi} = F(t)_{Zi} \tag{4.6}$$

where i = (thumb, index, middle, web, and pen-tip), global forces = (X, Y, Z), r = radial, t = tangential, v = vertical, λ = magnitude of Z axis rotation

Uncontrolled Manifold (UCM) Analysis

The framework of the Uncontrolled Manifold (UCM) analysis was used to quantify the digit synergies (Latash et al. 2001; Schöner 1995; Shim et al. 2008). UCM analysis allows quantifying synergistic actions of multiple elemental variables (e.g., finger forces) that are acting together in a redundant motor system. The following equations were constructed in such a way that the synergistic actions of hand-pen contact forces could be investigated in three dimensions through UCM analysis (Eqs. 4.7-4.11).

$$[U]\begin{bmatrix} F(t)_{r\_thumb} \\ F(t)_{r\_index} \\ F(t)_{r\_middle} \\ F(t)_{r\_web} \end{bmatrix} = \left[\mathrm{m}a(t)_{r\_COM} - F(t)_{r\_tip}\right] \quad (4.7)$$

$$[U]\begin{bmatrix} F(t)_{t\_thumb} \\ F(t)_{t\_index} \\ F(t)_{t\_middle} \\ F(t)_{t\_web} \end{bmatrix} = \left[\mathrm{m}a(t)_{t\_COM} - F(t)_{t\_tip}\right] \quad (4.8)$$

$$[U]\begin{bmatrix} F(t)_{v\_thumb} \\ F(t)_{v\_index} \\ F(t)_{v\_middle} \\ F(t)_{v\_web} \end{bmatrix} = \left[\mathrm{m}a(t)_{v\_COM} - F(t)_{v\_tip} - W\right] \quad (4.9)$$

where F(t) = force over time, $[U]$ *= unity matrix (1X4), (thumb, index, middle, web) = hand-pen contacts, tip = pen tip on writing surface, (r, t, v) = radial, tangential, vertical components,* m *= mass of pen, a = acceleration of pen's COM and W = weight of pen.*

For each force component (i.e., radial, tangent, and vertical), there is a four-dimensional (i.e., four pen-hand contact points) vector *F(t)* on the left hand side of each equation. Change in the right-hand side (ΔRHS) of the equations ($\left[\mathrm{m}a(t)_{r\_COM} - F(t)_{r\_tip}\right]$, $\left[\mathrm{m}a(t)_{v\_COM} - F(t)_{v\_tip} - W\right]$, and $\left[\mathrm{m}a(t)_{t\_COM} - F(t)_{t\_tip}\right]$) can be expressed in terms of the changes in the four-dimensional vector *F(t)* and the unity matrix [*U*]. Assuming that the mean time trajectory of the RHS over all twenty circles is the trajectory achieved by the CNS, one can construct the following equation with the condition of ΔRHS(t) = 0 for the mean trajectory of RHS(t) over twenty circles.

$$\Delta RHS(t) = [U]*[\Delta F(t)] \qquad (4.10)$$

Each manifold can be linearly approximated via the null space spanning the basis vector e(t) (Eq. 4.11).

$$0 = [U]*e(t) \qquad (4.11)$$

The total variance ($V_{TOT}(t)$) of four-dimensional space across the twenty circles was resolved into two components. The vectors *F(t)* were broken into their projection on, and orthogonal to, the null space (UCM). The variance within the UCM per degree of freedom ($V_{UCM}(t)$) was calculated. This component of total variability causes no change to RHS mean value. The variance orthogonal to the UCM ($V_{ORTH}(t)$) was also calculated. This component of total variability causes change in RHS mean values (i.e. errors in RHS). An index called ΔV was computed to account for varying magnitudes of variance between subjects and tasks by normalizing the V_{UCM} per UCM dimension by the V_{TOT} per degree of freedom (Eq. 4.12).

$$\Delta V(t) = \left(\frac{V_{UCM}(t)}{3} - \frac{V_{ORT}(t)}{1}\right) \Big/ \left(\frac{V_{UCM}(t) + V_{ORT}(t)}{4}\right) \qquad \mathbf{(4.}12)$$

A positive ΔV indicates that V_{UCM} is greater than V_{ORT} and consequently a synergy between the individual forces. Greater ΔV values represent greater kinetic synergy between pen-hand contact forces. That is, the four individual force components compensate for each other's errors to achieve the constant trajectory of circle drawing.

The ΔV index was computed for the whole circle over 20 consecutive circles starting with the 6^{th} circle for each condition.

Statistics

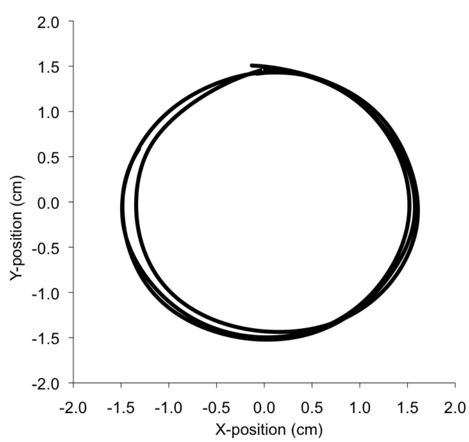
A within-subjects ANOVA was run with factors of Pace [2 levels: self and external], Direction [2 levels: clockwise and counter-clockwise], and Component [3 levels: radial, tangential, and vertical]. Additionally, analyses were run comparing the significance of time and position. Appropriate post-hoc comparisons and contrasts were performed for any differences detected as well as to examine significant interactions. Experiment-wise error rate was set at alpha = 0.05 with appropriate Bonferroni corrections.

Results

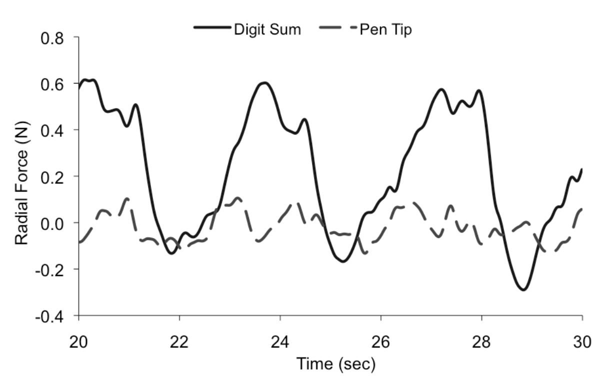
Kinematic and kinetic signals

All subjects performed the task while following a circular path centered on the origin with a radius of 1.5cm (Figure 4.2A). Figures 4.2B-D show the sum of the digit forces acting on the pen recorded by the sensors on the pen and the force of the pen tip on the writing surface recorded by the writing surface sensor during a ten second window from a single subject. Forces along the radial direction are illustrated in Figure 4.2B. The sum of digit forces in radial direction and the pen tip-surface radial force are in phase with one another with the sum of digits forces having larger amplitude. When the digit force sum is larger than the pen tip reaction force, the pen is moving across the writing surface as the forces acting on the pen (i.e. the digit forces) are larger than the forces resisting movement of the pen (i.e. frictional forces on the writing surface) in the radial direction. Forces along the tangential direction are illustrated in Figure 4.2C. Here, similar to the radial direction, the sum of digit forces and pen tip reaction force are in phase with one another with the sum of digit forces having larger amplitude. This exemplifies the digit forces overcoming the frictional forces of the writing surface to create movement of the pen. In the vertical direction (Figure 4.2D), the sum of digit forces matches those of the pen-tip forces in the opposite direction, indicating that there is a balance of forces in the vertical direction and there is minimum movement of the pen in the vertical direction. These force comparisons show that the force transformations from local to global coordinates and from Cartesian to radial and tangential components are qualitatively accurate. The small differences between the sum of the digit forces and the pen tip reaction force after taking the acceleration into account seems to be caused by the uncertainty of sensors and their propagations during digit sum calculations (Figliola and Beasley 2001; Shim et al. 2003; Taylor 1997).

A



B



C D

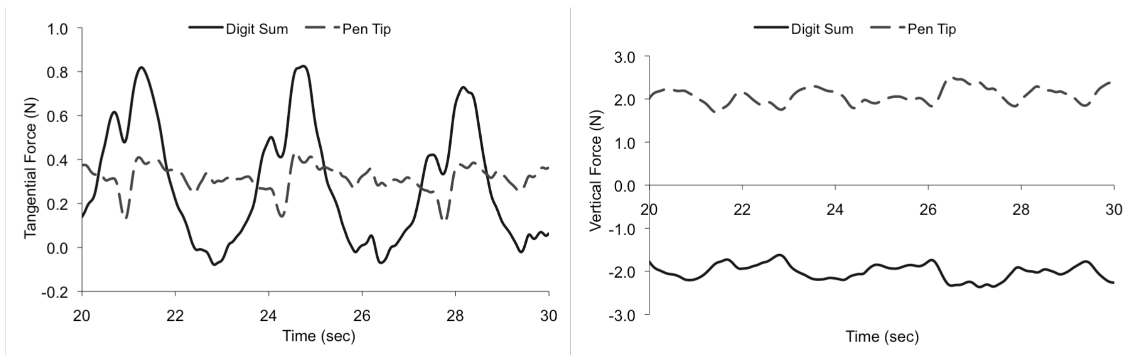
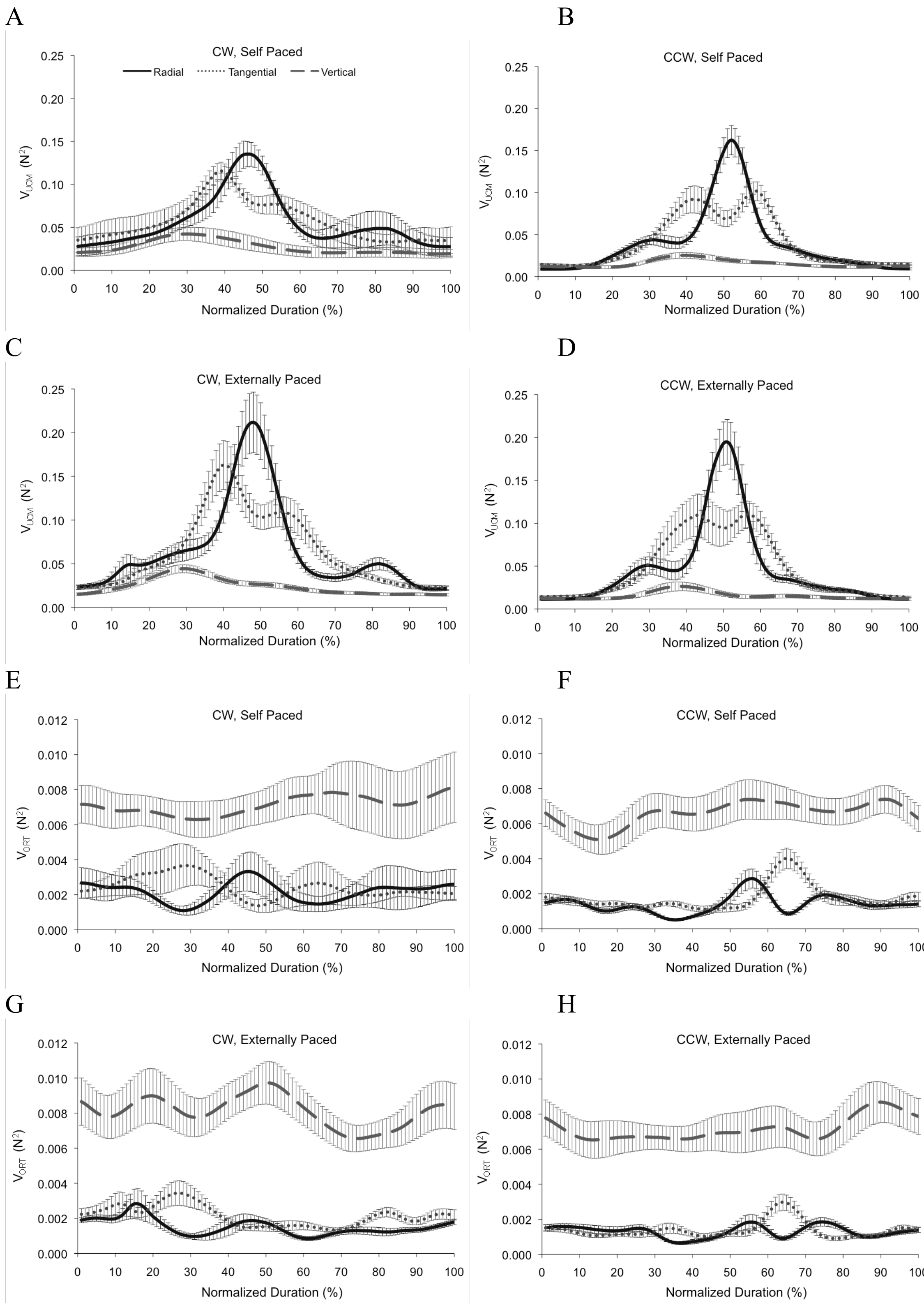


Figure 4.2. An example of a single subject's performance for the drawing of three consecutive circles. A) The two-dimensional pen tip trajectory on the writing surface. X- and Y-axes are parallel to the mediolateral and anteroposterior axes, respectively. The remaining plots show the summed digit force components on the pen compared to the pen-tip force along the B) radial C) tangential and D) vertical components

Uncontrolled Manifold Analysis

Illustrated in Figure 4.3, for each directional synergy over the temporal duration, controlling for direction and pace the variance components within (V_{UCM}) and orthogonal (V_{ORT}) to the UCM are compared. It is apparent in Figure 4.3A-D that the V_{UCM} tends to peak when the circle is about halfway completed for both the radial and tangential components with the radial component always having the highest peak values. The vertical component of V_{UCM} is more temporally stable than the other two components with a much more subtle peak occurring between the 20% and 40% range of the circle. The V_{ORT} (Figure 4.3E-H) shows less temporal change than V_{UCM} and the vertical component is always greater than the radial and tangential components. The synergy strength quantified by ΔV remains above 1.0 for the radial and tangential components and above 0.4 for the vertical components. It should be noted that there does not appear to be a significant drop in ΔV during the initiation and termination of the circle duration, nor are there significant changes in the error at these times, suggesting that the synergies are not dependent on the acceleration of the pen.


A
CW, Self Paced
Radial
Tangential
Vertical
V_UCM (N²)
Normalized Duration (%)
B
CCW, Self Paced
V_UCM (N²)
Normalized Duration (%)
C
CW, Externally Paced
V_UCM (N²)
Normalized Duration (%)
D
CCW, Externally Paced
V_UCM (N²)
Normalized Duration (%)
E
CW, Self Paced
V_ORT (N²)
Normalized Duration (%)
F
CCW, Self Paced
V_ORT (N²)
Normalized Duration (%)
G
CW, Externally Paced
V_ORT (N²)
Normalized Duration (%)
H
CCW, Externally Paced
V_ORT (N²)
Normalized Duration (%)

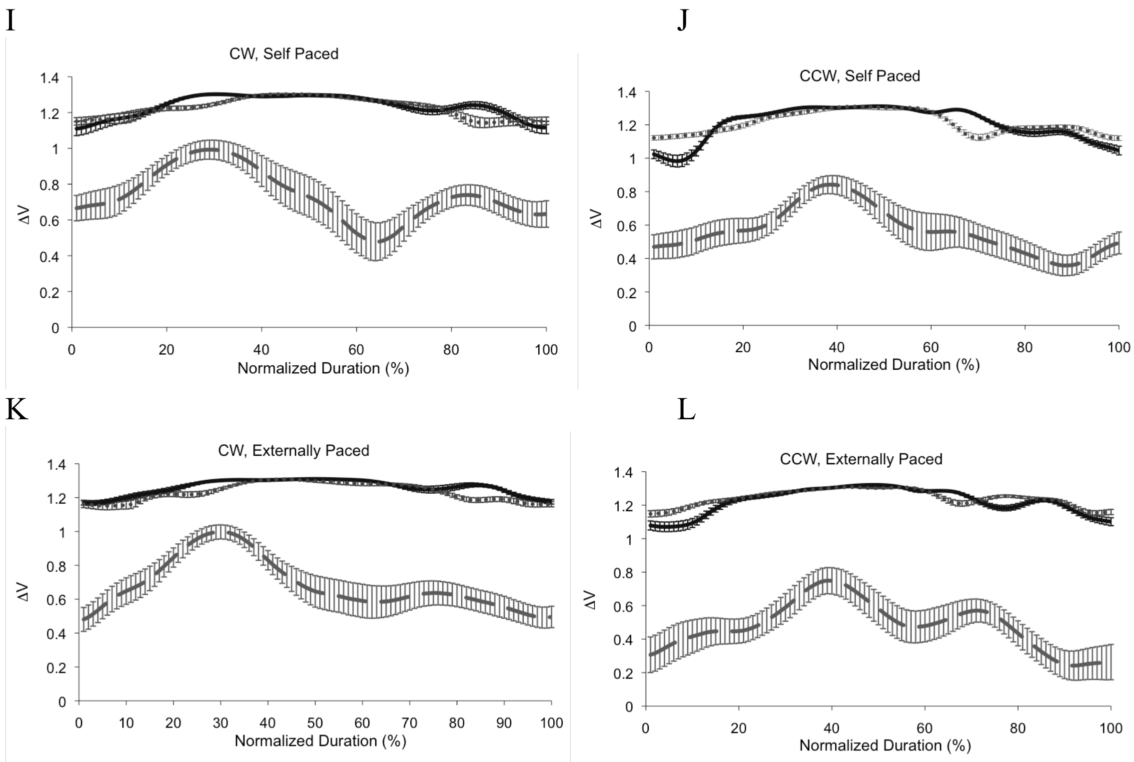


Figure 4.3. Plots of variance components over time across radial, tangential, and vertical components for each direction-pace condition using time normalization. A-D) Variance within the UCM, E-H) Variance orthogonal to the UCM, and I-L) Synergy strength measured by ΔV. Sets of four describe: clockwise, self-paced; counter-clockwise, self-paced; clockwise, externally paced; and counter-clockwise, externally paced, respectively. Means and standard errors across all subjects are presented.

The average of the ΔV time function was used for statistical comparisons of components, paces, and directions. The average ΔV supported the first and second hypotheses that synergies would exist across all control components and that the radial and tangential components would yield stronger synergies than vertical component, respectively. ΔV for the radial, tangential, and vertical components was significantly greater than zero. ΔV was also significantly greater in the radial and tangential components than in the vertical component under all directional and pace conditions as illustrated in Figure 4.4. These findings were supported by three-way ANOVA which showed a significant COMPONENT effect [$F(2,22) = 99.2$, $p < 0.0001$]. Pair-wise comparisons between components showed that the vertical component was significantly smaller than both the radial component [$p < 0.0001$] and tangential component [$p < 0.0001$], but the radial and tangential components showed no significant difference between each other [$p = 0.6093$].

The analysis partially supported the third hypothesis that there would be no significant difference between clockwise and counterclockwise directions. It was identified that there was a significant difference between directions with the clockwise direction having a greater ΔV than the counter-clockwise direction. This was only true for the radial and vertical components. This trend was very evident in the vertical component where the ΔV values had a difference of almost 0.3 and nearly insignificant in the radial component where the ΔV values had a difference of less than 0.03. These findings were supported by a significant DIRECTION effect [$F(1,23) = 17.6$, $p < 0.0001$] and significant DIRECTION x COMPONENT interaction [$F(2,22) = 18.4$, $p < 0.0001$], but a non-significant DIRECTION x PACE x COMPONENT interaction [$F(2,22) = 1.6$, $p = 0.219$]. Subsequent pair-wise comparisons between component-direction combinations showed that ΔV values in the clockwise direction were significantly larger than the ΔV values in the counter clockwise directions in the radial and vertical components [$p < 0.001$] and [$p = 0.05$], respectively.

The fourth hypothesis, that the self-paced condition would yield greater ΔV values than the externally paced condition, was not supported. No significant differences were identified between the paces. Within each component, ΔV in the self-paced condition was always within 0.1. This was supported by non-significant effects of PACE [$F(1,23) = 0.3$, $p = 0.617$], PACE x COMPONENT interaction [$F(2,22) = 0.9$, $p = 0.418$], and DIRECTION x PACE interaction [$F(1,23) = 0.06$, $p = 0.806$].

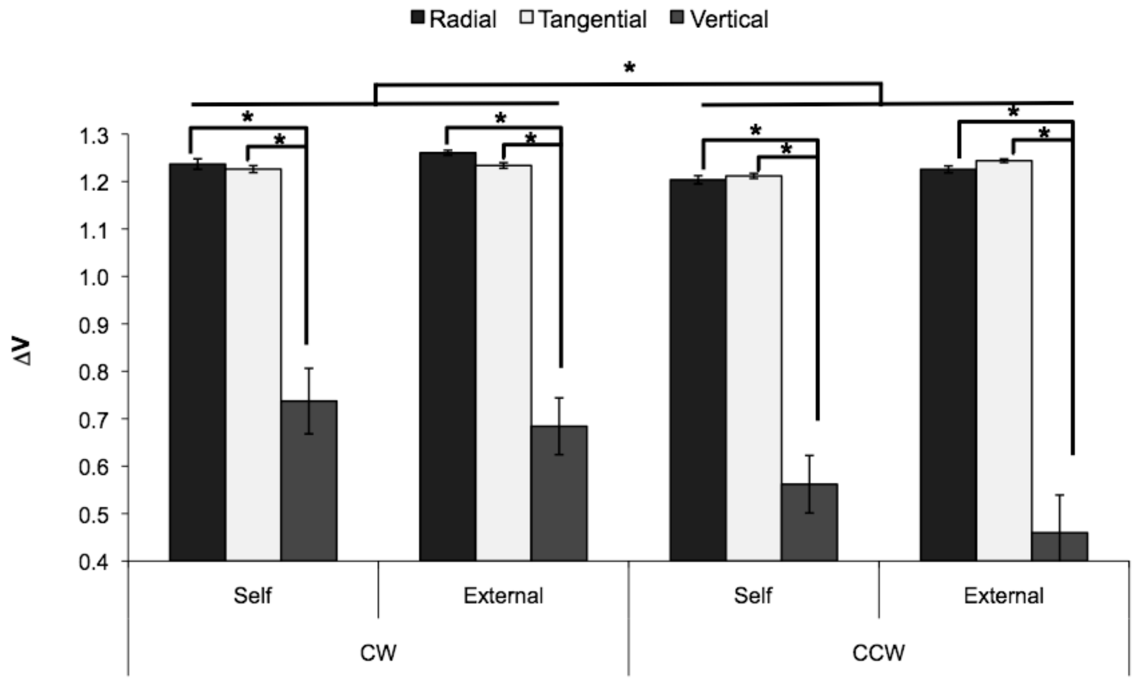


Figure 4.4. Synergy strength, measured by ΔV, for radial, tangential, and vertical components, across pace and direction conditions. Means and standard errors across all subjects are presented. * indicates statistical significance at the 0.05 level.

Discussion

This study investigated the multi-digit synergies along three dynamic, orthogonal components of pen kinetics during circle drawing across varying pacing and directional conditions. Given that previous studies have indicated that multi-digit synergies in other grasping tasks are broken into task related components (Shim et al. 2004; Shim et al. 2006), and that handwriting is a task requiring extensive precision and accuracy, it was hypothesized that multi-digit force synergies, as measured by ΔV, would be present across the radial, tangential, and vertical control components. Furthermore, the small range of Vorth along the radial and tangential components compared to the vertical component suggested that stronger synergies would exist along the radial and tangential components. In order to extend findings of previous kinematic handwriting studies to the kinetic domain, the relationships between digit force synergies and direction and pace were investigated. Previous studies showed no significant pen-tip kinematic differences between the clockwise and counter-clockwise directions (Bosga et al. 2003; Tseng and Scholz 2005). Therefore a difference in synergy strength between these directions was not expected. Lastly, handwriting kinetics would confirm the findings of previous pacing studies indicating an inherently strong internal pacing aspect of handwriting by showing decreased synergy strength under an externally paced condition (Knoblich and Flach 2003).

Synergies existed across all control components and were significantly stronger on the radial and tangential than vertical component. Not only were the synergies present in these cases, but they were overwhelmingly strong. Previous studies using the ΔV index on tasks with extensively proven synergies have yielded ΔV values from as low as 0.2 up to 0.8 (Shim et al. 2005b; Zatsiorsky et al. 2006). The ΔV in this study were well above that, exceeding 1.0 in the radial and tangential control components and ranging from 0.4 to 0.8 in the "weaker" vertical component. Given the high precision level of the system involved in the task, handwriting, these results are not surprising. That is, the manual dexterity necessary to write words, where a errors on the scale of millimeters can render script illegible, is very high relative to the dexterity necessary grasp a static object. As the level of complexity of the task in increased, as it is from grasping to writing, so should the level of precision with which the task is controlled, indicated here be high ΔV values during writing.

It is interesting to compare the findings of this study with those of previous studies which showed multiple, complimentary synergies (Shim et al. 2004; Shim et al.

2006; Zatsiorsky and Latash 2004). In both cases, the components yielding the strongest synergies were those in which the margin of highly consequential errors was smallest. This can be more clearly understood by comparing this study with previous grasping studies. In the case of object-grasping prehension, such as holding a glass of water, orientation control was found to have the strongest synergies. Orientation is controlled by the resultant torque applied on the object and as such has a very small window of acceptable errors, *i.e.*, preventing a handheld water glass from spilling. Its complimentary component of grasping forces have a larger window of acceptable values, *i.e.*, whether or not you drop or crush the glass, with synergies weaker than those of orientation control (Zatsiorsky and Latash 2004). This idea is maintained in the present study. Here, the components with the smallest range of acceptable errors were the radial and tangential components as errors here yield messy and illegible writing. This limited range was accompanied by stronger synergies in those components, similar to the strong synergies in orientation control in prehension. The range of acceptable errors in the vertical components of writing are relatively larger than those in the radial and tangential components as vertical errors only cause lighter/darker lines. This suggests that the CNS utilizes synergies that are not only task dependent but also able to prioritize components within a task to optimize the handwriting performance. This could be further tested in an experiment in which subjects writing on a very delicate piece of paper that will tear of any excessive force is applied. In such a situation, the range of acceptable error in the vertical force component would be greatly reduced and the response by the CNS in terms of control of kinetic synergy components could yield more knowledge on this system.

More specifically, such an experiment would test the robustness and adaptability of the synergies identified in the present study.

The ΔV in the clockwise direction was significantly greater than in the counter-clockwise direction in the vertical component. To investigate this further, ΔV was normalized by position and plotted such that one could see how ΔV changes with position of the pen tip on the circle. The vertical component showed a difference between directions on certain parts of the circle (Figure 4.5).

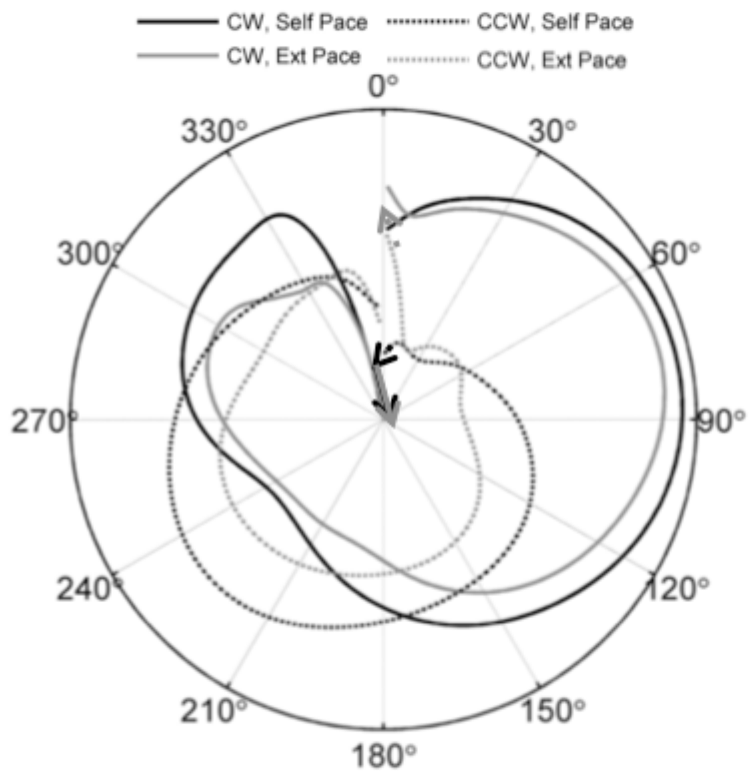


Figure 4.5. Illustration of direction and pace conditions on synergy strength over absolute position, measured by ΔV, in the vertical component. The circle border represents ΔV = 1.

It is apparent that the significant directional differences of the vertical component come from the 0° to 180° range, or left half of the circle. While the ΔV value approaches 1 in the clockwise direction, it is less than 0.5 in the counterclockwise direction within that range. One possible explanation can be compared to a study by Dounskaia, in which subjects preformed one circle drawing task and a series of line-drawing tasks in which the coordination of the fingers and wrist were controlled in different ways and found that this part of the circle requires a more complex joint coordination combination than other parts due to the wrist is flexing while the fingers are extending (Dounskaia et al. 2000). However, why this would results in a ΔV decrease exclusively along the vertical component is currently unknown. It can be argued that during this range of angles, the position of the hand becomes more squished and fist-like, increasing joint stiffness. Increased joint stiffness has been shown to cause decreased handwriting fluency which may account for the drop in synergy strength (van Den Heuvel et al. 1998). Additionally, van Den Heuvel showed that increased processing demands cause joint stiffness as well increase pen tip vertical forces. While increased pen tip vertical forces do not necessarily decrease pen control in the vertical component, the fact that forces increased along the vertical force component may explain why ΔV dropped uniquely that component. Further investigations into this finding should include a kinematic motion capture of the digits and hand during the task. This would allow experimenters to see if the position of the hand differs depending on the direction and pen tip location.

A relationship between component strength and pacing was hypothesized from the idea that handwriting is an inherently self-paced task, thus having to follow an outside pace regulator may adversely affect the force synergies being controlled. Previous pacing studies involving drawing tasks support this idea and have indicated that rhythmic movements are generated by internal clocks originating in the cerebellum (Spencer and Zelaznik 2003; Welsh et al. 1995). This clearly did not prove to be the case as under no circumstances was there a significant difference in synergy strength between paces. A possible explanation is that the controlling synergies are robust and flexible enough that they can easily make temporal adaptations or that the task of having subjects match an external pace based on their individual, “comfortable”, pace, determined by their internal clock did not differ enough from their normally paced writing. A future study could test the latter of these possibilities by having subjects draw at a range of non-self-selected paces and comparing the synergy strength to those in which the subjects pace themselves.

Currently the Kinetic Pen is the only writing apparatus reported which provides three-dimensional forces and moments of force at each contact between the pen and hand. Previous research on handwriting kinetics has focused on force relationships between the writing surface and pen-tip (van Den Heuvel et al. 1998; Wann and Nimmo-Smith 1991), as well as one-dimensional grasping forces on the pen (Herrick and Otto 1961). A more recent attempt at measuring pen grip forces investigated total grasping force as well as digit-force specificity via contour plots (Chau et al. 2006). These techniques are limited in their inability to implement inverse dynamics due to their uni-dimensionality. By using inverse dynamics, one can calculate joint torques and possibly muscle forces during an actual handwriting task using the Kinetic Pen. Such a technique has potential to make great progress in understanding the etiology of writer’s cramp and other focal dystonias (Cohen and Hallett 1988; Sheehy and Marsden 1982).

Techniques used here could be developed for possible clinical use as handwriting is already a common tool used in identifying the presence, severity, and treatment effects of many movement disorders. More specifically, the ability to look at individual digit kinetics and how the digit synergies are functioning could potentially provide great clinical insight. The demand for such as analytical tool has already been called for by some Parkinson’s studies who hypothesize that patients’ difficulties with writing stems from the inability of patients to release, not generate, digit forces (Van Gemmert et al. 2001). Also, many of these studies deal with kinematic scaling as key identifier of neurological problems (Contreras-Vidal et al. 1998; Contreras-Vidal et al. 2002; Teulings et al. 2002; Van Gemmert et al. 2001). Therefore running a similar study with a comparison between writing sizes would provide a baseline of kinetic synergies for the normal population to which patient populations cold be compared.

Previous research suggests that multi-finger synergies to stabilize the resultant moment of a prehensile object are more likely to be present during handwriting (Latash et al. 2003; Shim et al. 2004; Shim et al. 2005c) in addition to the force synergies the current study investigated. However, multi-synergies to control the moment of the pen was not investigated in the current study and it opens revenue for a future study. The techniques developed in the current study can be utilized to study persons with handwriting abnormalities such as Writer's Cramps (Cohen and Hallett 1988; Marsden and Sheehy 1990), Parkinson's disease (Contreras-Vidal et al. 1995; Jankovic 2008), and children with developmental dysgraphia (Adi-Japha et al. 2007).

CHAPTER 5: CONCLUSION

Handwriting is a complex motor task that is both widely used and largely misunderstood from a control perspective. The development and research presented here provides insight on the kinetic aspect of handwriting that was previously immeasurable due to technical limitations. The first phase in accomplishing this task was to develop the Kinetic Pen, a device capable of recording six-dimensional, instantaneous kinetics at each of the contacts between the pen and hand during writing. The second phase was the implementation of a study in which the synergistic actions of the contact forces, defined as kinetic synergies, were investigated in three orthogonal spaces: radial, tangential, and vertical to the circle edge during a circle drawing task. Strong kinetic synergies were quantitatively identified under all conditions and components. It was found that the CNS gives priority to the components of writing that affect the shape and legibility of the script versus the component that affects the pressure of the pen on the paper. It was also found that the direction in which one draws a circle has an effect on the ability of the CNS to control the motion via a synergy. Perhaps the greatest conclusion to be made from this work is that a tool with the ability to record previously unattainable dimensions of handwriting, as well as a technique with which the new dimensions can successfully quantify kinetic synergies, have been developed, opening the door to a wide range of future research and clinical applications.

APPENDIX 1

Subject ID:

EDINBURGH HANDEDNESS INVENTORY

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column.* Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put* ++. If in any case you are really indifferent *put + in both columns.*

		Left	***Right***
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking match (match)		
10	Opening box (lid)		
i.	Which foot do you prefer to kick with?		
ii.	Which eye do you use when using only one?		

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

APPENDIX 2

Subject ID:

Health Status Questionnaire

Name ______________________________________ Telephone ___________________
Address ____
____
Date of birth ________ Age ________ Height ________ Weight ________
Hearing impairment Yes ____ No ____ If yes, describe ______________________
Color blind Yes ____ No _____ Gender M _____ F _____
Years of education (high school = 12, college + 16) ____________
Current marital status Married _____ Single _____ Widowed _____ Divorced _____
Medications Are you presently taking or have taken any of the following medications within the past two months?
Aspirin, Bufferin, Anacin Tranquilizers
Blood pressure pills Weight reducing pills
Cortisone Blood thinning pills
Cough medicine Dilantin
Digitalis Allergy shots
Hormones Water pills
Insulin or diabetic pills Antibiotics
Iron or blood medications Barbituates
Laxatives Phenobarbital
Sleeping pills Thyroid medicine
Other medications not listed ____
____
Have you taken any non-prescription medications or drugs in the past two weeks?
Name what for? Dose/frequency last dose
1
2
3

Do you currently or have you ever had any of the following medical disorders?
Heart attack Yes ____ No ____
Chest pain Yes ____ No ____
Hardening of the arteries Yes ____ No ____
Irregular heart beat Yes ____ No ____
Kidney disease Yes ____ No ____
Diabetes Yes ____ No ____
Cancer Yes ____ No ____
Gout Yes ____ No ____
Asthma Yes ____ No ____
Epilepsy or seizure disorder Yes ____ No ____

Migraine headaches Yes ____ No ____ if yes, frequency/intensity _____
Psychiatric disorder Yes ____ No ____ if yes, what diagnosis _________

List the name of any diseases, illnesses or accidents you have had which required hospitalization. ____
____
____

Serious illnesses you have had not requiring hospitalization. _______________________
____
____

Have you ever been told you have high blood pressure?
Yes ___ No ____ if yes, when _________________
Do you have any other chronic illnesses or disabilities?

____
Have you ever lost consciousness in the last 10 years?
Yes ____ No ____ if yes, when and why ___________________________________
Do you use tobacco products?
Yes ____ No ____ if yes, number of years __________________________________
Cigarettes ____ Pipe ____ Cigar ____ Chewing tobacco ____
How many alcoholic drinks do you drink on any given day? _______________________
(1 drink = 12 oz. Beer, 4 oz. Wine, or 1oz. Hard liquor)
How much caffeine do you drink on any given day? _____________________________
(number of cups of coffee, tea, cola; how many ounces)
Time since last intake of:
Caffeine ______________
Tobacco ______________
Alcohol ______________

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