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FINGER INTERACTION IN A THREE DIMENSIONAL PRESSING TASK: CONTROL OF FORCE MAGNITUDE AND DIRECTION AND AGE RELATED DIFFERENCES

A Thesis in

Kinesiology

by the

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ABSTRACT

This thesis addresses the indices of finger interaction in single- and multi-finger pressing tasks in different directions and the effects of aging on these interactions. Accurate control of forces produced by the fingers is essential for performing object manipulation. The first study presented in this thesis examines the indices of finger interaction when accurate time profiles of force are produced in different directions, while using one of the fingers or all four fingers of the hand. We hypothesized that patterns of unintended force production among shear force components may involve features not observed in the earlier studies of vertical force production. In particular, we expected to see unintended forces generated by non-task fingers not in the direction on the instructed force but in the opposite direction, as well as substantial force production in directions orthogonal to the instructed direction. We also tested a hypothesis that multi-finger synergies, quantified using the framework of the uncontrolled manifold hypothesis, will help reduce across-trials variance of both total force magnitude and direction. Young, healthy subjects were required to produce accurate ramps of force in five different directions by pressing on force sensors with the fingers of the right (dominant) hand. The index finger induced the smallest unintended forces in non-task fingers. The little finger showed the smallest unintended forces when it was a non-task finger. Task fingers showed substantial force production in directions orthogonal to the intended force direction. During four-finger tasks, individual force vectors typically pointed off the task direction, with these deviations nearly perfectly matched to produce a resultant force in the task direction. Multi-finger synergy indices reflected strong co-variation in the space of finger modes (commands to fingers) that reduced variability of the total force magnitude and direction across trials. The synergy indices increased in magnitude over the first 30% of the trial time and then stayed at a nearly constant level. The synergy index for stabilization of total force

magnitude was higher for shear force components as compared to the downward pressing force component. The results suggest complex interactions between enslaving and synergic force adjustments, possibly reflecting the experience with everyday prehensile tasks. For the first time, the data document multi-finger synergies stabilizing both shear force magnitude and force vector direction. These synergies may play a major role in stabilizing the hand action during object manipulation.

In the second study done on elderly participants, we looked at how the indices of finger interaction change with aging. We hypothesized that elderly participants will show lower enslaving not only for normal forces but also for shear forces. We expected the elderly to be less accurate in both force magnitude and direction. We expected the higher motor variability in the elderly to be associated with lower indices of synergies stabilizing those variables. These hypotheses have been confirmed. In addition, we found that, compared to younger participants, the elderly participants produced larger forces in directions orthogonal to the instructed force direction. This finding contrasts the lower indices of unintended force production by non-instructed fingers in the elderly. The time profiles of the synergy indices computed for both force magnitude and direction were similar across the younger and elderly groups: Both showed stronger synergies later in the trial. Quantitatively, however, these indices were significantly smaller in the elderly participants. This study has shown that aging is associated not only with lower voluntary force magnitude and lower accuracy of force production but also with changes in finger interaction. There is a tendency towards preference for individual finger involvement (lower indices of enslaving) accompanied by worse synergic control of fingers in multi-finger tasks. However, the control of individual finger force direction is impaired in the elderly as demonstrated by the increased index of finger force production orthogonal to the instructed direction. These findings may have implications for exercises to prevent the deterioration of the hand function with age and for rehabilitations of the hand function.

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CHAPTER – 1

INTRODUCTION

The field of Motor Control deals with the study of how the Central Nervous System governs various aspects of the complex human movement. In early 1900s, Bernstein formulated the problem of motor redundancy, commonly known as Bernstein's problem. In his famous blacksmith experiment, Bernstein found that the CNS did not follow a unique solution for the problem of controlling the end-effector (the hammer) by a coordinated involvement of the arm joints but rather explored the whole variety of solutions to ensure accurate task performance. This problem has been the basis for a plethora of research going on in the field of Motor Control. Like many other researchers in the field, we chose to approach the problem of how the brain controls human movement by studying finger pressing tasks.

The two phenomena of finger interaction well established in the literature are that of *enslaving* and *force deficit*. Enslaving refers to the unintentional force produced by non-task fingers when a finger from the same hand is instructed to produce force. Force deficit refers to the lower maximal force produced by fingers in multi-finger tasks as compared to single-finger tasks.

In pressing tasks, human fingers produce vectors of force that can vary in both magnitude and direction within a broad range. Until now, most studies of pressing tasks have focused only on normal force production (reviewed in Kilbreath and Gandevia 1994; Li et al. 1998a; Zatsiorsky and Latash 2008) and paid little attention to possible intentional and unintentional shear force production. In particular, studies of normal force production described phenomena of finger interaction such as unintentional force production by uninstructed fingers (enslaving) and lower maximal force produced by fingers in multi-finger tasks as compared to single-finger tasks (force deficit) (Ohtsuki 1981; Kilbreath and Gandevia 1994; Li et al. 1998a; Zatsiorsky et al.1998, 2000).

Another line of research investigated multi-finger synergies defined as co-varied patterns of commands to fingers across trials that kept total force or total moment of force relatively unchanged (reviewed in Latash and Zatsiorsky 2009). These studies used the framework of the uncontrolled manifold hypothesis (UCM hypothesis, Scholz and Schöner 1999; reviewed in Latash et al. 2007). This hypothesis assumes that the neural controller acts in a space of elemental variables (commands to the fingers) and keeps across-trials variance to a sub-space (UCM) corresponding to a desired value of a performance variable (total force or total moment of force).

The current study has two major objectives: First, to quantify finger interdependence in tasks that require force production in different directions; and second, to explore the existence of multi-finger synergies stabilizing both the magnitude and the direction of the total force vector by co-varying involvement of individual fingers across trials. Within the first objective, we explored unintentional force production for different force directions. Under the term "unintentional force" we imply forces produced by non-task fingers and/or by the task fingers in directions not required by the explicit task, whether due to mechanical, anatomical, or neurophysiological reasons. Unintentional force production includes two components. First, there is enslaving, studied primarily in normal force production tasks (reviewed in Zatsiorsky and Latash 2008). Second, we also studied a novel phenomenon of within-a-finger unintentional force production in non-instructed directions.

Several studies explicitly or implicitly addressed force production by human digits in different directions. Most of these studies explored single-digit force production. In particular, maximal index fingertip force production in all directions was studied by Li et al. (2003). Valero-Cuevas et al. (1998) examined the patterns of muscle activation when subjects produced static forces in five directions (palmar, distal, lateral, dorsal, and medial). Two more studies addressed index finger force production in the flexion-extension plane (Milner and Dhaliwal 2002; Yokogawa and Hara 2002). Valero-Cuevas and his colleagues (2003) also studied the task of compressing a spring with a finger, which imposes restrictions on shear force production.

All these lines of research addressed single-digit tasks and did not consider phenomena of finger interaction. In a study of accurate force production in two different directions, multi-finger synergies stabilizing force direction have been documented: Variance of the resultant force vector was consistently smaller than variances of the individual finger force vectors (Gao et al. 2005). That study, however, considered only two possible directions of force production and did not address phenomena of unintentional force production. Pataky et al. (2007) examined force production in two directions, normal and radial/ulnar, and observed non-zero forces in directions perpendicular to the instructed direction. However, in that study, the fingers pushed against the walls of slots, which prevented motion of the fingers in the radial/ulnar direction, rather than relying on friction as in typical prehensile tasks and in the present study.

It is well known that load-resisting (shear) and grip forces are tightly coupled during object manipulation (Johansson and Westling 1984; Jaric et al. 2005; De Freitas and Jaric 2009). This coupling has been discussed as a consequence of neural strategies, in particular as reflected in synchronization of motor unit action potentials to different muscles and muscle compartments (Santello and Fuglevand 2004). It has also been reported that fingers differ in their roles during typical prehensile tasks, for example the lateral fingers (index and little) play a major role in the generation of the total moment of force on the hand-held object, while the middle finger is primarily involved in resisting the gravitational load (Zatsiorsky et al. 2002). Overall, patterns of unintended force production in three dimensions may be expected to reflect, to a larger degree, synergic finger interactions developed during typical everyday prehensile tasks (for a review see Latash and Zatsiorsky 2009). Therefore, we hypothesized that patterns of unintended force production among shear force components may involve features not observed in the earlier studies of force enslaving during vertical force production. In particular, we expected to see unintended forces not in the direction of the instructed force but in the opposite direction as well as substantial force production in directions orthogonal to the instructed direction. Our second main hypothesis has been based on earlier studies of multi-finger force production (Latash et al. 2002a; Shim et al. 2007; Gao et al. 2005), which suggest that there may be strong multi-finger synergies stabilizing both magnitude and direction of the total force vector in three dimensions.

CHAPTER – 2

BACKGROUND AND LITERATURE REVIEW

Introduction

Hands play a crucial role in almost all the activities of daily living. Hands are the chief organs for physically manipulating the environment. They are used for both gross motor skills, such as grasping a glass of water as well as for fine motor skills, such as writing. Performing even the simplest tasks such as drinking water from a glass requires precise coordination of finger forces and moments of force.

Proper control of the hand is crucial to performing many tasks that require precise coordination of finger forces and movements in order to be performed successfully. There has been a great deal of research in the motor control area involving hand. But still a lot more needs to be investigated as all current robotic manipulators are far from matching the dexterity and precision of movement exhibited by human hand. Another reason that makes hand a good candidate for studying motor control is that it allows to measure peripheral outputs resulting from the central nervous system commands.

This literature review would be divided into four sections: 1) Anatomy and Physiology of Hand. 2) Cortical control of Hand. 3) Finger Enslaving. 4) Multi-digit Synergies.

2.1 Anatomy and Physiology of Hand

Bones and Joints

The anatomy of the hand is both complex and fascinating. Each human hand has twenty seven bones that constitute its basic skeleton. Eight out of these twenty seven, called carpals, account for the wrist and are arranged in two rows of four each. The palm contains five bones called metacarpals. The remaining fourteen are the digital bones that constitute fingers and thumb (refer to Figure 1).

The bones in the proximal row of the wrist are scaphoid, lunate, triquetral and pisiform (from lateral to medial) and those in the distal row are trapezium, trapezoid, capitate and hamate (in the same order). These bones fit into a shallow socket formed by the bones of the forearm (radius and ulna). The articulations between the carpal bones are called intercarpal joints. The structure of each metacarpal bone in the palm consists of a head, a shaft and a base. The base of a metacarpal bone articulates with a distal carpal bone to form a carpometacarpal (CMC) joint. Each finger has a distal, middle, and proximal phalanx, while the thumb has only distal and proximal phalanges. The structure of digital or phalanx bones consist of a proximal base, an intermediate shaft, and a distal head. The base of proximal phalanx articulates with the head of metacarpal and forms metacarpophalangeal (MCP) joint. MCP joints allow flexion/extension and abduction/adduction. The proximal interphalangeal (PIP) joints are the joints between the proximal and middle phalanges. The distal interphalangeal (DIP) joints are the joints between the middle and distal phalanges. Interphalangeal joints only allow one degree of freedom, which is in the flexion/extension direction.

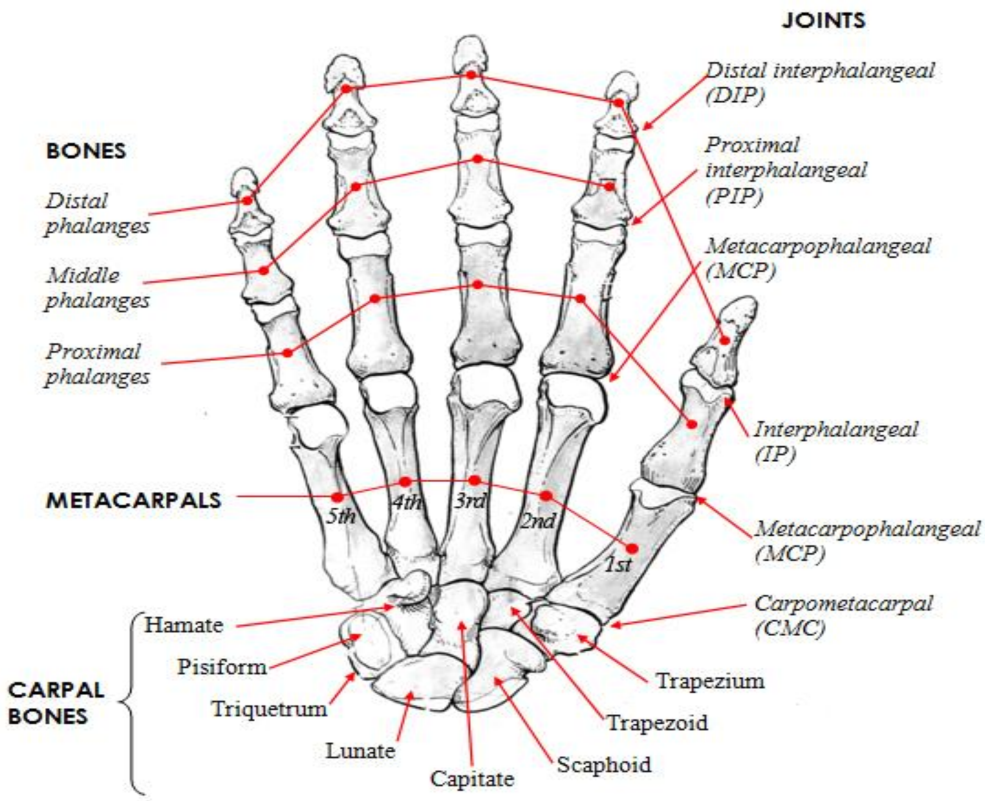

Figure 1: Bones and joints of human hand.

Muscles

The muscles of the hand are divided into two groups: Intrinsic and Extrinsic. The intrinsic muscles are located within the hand itself, whereas the extrinsic muscle bellies are located proximally in the forearm and insert to the hand by long tendons. The long flexors and the extensor muscles (except for the interosseous-lumbrical complex involved in IP joint extension) constitute the extrinsic muscles. The long flexor muscles include flexor carpi ulnaris, flexor carpi radialis, flexor digitorum superficialis, flexor digitorum profundus, flexor pollicis longus , palmaris longus, pronator teres, and pronator quadratus. The extensor muscles include extensor carpi radialis longus, extensor carpi radialis brevis, extensor carpi unlaris, extensor digitorum, extensor digiti minimi, extensor pollicis longus, extensor pollicis brevis, extensor indicis, abductor pollicis longus, and the supinator. Intrinsic muscles include the thenar muscles (abductor pollicis brevis, flexor pollicis brevis, opponens pollicis and adductor pollicis), the hypothenar muscles (abductor digiti minimi, flexor digiti minimi, and opponens digiti minimi), the interossei muscles (palmar and dorsal interossei) and the lumbrical muscles.

Innervation

The hand is innervated by three nerves: the median, ulnar, and radial nerves. Each of these three nerves, has both sensory and motor components.

The median originates from the medial and lateral cords of the brachial plexus (C5-T1). It innervates pronator teres, flexor carpi radialis, palmaris longus and flexor digitorum superficialis muscles in the forearm. The interosseous branch of median nerve supplies the deep muscles of the forearm which are flexor pollicis longus, flexor digitorum profundus (index and middle finger), and pronator quadratus muscles. The recurrent motor branch innervates the thenar muscles (abductor pollicis brevis, opponens pollicis, and superficial head of flexor pollicis brevis) and lumbrical muscle (index and middle finger). The cutaneous branches of the median nerve provide sensation to thenar eminence, thumb, index, middle and radial side of the ring finger.

The ulnar nerve originates from the medial cord of the brachial plexus (C8-T1). It innervates the flexor carpi ulnaris, flexor digitorum profundus (ring and little finger), hypothenar muscles (abductor digiti minimi, opponens digiti minimi, flexor digiti minimi, and palmaris brevis), all interossei, the two medial lumbricals, the adductor pollicis, and the deep head of the flexor pollicis brevis. Its cutaneous branches provide sensation to the hypothenar eminence, ulnar portion of the hand, little finger, and part of the ring finger.

The radial nerve originates from the posterior cord of the brachial plexus (C6-C8). It innervates brachioradialis, extensor carpi radialis longus and brevis, supinator, extensor digitorum communis, extensor digiti minimi, extensor carpi ulnaris, extensor indicis, extensor pollicis longus, extensor pollicis brevis, and abductor pollicis longus. Its sensory branches provide sensation to the radial aspect of the dorsum of the hand, the dorsum of the thumb, and the dorsum of the index, middle, and radial half of the ring finger proximal to the distal interphalangeal joints.

2.2 Cortical Control of Hand

Human hand has a fascinating, intricate and complex cortical control which is crucial for hand functioning. The areas of the cerebral cortex that contribute directly to the control of hand movements includes the primary motor cortex (M1), the supplementary motor area (SMA), the pre-supplementary motor area (pre-SMA), and the pre-motor cortex. The primary motor cortex can produce both excitatory and inhibitory effects on α-motor neurons of hand muscles on the contralateral side of the body via the neurons in corticospinal tract. Cortical representation of hand based on the classical work of Wilder Penfield has been shown in the homunculus shown in the Figure 2. However, recent studies have challenged the homunculus representation of the body in cortical areas (Schieber 2001; Schieber and Santello 2004). *Convergence* (projections from two different sources on same target neuron) and *divergence* (projection from a single neuron or a group of neurons to several targets) characterize the motor projections from M1 to hand and sensory projections from hand to M1. Such an organization suggests that the activity of cortical neurons relates to multi-joint and multi-finger action rather than to the activation of individual muscles. Several studies have shown major changes in cortical representations following hand injuries or specialized training (Merzenich et al. 1984; Classen et al. 1998). Such reorganizations and ability of cortex to adapt to changes following injury or practice is termed as *neural plasticity*.

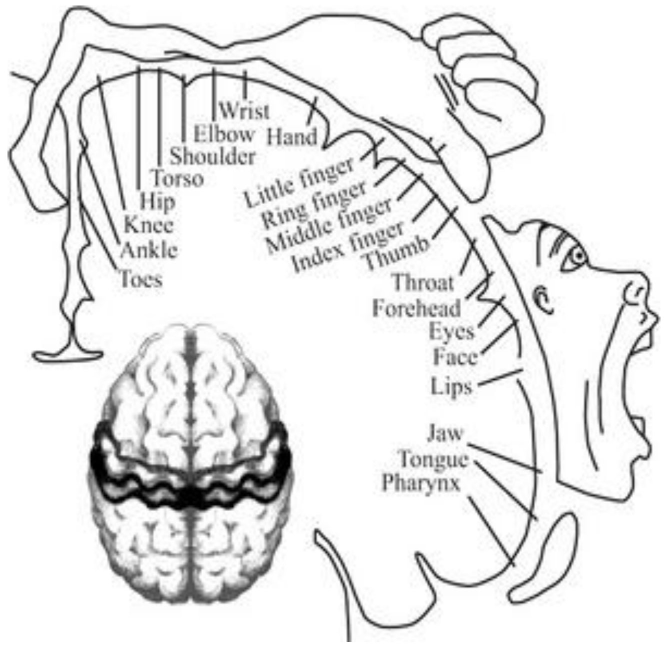

Figure 2: Somatotopic organization in the cerebral cortex: Homunculus.

2.3 Finger Enslaving

Many studies on hand have documented unintentional force production by fingers not explicitly involved in the force-production task. This phenomenon has been termed 'enslaving' as the non-involved or slave digits behave involuntarily in the same manner as the involved or master digit (Zatsiorsky et al. 2000). This phenomenon of enslaving has been potentially thought to be the result of anatomical coupling, existence of multi-digit motor units in the extrinsic flexor and extensor, and a common neural drive to the muscles of the hand. The anatomical coupling of the digits is partially due to the intermuscular connections among the four parallel compartments of flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP), which flex the fingers. In addition, passive inter-finger links also exist within the connective tissues found in the hand. Though there is strong evidence of mechanical coupling among the fingers, the largest source of enslaving has been identified as common neural drive to the fingers (Latash et al 2002a; Li S et al. 2003, 2004; Olafsdottir et al. 2005; Schieber and Santello 2004; Zatsiorsky et al. 2000). The existence of common motorneuron pool within both the FDS and FDP accounts for most of the enslaving due to neural drive (Schieber and Santello 2004).

2.4 Multi-digit Synergies

A common feature of human movement is motor variability and one obvious reason of motor variability is motor redundancy, also known as the Bernstein problem (Bernstein 1967; Turvey 1990 ; Latash et al 2002). Bernstein observed the discrepancy between the large number of degrees-of-freedom (DOFs) of the anatomical design of the human limbs and the fewer constraints imposed by most of the everyday tasks (Bernstein 1947; 1967). At each level of analysis of the system for the production of voluntary movements, there are many more elements contributing to performance than are absolutely necessary to solve a motor task (Latash et al 2002). Synergies or the co-variation among the elements to keep the performance constant, allow the controller to take advantage of flexible motor patterns to solve typical tasks that might be useful in the presence of perturbations and/or secondary tasks using the same elemental variables.

In terms of multi-digit isometric force production tasks, synergies have been defined as negative co-variation of individual finger forces to maintain a required total force output (Latash et al. 2004; Kang et al. 2004; Li ZM et al. 1998).

Uncontrolled Manifold Hypothesis

Several studies have used the framework of the Uncontrolled Manifold (UCM) Hypothesis to quantify multi-digit synergies (Scholz and Schöner 1999). The UCM hypothesis assumes that, when a controller of a multi-element system wants to stabilize a particular value of a performance variable, it selects a subspace within the state space of the elements such that, within the subspace, the desired value of the variable is constant. This subspace has been termed the “uncontrolled manifold” (UCM). After selecting a UCM, the controller selectively restricts the variability of elements along directions within the state space that do not belong to the UCM, but not along directions within the UCM. This means that the controller allows the elements to show high variability (have more freedom) as long as it does not affect the desired value of the variable (Latash et al 2002). This analysis quantifies two components of variance in the space of elemental variables, one that does not affect a certain value of a performance variable (Variance in UCM sub-space, V_{UCM}), and the other that does (Variance orthogonal to UCM sub-space, V_{ORT}). The index of synergy ΔV is computed as the difference between the variance within UCM and the variance orthogonal to UCM, divided by the total variance (all computed per DOF). This index of synergy corresponds to the amount of variability among the elemental variables that is used to stabilize the performance variable. A result of $\Delta V > 0$ indicates negative co-variation of elemental variables, interpreted as synergy; whereas a result of $\Delta V \leq 0$ indicates independent co-variation of finger forces, interpreted as an absence of synergy (Latash et al 2002).

2.5 Effects of Aging

Advancing age can greatly influence the ability of an individual to perform activities of daily living such as postural tasks, gait, and manipulation of hand held objects. Aging is accompanied by a decline in both strength and dexterity of hands. These changes can be attributed both to age related changes in peripheral structures such as muscles, tendons and joints; and to the alterations in command from central nervous system. These alterations in central command may be imposed by aging of neural structures itself that involve the progressive decrease in the number of larger alpha-motoneurons, or may represent the adaptations that try to mitigate the effects of aging on execution of motor tasks (Latash 2008).

Several studies have looked at the changes in object manipulation as a result of aging. It has been shown that elderly individuals grip objects with twice the amount of force produced by young (Cole 1991, Gilles and Wing 2003, Danion et al 2007). Motor variability increases with advancing age (Enoka 2003).

A number of studies have looked at the effects of aging in the indices of finger interaction in MVC pressing tasks (Olafsdottir, 2005; Shinohara et al. 2004). As compared to the young individuals, elderly produce smaller peak forces, are less enslaved but show larger force deficit. A decrease in enslaving is a counter-intuitive result that might indicate better control of individual finger forces and hence increasing dexterity (Li et al 2000). On the other hand, enslaving has been shown to help stabilize the moment of force the fingers of the hand produce (Zatsiorsky et al. 2000); hence, smaller enslaving in the elderly may lead to worse performance of rotational tasks (demonstrated by Olafsdottir et al. 2007). Some of the changes in the physiology of peripheral structures might make one expect that the enslaving should increase with aging, if it were just because of peripheral structures. The decrease in the compliance of tendons and the increase in the amount of connective tissue with aging (Macaluso et al. 2002) should result in increased enslaving due to parallel force transmission among the structures connecting to individual fingers. Aging has also been shown to result in the enlargement of motor units (Doherty and Brown, 1997). This should also result in an increase in enslaving because of the increased probability of simultaneous recruitment of fibers of the extrinsic muscles that connect to multiple fingers. Hence we might conclude that the decrease in enslaving with aging shown experimentally indicates a change in command of the central nervous system.

Several studies have shown that the multi-digit synergies stabilizing the total force magnitude and total moment of force during a rotational action are weaker in elderly people as compared to the young (Shinohara et al 2004, Shim et al 2004).

2.6 Formulation of Research Problems

The main objectives of our studies were as follows:

First Study (Young Participants): To explore the indices of finger-interaction in one-finger and multi-finger pressing tasks in different directions.

1. To explore the patterns of unintended force production among shear force components. In particular, we expected to see unintended forces not in the direction of the instructed force but in the opposite direction as well as substantial force production in directions orthogonal to the instructed direction.

2. To test the hypothesis of strong multi-finger synergies stabilizing both magnitude and direction of the total force vector in three dimensions.

Second Study (Elderly Participants): To investigate the effects on advancing age on the indices of finger interaction in one-finger and multi-finger pressing tasks in different directions.

1. To test the hypothesis of lower accuracy in both force magnitude and direction in elderly.

2. To test the hypothesis of lower enslaving in the elderly for both normal and shear forces.

3. To test the hypothesis of lower indices if synergy stabilizing both force magnitude and direction.

CHAPTER – 3

COMMON METHODOLOGY

The thesis comprises two studies exploring the control of hand in a multi finger three dimensional pressing tasks. This chapter explains the methodology that was common to both the Young and the Elderly study.

3.1 Apparatus

Two setups were used in the experiments. The main part of the experiment used four multi-component force transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) to measure the three components of the force vector applied to the sensor surface by the tip of each finger of the right hand. The transducers were placed within a frame such that the horizontal distance between the centers of two adjacent transducers was 2 cm. The forward-backward location of the sensors could be adjusted for differences in the lengths of the subjects' fingers. The sensor surfaces were covered by P-100 sand paper to increase friction. The transducers were oriented such that the force signals along the three orthogonal axes increased upward (Z axis), to the right (X axis), and forward (Y axis) (as shown in Figure 3B). The frame with the sensors was placed on the surface of a table. The subjects sat comfortably in front of the table with the right elbow flexed at about 90 degrees, and the right shoulder slightly flexed and abducted (as shown in Figure 3A). A hand rest was placed below the palm to help maintain a comfortable and constant hand configuration. The subjects maintained the same position of the upper extremity throughout the experiment.

The second setup was used in the tests with downward maximal voluntary force production (MVC tests, see the next subsection). Finger forces were measured with a set of unidirectional force sensors (model 208C02; PCB Piezotronics, Inc.) because the multicomponent sensors saturated at high forces. Otherwise, the setup used in the MVC tests was similar to the described one (Figure 3A).

The signals from the sensors were amplified and sampled at 16 bits using a digital-to analog converter (NI PCI-6225, National Instruments, Austin, TX, USA) at a frequency of 200 Hz. The data were collected on a desktop computer with custom software written in LabView (National Instruments).

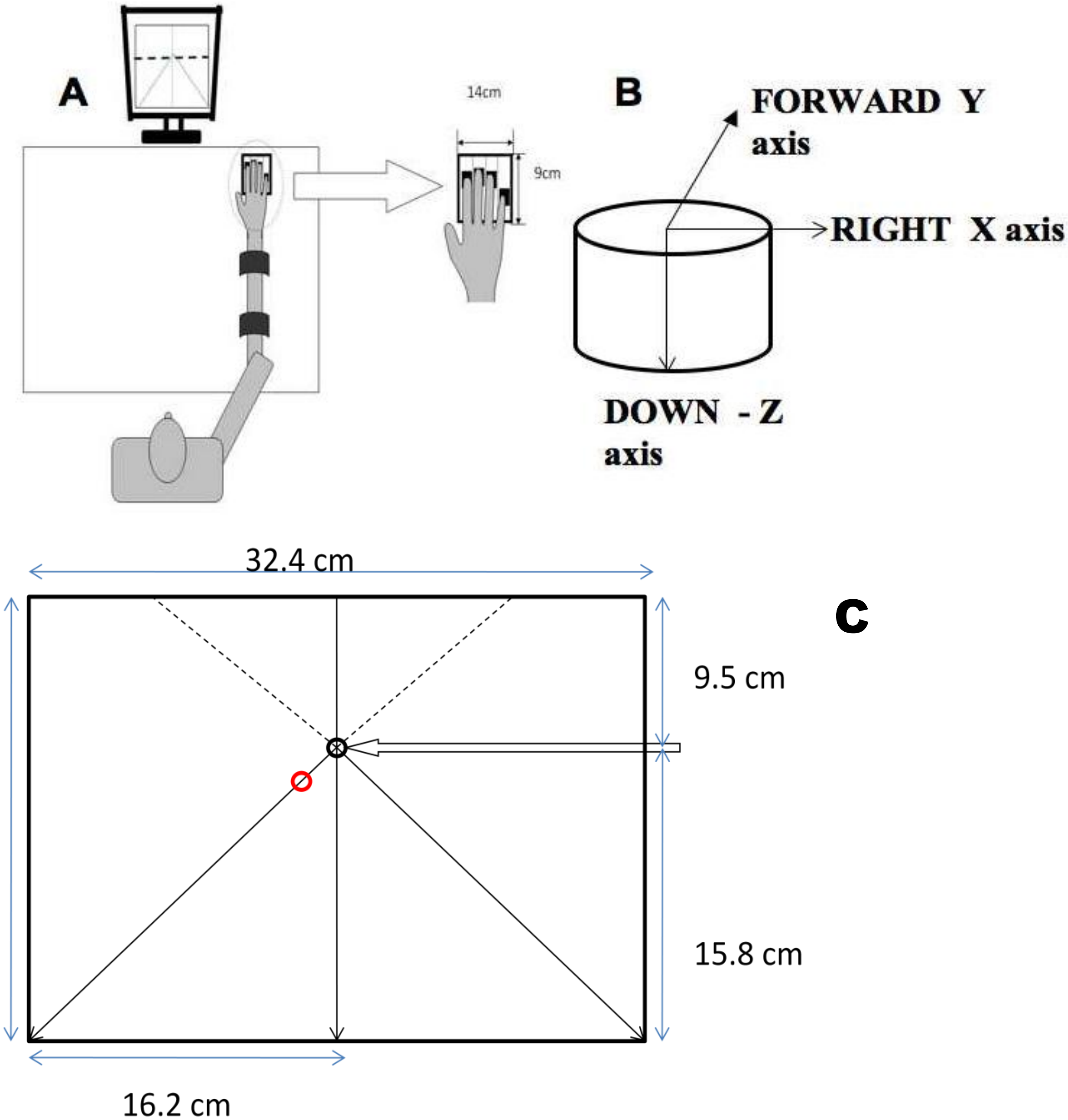

Figure 3: A: The experimental setup. B: Orientation of the 6D sensors. C: A schematic of the feedback screen shown to the subject.

3.2 Procedure

The experiments consisted of two parts – one-finger pressing tasks and four-finger pressing tasks, which were conducted in two different sessions. Prior to the main part of the experiment, MVCs were recorded for each of the four fingers and for the four fingers acting together, in a random order. In those trials, the subjects had up to 3 s to produce maximal pressing force in the downward direction. Subjects were instructed to “press as hard as possible”. Two MVC trials were performed in a row by each finger and by the four fingers together, and the maximum force produced over the two trials was used in the later calculations. The intervals between the MVC trials were 30 s. The subjects were shown feedback on the screen of the downward force produced by the task finger as a function of time. The order of finger MVC tasks was balanced across subjects.

The main part of the experiment consisted of one- and four-finger tests with accurate force production in five different directions – down, down and right, down and left, down and forward, and down and backward (referred to as D, DR, DL, DF, and DB). All these five directions were used in the Young study. However, the Elderly study was limited to just three directions (discussed later in Chapter -5). The D task was performed under two instructions, to keep the force in the right – left direction zero (referred to as D_{RL}) and to keep the force in the forward - backward direction zero (referred to as D_{FB}). In those trials, visual feedback was provided for the force component that the subjects were instructed to keep at zero level. Feedback in the direction not related to the task was not provided. In all trials, the subject was instructed to keep all the fingers in contact with the sensors at all times and not to pay attention to possible force production by non-instructed fingers. An additional one-finger condition was used, pressing down without any feedback on the force along the X or Y axis (referred to as D).

The targets were set at 22.5% MVC for the downward direction, 3.75% MVC for the right–left force directions, and 10% MVC for the forward–backward direction. These values were selected based on a set of pilot trials to allow for comfortable performance of all the tasks and comparable efforts associated with performing the tasks. The feedback was shown to the subjects on the computer screen placed in front of the subjects at a distance of about 65 cm. A schematic of the feedback screen is shown in Figure 3C. One circle (which has an arrow pointing to it in Figure 3C, and was black in the experiment) provided feedback on the current force produced. The subjects were required to apply force such that they cause the location of this circle to match the location of the other circle (which was red in the experiment). The red circle moved with a constant velocity along one of the three lines shown. The target moved along the vertical line for D tasks (D_{RL}, D_{FB} and D), along the right slanted line for DR and DF tasks, and along the left slanted line for DL and DB tasks. While the black circle began at the location corresponding to zero force (shown by an arrow in Figure 3C), the red circle began moving from the top of the screen, to give subjects time to prepare. The red circle took 3 s to reach the starting point. The subjects were required to start pressing as soon as the red circle reached the starting point such that the black circle was always on top of the red one, for 5 s. Each circle was 3 mm in diameter.

Feedback gain for movement of the target point along each axis was calculated in percent of MVC per cm. This gain was computed as the percentage of MVC set as target for each direction divided by the length of the line of the screen representing that amount of force. The gain for the three axes was as follows:

For Z axis: 1.424% of MVC/cm

For X axis: 0.231% of MVC/cm

For Y axis: 0.617% of MVC/cm

Before each trial, the subject was instructed in which direction he or she had to press in and along which one of the three lines the cursor would move. Prior to performing these tasks, the subjects were given sufficient practice time (about 10 min), during which they practiced accurate force production by individual fingers and by all four fingers along each of the force vector directions without a moving target. For the one-finger pressing tasks, there was one practice trial with the moving target followed by three recorded trials for each condition. For these trials, subjects were instructed to "focus only on the task finger" but not to lift any fingers off the sensors at any time. For the four-finger tasks, there were

three practice trials with the moving target followed by 15 recorded trials. There were 12-s intervals between the trials. A resting time of 1 minute was provided between sets of trials. None of the subjects complained of pain or fatigue during or after the experiment. Additional rest periods were given when requested.

3.3 Data Processing

One-finger pressing tasks were used for calculating enslaving indices and four-finger pressing tasks were used for computing sharing indices and indices of multi-finger synergies (see later). The data were filtered using a two-way 2nd order Butterworth low-pass filter at 2.5 Hz. We tried other (higher) filtering frequencies and found no significant differences in any of the main outcome variables; the 2.5 Hz filter resulted in most consistent within-a-subject data. The data collected at 200 Hz were later resampled into 100 data points for each 5-s trial.

Task Performance

Accuracy of the performance was estimated using the RMS error, which was computed for forces produced in X, Y and Z directions for different tasks.

$$RMS = \frac{1}{F_{Pk}^{N}}\sqrt{\frac{\sum_{i=1}^{N}\left(F_k^i - F_{Pk}^i\right)^2}{N}} \qquad (1)$$

where $F_k^{\ i}$ is the measured force at sample *i* along the *k* axis, F_{Pk} is the instructed force shown by the moving target, and *N* the number of samples (100). The *RMS* was normalized by the maximum instructed force for each condition.

RMS error was also calculated for the direction of force production:

$$RMS_{\theta} = \sqrt{\frac{\sum_{i=1}^{N}\left(\tan^{-1}\left(\frac{F_z^i}{F_k^i}\right) - \tan^{-1}\left(\frac{F_{Pz}}{F_{Pk}}\right)\right)^2}{N}} \qquad (2)$$

where F_z and F_k are the produced force in the *Z* and other (*X* or *Y*) task direction respectively. *RMS* error was calculated for each trial and averaged across all trials within a series and then across the subjects for each condition separately.

Enslaving

This index reflects unintentional force production in one-finger tasks either by non-instructed fingers or by the instructed finger in a non-instructed direction. A four-by-four enslaving matrix was computed for each relevant direction (*Z* and/or either *X* or *Y*), for each of the six pressing tasks, resulting in a total of 13 enslaving matrices, **E** (12 for the six 2D tasks and one for the Down pressing task). Similarly to earlier studies of enslaving, we assumed linear relationships among individual finger forces (Zatsiorsky et al. 1998, 2000; Danion et al. 2003). To obtain entries of the **E** matrix, the forces produced by non-instructed fingers were regressed on the force produced by the task finger over the whole trial duration:

$$F_{jk} = a_{jk} + b_{jk} F_k , \qquad (3)$$

where F_{jk} is force produced by finger *j* when *k* is the task finger and F_k is the force produced by the task finger in a particular direction. Further, the **E** matrix was computed as:

$$\mathbf{E} = \begin{bmatrix} b_{I,I} & b_{I,M} & b_{I,R} & b_{I,L} \\ b_{M,I} & b_{M,M} & b_{M,R} & b_{M,L} \\ b_{R,I} & b_{R,M} & b_{R,R} & b_{R,L} \\ b_{L,I} & b_{L,M} & b_{L,R} & b_{L,L} \end{bmatrix} \qquad (4)$$

where $b_{j,k}$ is the slope of the regression equation when the force produced by finger *j* is regressed on force produced by finger *k*, which is the task finger. We used the best out of the three trials for each condition, where best was defined as the one with the highest mean R^2 (square of correlation coefficient) value.

The enslaving index $|E|$ was calculated as the sum of all non-diagonal entries of the enslaving matrix. Two more indices, E_j and E_i were computed for the *Z* direction only. E_j is the measure of how each finger enslaves the other fingers in *Z* direction (the sum of entries over the corresponding column of the enslaving matrix minus 1). E_i is a measure of how a given finger is enslaved by other fingers in Z direction during different pressing conditions (the sum of entries over the corresponding row of the enslaving matrix minus 1).

The enslaving index $|E|$ was also calculated based on the enslaving matrices obtained from single-finger ramp tasks using uni-dimensional sensors, in a similar way. The results for the enslaving matrices were not different from the data obtained from uni-dimensional and 6D sensors. So, in the remaining text we only present 6D sensor data.

Another measure F_{UN}, was used to characterize unintended force production within each finger across different directions across one-finger pressing tasks. F_{UN} reflects the amount of force produced by the task finger acting downward (along the Z axis) in a non-instructed direction (X or Y): $F_{UN} = F$ (non-Z, non-task) / F_Z,task.

F_{UN} was also calculated using linear regressions. Force produced by the task finger in the non-instructed direction was regressed on force produced by the task finger in the Z direction. $F_{UNki} = a_{ki} + b_{ki} F_{UNkz}$, where F_{UNki} is the force produced by task finger k in non-instructed direction i, F_{UNkz} is the force produced by the task finger k in Z direction; b_{ki} is the slope of the regression line. Means and standard deviations of F_{UN} in the Y direction were computed, across subjects, for each finger individually for three task conditions involving the X axis. It was repeated for F_{UN} in the X direction for tasks involving Y axis.

Analysis of multi-finger synergies

We quantified multi-finger synergies stabilizing the magnitude of total force and its direction in four-finger trials using the framework of the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999). This analysis quantifies two components of variance in the space of elemental variables (finger modes, see later), one that does not affect a certain value of a performance variable (force magnitude or force direction in our study), and the other that does. We will address these two components as variance within the UCM (V_{UCM}) and variance orthogonal to the UCM (V_{ORT}). To eliminate the co-variation of finger forces due to enslaving, finger forces were transformed into another set of variables, finger modes (Zatsiorsky et al. 1998; Latash et al. 2001; Danion et al. 2004):

$$d\mathbf{F} = \mathbf{E}\, d\mathbf{m} \qquad (5)$$

$$d\mathbf{m} = \mathbf{E}^{-1}\, d\mathbf{F} \qquad \text{(assuming that } \mathbf{E} \text{ is an invertible matrix)}$$

where $d\mathbf{F}$is the change in force produced, **E** is a 4 × 4 enslaving matrix, and $d\mathbf{m}$ is the change in mode magnitudes.

Rather than taking the regular matrix inverse, the pseudoinverse was calculated, using the singular value decomposition:

$$\mathbf{U}\,\mathbf{S}\,\mathbf{V}^{T} = \mathbf{E} \qquad (6)$$

The pseudoinverse was then calculated from:

$$\mathbf{E}^{-1} = \mathbf{V}\,\mathbf{S}^{*}\,\mathbf{U}^{T} \qquad (7)$$

where $\mathbf{S}^{*}$ is the reciprocal of the non-zero elements in **S**. However, small values in elements of **S** (below 0.01) were set to zero before calculating $\mathbf{S}^{*}$. For most cases, the result was equivalent to taking the regular matrix inverse, but the removal of small values in S prevented very large values of the inverse of the enslaving matrix in a small number (< 10%) of extreme cases.

Before calculating variance, the forces in each direction were normalized with respect to the maximum task force in that direction, i.e., the force magnitude in each direction, which the subject was asked to produce. The components of the task force were always considered for each direction separately.

In our study, two performance variables were considered. The first was the sum of the forces (F_{TOT}) produced by the four fingers in a given task-relevant direction (*Z*, and either *X* or *Y*): $F_{TOT,k} = F_{I\,k} + F_{Mk} + F_{Rk} + F_{Lk}$, where F_{Ik} is the force produced by the index finger in the *k* direction (*X*, *Y* or *Z*).

The Jacobian defines the transformation between small changes in the individual finger force magnitudes and changes in F_{TOT}:

$$dF_{TOT,k} = [1\,1\,1\,1]\begin{bmatrix} dF_{Ik} \\ dF_{Mk} \\ dF_{Rk} \\ dF_{Lk} \end{bmatrix} \qquad (8)$$

where dF_{jk} is the change in force produced by *j* finger in *k* direction (*X*,*Y* or *Z*).

$$dF_{TOT,k} = \mathbf{J}\, d\mathbf{F} \qquad (9)$$

In the space of finger modes, we can express this relationship as:

$$dF_{TOT,k} = \mathbf{J}\,\mathbf{E}\, d\mathbf{m} \qquad (10)$$

The UCM was approximated linearly as the null-space of **J** spanned by basis vectors, $\mathbf{e}_i$ from the following equation:

$$0 = \mathbf{J}\,\mathbf{E}\,\mathbf{e}_i \qquad (11)$$

We calculated $\mathbf{f}_{\|}$ as the sum of mean-free mode vectors projected onto the UCM:

$$\mathbf{f}_{\|} = \sum_{i=1}^{n-k} \left(\mathbf{e}_i^T \cdot d\mathbf{m}\right)\mathbf{e}_i \qquad (12)$$

where n=4 is the number of elemental variables and k=1 corresponds to the one-dimensional performance variable. $\mathbf{f}_{\perp}$ is the component of mode vectors perpendicular to the null space:

$$\mathbf{f}_{\perp} = d\mathbf{m} - \mathbf{f}_{\|} \qquad (13)$$

Then the variance per degree-of-freedom (DOF) within the UCM, i.e. V_{UCM} was computed as follows:

$$V_{UCM} = \frac{\sum_{trials} \left|\mathbf{f}_{||}\right|^2}{\left((n-k)N_{trials}\right)} \tag{14}$$

Similarly, V_{ORT} , i.e. variance per DOF orthogonal to the UCM was calculated as follows:

$$V_{ORT} = \frac{\sum_{trials} \left|\mathbf{f}_{\perp}\right|^2}{\left(kN_{trials}\right)} \tag{15}$$

Further, to allow comparison across subjects, an index, □V was computed as the difference between the variance within UCM and the variance orthogonal to UCM, divided by the total variance (all computed per DOF).

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}} \tag{16}$$

ΔV indices were computed separately for each of the two relevant directions for each task (Z and X or Y) and each subject separately. Positive ΔV would indicate a multi-finger synergy stabilizing the performance variable, while zero or negative ΔV would mean no such synergy.

The second performance variable considered was the ratio between the two vector components reflecting the direction of the vector. It was defined as the force in the non-Z task direction k (i.e., X or Y) divided by the force in the Z direction:

$$R = \frac{\sum_{i=1}^{4} F_k^i}{\sum_{i=1}^{4} F_Z^i} \tag{17}$$

This ratio represents the tangent of the force direction angle. In this analysis, forces were used, rather than modes, to ensure that the units are the same for the numerator and denominator. In this case, the performance variable was R; it depended on eight elemental variables, the eight force components of the four finger force vectors.

For forces in a non-Z direction, the elements of the Jacobian were:

$$\frac{\partial R}{\partial F_k^i} = \frac{1}{\sum_i F_Z^i} \tag{18}$$

The elements of the Jacobian for the forces in Z direction were:

$$\frac{\partial R}{\partial F_z^i} = \frac{-\sum_i F_k}{\sum_i (F_Z)^2} \tag{19}$$

Thus the Jacobian matrix was:

$$\begin{bmatrix} \frac{1}{\sum_i F_Z^i} & \frac{-\sum_i F_k}{\sum_i (F_Z)^2} & \frac{1}{\sum_i F_Z^i} & \frac{-\sum_i F_k}{\sum_i (F_Z)^2} & \frac{1}{\sum_i F_Z^i} & \frac{-\sum_i F_k}{\sum_i (F_Z)^2} & \frac{1}{\sum_i F_Z^i} & \frac{-\sum_i F_k}{\sum_i (F_Z)^2} \end{bmatrix} \tag{20}$$

The remainder of the analysis was equivalent to the procedure described above. Briefly, the null-space of the Jacobian was used to approximate the UCM. For each sample over the 5-s trial, mean-free finger forces were projected onto the UCM and onto the orthogonal complement. Variance was computed within both sub-spaces and normalized per degree-of-freedom (the UCM is 7-dimensional and the orthogonal sub-space in one-dimensional). These indices, V_{UCM} and V_{ORT}, were used to compute the index of multi-finger synergy (ΔV) stabilizing force vector direction.

Since V_{UCM}, V_{ORT} and V_{TOT} are computed per degree-of-freedom, the index of synergy ΔV for stabilizing force magnitude ranges between 1.334 (all variance is within the UCM) and – 4 (all variance is in orthogonal sub-space). For statistical analysis, the ΔV indexes for Force magnitude stabilization were transformed using Fisher's z-transformation, modified according to the boundaries of ΔV:

$$z_{\Delta V} = 0.5\log_{10}\left(\frac{4+\Delta V}{1.33-\Delta V}\right) \tag{21}$$

The index of synergy ΔV computed for force direction ranges between 1.143 (all variance is within the UCM) and – 8 (all variance is in the orthogonal sub-space). For statistical analysis, the ΔV indexes for Force direction stabilization were transformed using Fisher's z-transformation, modified according to the boundaries of ΔV:

$$z_{\Delta V} = 0.5\log_{10}\left(\frac{8+\Delta V}{1.143-\Delta V}\right) \tag{22}$$

CHAPTER – 4

FINGER INTERACTION IN A THREE DIMENSIONAL PRESSING TASK: YOUNG PARTICIPANTS

4.1 Introduction

In different activities of daily living, human fingers produce vectors of force that can vary in both magnitude and direction within a broad range. The current study has two major objectives: First, to quantify finger interdependence in tasks that require force production in different directions; and second, to explore the existence of multi-finger synergies stabilizing both the magnitude and the direction of the total force vector by co-varying involvement of individual fingers across trials. Within the first objective, we explored unintentional force production for different force directions. Under the term "unintentional force" we imply forces produced by non-task fingers and/or by the task fingers in directions not required by the explicit task, whether due to mechanical, anatomical, or neurophysiological reasons. Unintentional force production includes two components. First, there is enslaving, studied primarily in normal force production tasks (reviewed in Zatsiorsky and Latash 2008). Second, we also studied a novel phenomenon of within-a-finger unintentional force production in non-instructed directions.

4.2 Participants

Eight subjects (four males and four females) volunteered to participate in the study. Their age was 27.5 ± 3.7 years (mean ± standard deviation), height 169.8 ± 4.9 cm , weight 68.0 ± 12.0 kg, hand length from the proximal palmar crease to the tip of the middle finger, 17.8 ± 0.7 cm and hand width, at the level of metacarpal heads, 8.1± 0.7 cm. All subjects were healthy adults, right-handed according to their hand usage during writing and eating, and none of them reported to have any neurological or right upper extremity pathology. None of them reported to be engaged in any activity that may affect hand dexterity (such as being a professional typist or piano player). Prior to study all subjects gave informed consent according to the procedures approved by the Office for Research Protections of the Pennsylvania State University.

4.3 Methods

The methods have been explained in the chapter on Common Methodology (Chapter – 3). In the Young study, one-finger accurate ramp force production trials were also performed using 1D sensors to compare the enslaving matrices obtained from 6D sensors with those from 1D sensors. The subjects performed two trials with each finger. The subjects were asked to press with the instructed finger, slowly increasing the force, so as to follow a ramp template shown on the screen. They were asked to keep all other fingers in contact with the sensors. Visual feedback on the pressing force was provided to the subjects as a thick line. The template shown was a horizontal line corresponding to zero force, for three seconds, followed by a diagonal line going up to 22.5% of the subject's MVC, over the next 5 s. The subjects were instructed in press all different directions described in Chapter – 3.

4.4 Statistics

Paired t-tests were performed on the enslaving indices obtained from uni-dimensional (used for calculating MVC) and 6D sensors (used for the experiment). To explore the differences in performance between one-finger and four-finger pressing tasks, repeated measures two-way ANOVA was done on the *RMS* errors of the force vector angle with *Fingers* (I, M, R, L, IMRL) and *Conditions* (D_{RL}, D_{FB}, DR, DL, DF and DB) as factors. A similar ANOVA was run on the *RMS* errors of force magnitude in Z direction. In these ANOVAs only the first three trials of the four-finger tasks were included to avoid effects of practice.

To compare the Enslaving index $|E|$ in X direction, we used the Student's t-test for conditions DR and DL. Similarly, to compare the Enslaving index $|E|$ in Y direction, we used thet-test for conditions DF and DB.

Two-way ANOVA with repeated measures was conducted on Enslaving index $|E|$, with factors *Feedback* (none, F_X, F_Y) and *Finger* (Index, Middle, Ring, Little) to explore the effect of feedback on enslaving in Z direction in D tasks. To explore the trend ofE_j across different fingers and conditions, two-way ANOVA with repeated measures was done on Ej (index of how a finger enslaves other fingers), with *Finger* (I, M, R, L) and *Condition* (7 levels – D, D_{RL}, D_{FB}, DR, DL, DF and DB) as factors. A similar ANOVA was done on E_i.

The index of unintended force production in the non-instructed direction (F_{UN}) along Y axis was explored with repeated measures ANOVA with factors *Finger* and *Task-direction* (three levels of tasks involving X axis, D_{RL}, DR and DL). A similar ANOVA was done on F_{UN} along X axis with *Finger* and *Task directions* (involving Y axis, D_{FB}, DF, DB) as factors.

In order to analyze the index of synergy for stabilizing force magnitude, we did two-way ANOVA with repeated measures on the z-transformed ΔV value averaged over the whole time interval of the task, with *Condition* (6 levels, D_{RL}, D_{FB}, DR, DL, DF and DB) and *Axis* (two relevant axes for each condition – Z and X or Y) as factors. To explore the time profile of the synergy index, a two-way ANOVA was run with repeated measures on the z-transformed ΔV value averaged over every 10% of time interval for each subject, with *Condition* (6 levels) and *Time* (10 levels: 10%, 20%, 30%, 40% , 50%, 60%, 70%, 80%, 90% and 100%) as factors. This ANOVA was done separately for the z-transformed ΔV values for the Z axis and for the other relevant axis (X or Y).

A one-way ANOVA with repeated measures was done on the z-transformed ΔV values for stabilizing force direction, with *Condition* (6 levels, D_{RL}, D_{FB}, DR, DL, DF and DB) as the factor. Further, a two-way ANOVA with repeated measures was done on ΔV values (averaged over every 10% of time-interval for each subject and then z-transformed), with *Condition* (6 levels) and *Time* (10 levels) as factors.

For all the ANOVAs, the assumption of sphericity was checked using Mauchly' sphericity test. If sphericity was violated, the degrees of freedom were adjusted as necessary using Greenhouse-Geisser corrections.

4.5 Results

Accuracy of Task Performance

The following general features characterized one-finger task performance across all subjects. In one-finger tasks, the subjects produced forces in the task directions by the task finger that, on average, matched closely the target (see Fig. 4A, the solid lines match closely the dashed thin target lines). Non-task fingers typically also produced forces with magnitudes that increased in parallel with the task finger force (this is shown for the normal (z) force for M, R and L fingers in Fig. 4A). This was true for both the downward force component (F_Z) and shear force components (F_Y in Fig. 4A). When the subjects were instructed to produce force in the downward direction, typically non-zero forces were produced along the non-task horizontal axes (e.g., see F_Y-I in Fig. 4B).

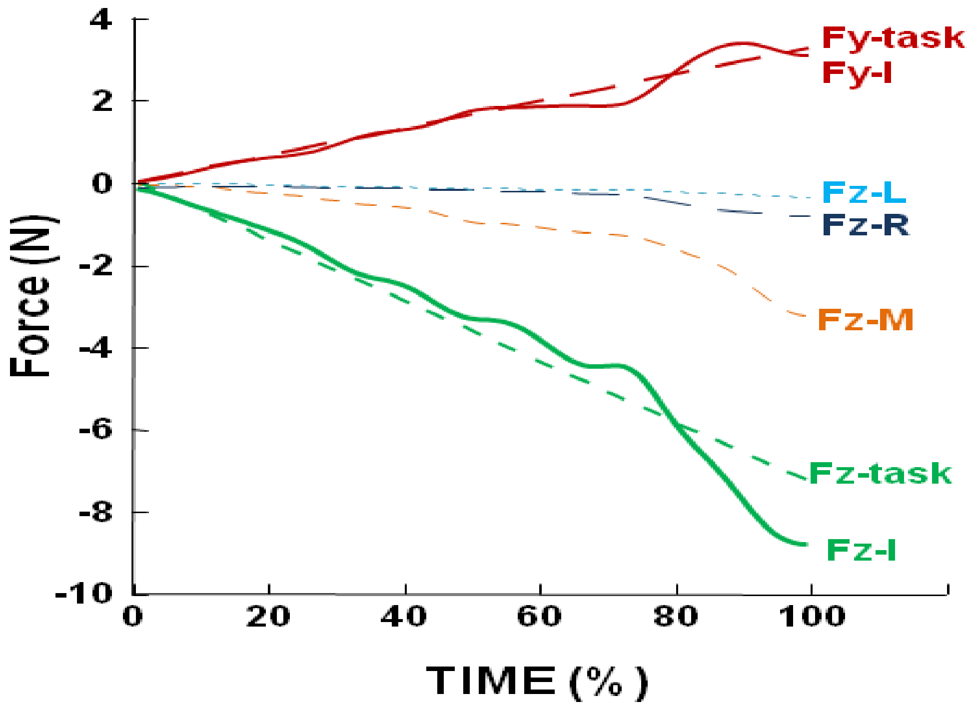

Figure 4: A: Force time series of a typical representative trial by the Index finger in the Down Forward (DF) task. The thin dashed lines indicate the desired force profile. Thick solid lines indicate the force produced by task finger in instructed directions. Thick dashed lines indicate the force produced by the non task (enslaved) fingers along Z axis. F_Z_task: Force template in –Z (down) direction. F_Y_task: Force template in +Y (forward) direction. F_Z _I : Index finger force in Z direction. F_Y_I: Index finger force in +Y (forward) direction. F_Z_M: Middle finger force in –Z direction. F_Z_R: Ring finger force in –Z direction.

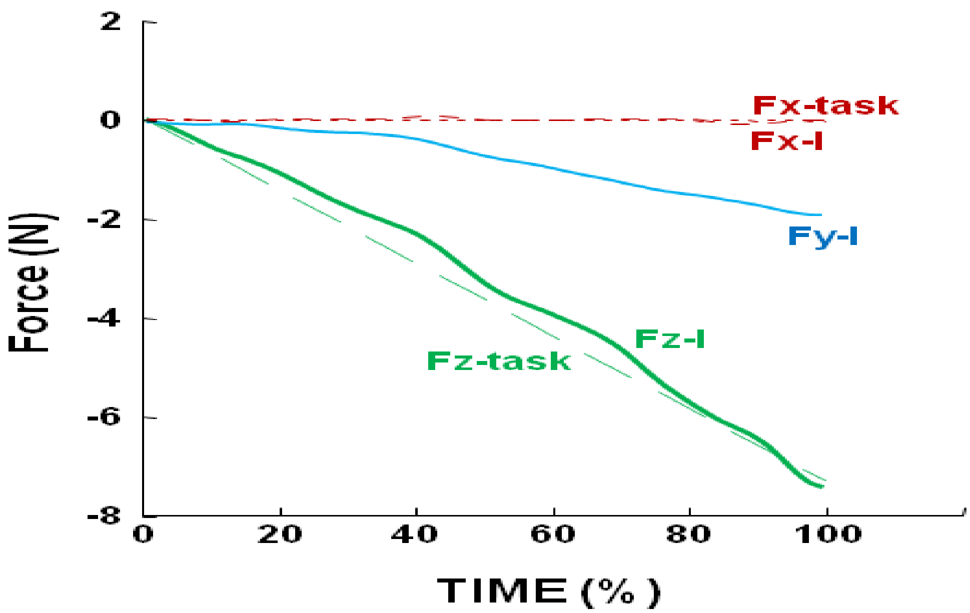

Figure 4B: Force time series of a typical representative trial by the Index finger in the Down task with feedback on the right-left force deviations (D_{RL}). The thin dashed lines indicate the desired force profile. Thick solid lines indicate the force produced by the subject in the instructed direction and thick dashed line indicates unintended force production (F_{UN}) along Y axis. F_Z _task: Force template in –Z direction. F_X_task: Force template along X (right-left) axis. F_Z_I : Index finger force in –Z (backward) direction. F_X_I : Index finger force along X (right-left) axis. F_Y_I: Index finger force along Y (forward-backward) axis.

To study how accurately the subjects followed the task direction of force, RMS of force vector angle was computed for both one-finger and four-finger tasks with respect to the task force direction over time. The *RMS* indices were averaged across trials for each subject, and then averaged across all subjects. The data for different conditions are presented in Table 1. The subjects were significantly more accurate in four-finger tasks as compared to one-finger tasks.

Directional errors were higher in the DB (Down-backward) condition as compared to the DL (Down-left), DR (Down-right), D_{RL} (Down, feedback RL) and D_{FB} (Down, feedback FB) conditions.

These findings were confirmed by repeated measures, two-way ANOVA on RMS errors of force vector angle with *Fingers* (I, M, R, L, IMRL) and *Condition* (D_{RL}, D_{FB}, DR, DL, DF and DB) as factors. *Fingers* and *Condition* had significant main effects ($F_{4, 203}= 7.29$, $p < 0.001$ and $F_{5, 203} = 2.81$, $p < 0.05$). Tukey comparisons showed that *RMS* error was less for the four-finger pressing task compared to the one-finger tasks (IMRL < M,R,L,I). The differences among the fingers were not significant. Among conditions, only the DB condition was found to have significantly greater *RMS* error than the D_{RL} and DF conditions ($p <0.05$). The interaction between *Finger* and *Condition* was not significant.

There was no significant difference in the *RMS* error of force magnitude in the Z direction between one-finger and four-finger trials (see Table 2 for the data), which was confirmed by repeated measures ANOVA with *Condition* (6 levels) and *Fingers* (5 levels) as factors. There was only a significant main effect of *Condition* ($F_{2.84,19.92} = 4.93$, $p < 0.05$). The *RMS* error for the DF condition was significant less than for DB, DR and D_{RL} conditions ($p < 0.05$).

<u>Indices of Finger Interaction</u>

Enslaving across fingers

Enslaving across fingers was defined as the involuntary force production by non-task fingers. For each condition, enslaving matrices (**E**) and indices of enslaving were calculated separately for the forces produced along the three axes (see Methods). To compute entries of the

E matrix, the forces produced by non-instructed fingers were regressed on the force produced by the task finger over the whole trial duration. Different columns correspond to different task fingers and different rows correspond to different enslaved fingers.

A typical **E** matrix along *Z*-axis for the D_{RL} task for a typical subject looked as follows:

$$\begin{bmatrix} \mathbf{1.0000} & \mathbf{0.6611} & \mathbf{0.3240} & \mathbf{0.2557} \\ \mathbf{0.0249} & \mathbf{1.0000} & \mathbf{0.8023} & \mathbf{0.1049} \\ \mathbf{0.0759} & \mathbf{0.2760} & \mathbf{1.0000} & \mathbf{0.2768} \\ \mathbf{0.0137} & \mathbf{0.2092} & \mathbf{0.4896} & \mathbf{1.0000} \end{bmatrix}$$

It should be noted that this matrix is strongly non-symmetric, i.e. there are large differences between indices of how a finger enslaves another finger and how it is enslaved by that finger.

Enslaving matrices along non-*Z* axis could have negative entries meaning that non-task fingers produced force in a direction opposite to the force produced by the task finger. Here follows an example of the **E** matrix along the *X*-axis for the DL task (a typical subject):

$$\begin{bmatrix} \mathbf{1.0000} & \mathbf{0.1184} & \mathbf{-0.0741} & \mathbf{-0.1199} \\ \mathbf{0.1347} & \mathbf{1.0000} & \mathbf{-0.5434} & \mathbf{-0.2755} \\ \mathbf{0.1282} & \mathbf{0.2387} & \mathbf{1.0000} & \mathbf{0.1481} \\ \mathbf{0.0226} & \mathbf{0.0960} & \mathbf{0.4265} & \mathbf{1.0000} \end{bmatrix}$$

The numbers of negative entries found in the **E** matrices across non-D force production tasks, averaged across all the subjects are shown in Table 3.

The enslaving index |*E*| was calculated as the sum of all non-diagonal entries of the enslaving matrix. Table 4 shows |*E*| (enslaving index) for different task conditions averaged across all subjects. Enslaving in the *X* (right-left) direction was found to be asymmetrical whereas enslaving in the *Y* (forward-backward) direction was nearly symmetrical (Table 4).

The |*E*| index in the *X*-direction for the DR task was significantly higher than that for the DL task, as supported by a t-test ($p < 0.01$). In contrast, the |*E*| index in the *Y*-direction was not different between the DB and DF conditions ($p > 0.4$).

$|E|$ in Z-direction did not depend on feedback or instruction about forces in the other direction (X or Y). ANOVA was conducted on $|E|$, with factors *Feedback* (none, F_X, F_Y) and *Task-finger* (I, M, R, L) in Down tasks. There was no significant effect of *Feedback* and no significant interaction *Feedback* × *Task-finger*. However, *Task-finger* showed a significant effect ($F_{1.6, 11.25} = 7.09$ $p < 0.05$). In Down tasks (D, D_{RL}, D_{FB}), the Ring finger enslaved other fingers in Z direction to a greater extent as compared to the Index and Middle fingers ($p < 0.05$). Also, the Little finger enslaved other fingers more as compared to the Index finger ($p < 0.05$).

E_j was used as the measure of how a finger enslaves the other fingers in the Z-direction (it is the sum of entries over a column of the **E** matrix minus 1). Figure 5 shows that the ability to enslave other fingers was the lowest for the Index finger, followed by the Middle, Ring and Little fingers (I < M < R, L). This was supported by repeated measures ANOVA on E_j, with *Finger* (I, M, R, L) and *Condition* (7 levels – D, D_{RL}, D_{FB}, DR, DL, DF and DB) as factors. There was a significant effect of *Finger* ($F_{3,189} = 26.10$, $p < 0.05$) without other effects.

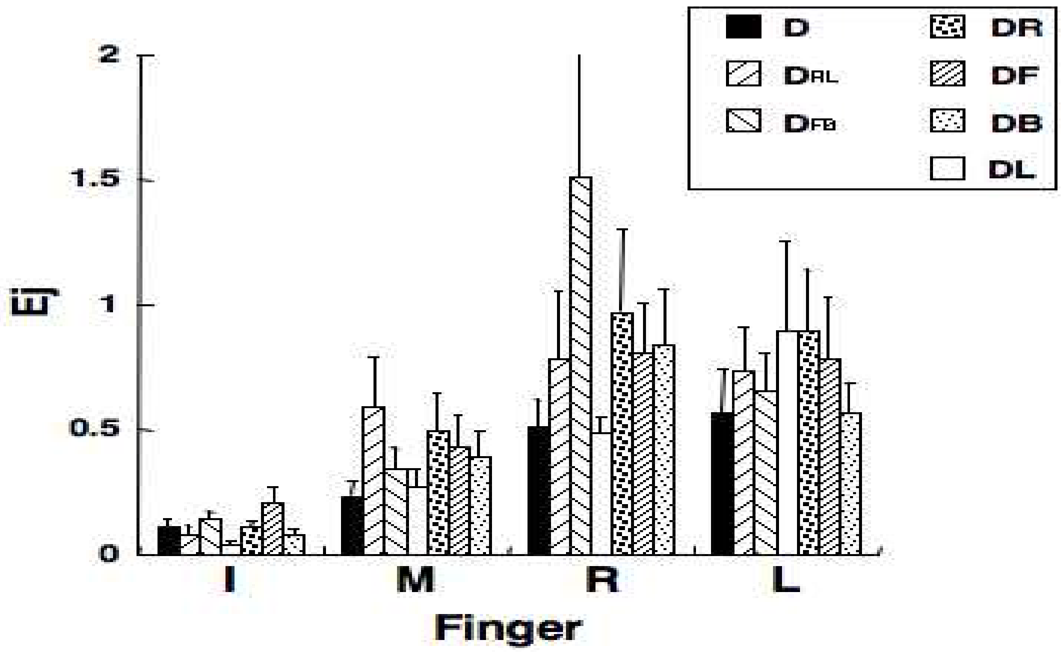

Figure 5: Ej (how a finger enslaves other fingers) values for different conditions. Values have been averaged across all subjects (with standard error bars). D: Down only, D_{RL}: Down – feedback on the right-left force changes, D_{FB}: Down – feedback on the forward-backward force changes, DL: Down left, DR: Down right, DF: Down forward, DB: Down backward.

E_i was used as a measure of how a finger is enslaved by other fingers in *Z*-direction (it is the sum of entries over a row of the **E** matrix minus 1). Figure 6 illustrates that the Index, Middle and Ring fingers were enslaved by other fingers stronger than the Little finger was. This was supported by repeated measures ANOVA on E_i, with *Finger* (I, M, R, L) and *Condition* (7 levels – D, D_{RL}, D_{FB}, DR, DL, DF and DB) as factors. There was a significant effect of *Finger* ($F_{3,189}$ =

14.11, $p < 0.05$) without other effects. Tukey comparison revealed that the Little finger was the least enslaved as compared to the Index, Middle and Ring fingers ($p < 0.05$).

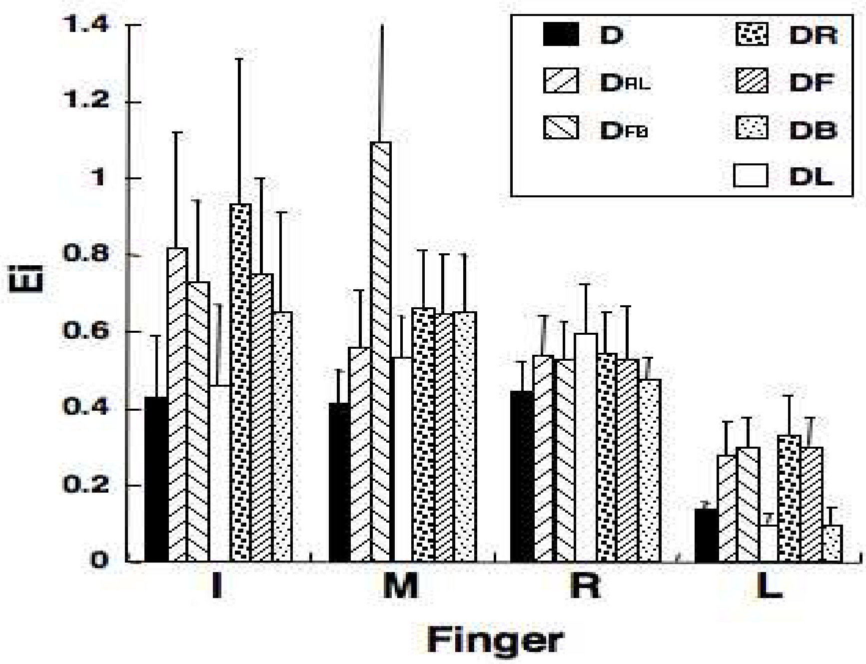

Figure 6: Ei (How a finger is enslaved by other fingers) values for different conditions. Values have been averaged across all subjects (with standard error bars). For abbreviations see Figure 5.

Unintended force production by a finger across directions (F_{UN})

F_{UN} was defined as a measure of the amount of force produced by the task finger in a non-instructed direction (*X* or *Y*) while pressing downward (along the *Z* axis). Unintended force along the *Y*-axis changed with the changes in the task requirements with respect to the X-axis, i.e. whether the task was along +*X* (right) axis or along –*X* (left) axis (Figure 7). In contrast, unintended force along *X*-axis remained the same irrespective of the task requirement changes with respect to *Y*-axis, i.e. irrespective of whether the task was along +*Y* (forward) axis or –*Y* (backward) axis (Figure 8). In order to study if F_{UN} is a function of task direction and task finger, an ANOVA was run on F_{UN} with factors *Finger* and *Task-direction*. This was done separately to study F_{UN} along the Y-axis for the three conditions involving the *X*-axis (D_{RL}, DL and DR) and to study F_{UN} along the *X*-axis for the three conditions involving the *Y*-axis (D_{FB}, DF and DB).

There was a significant effect of *Task-direction* on F_{UN} for the *Y*-axis. ($F_{2,77} = 11.74$, $p < 0.001$). The effect of *Finger* was also significant ($F_{3,77} = 5.24$, $p < 0.005$). Tukey comparisons showed that F_{UN} was significantly greater for the DL condition than for the DR and D_{RL} conditions ($p < 0.001$) without a difference between DR and D_{RL}. The *Finger* × *Task-direction* interaction was not significant. Thus F_{UN} along *Y* axis in increasing order was: D_{RL}, DR < DL. Also, Tukey comparison revealed that F_{UN} along *Y* axis was higher during the Index finger tasks as compared to the Middle, Ring and Little finger tasks ($p < 0.05$).

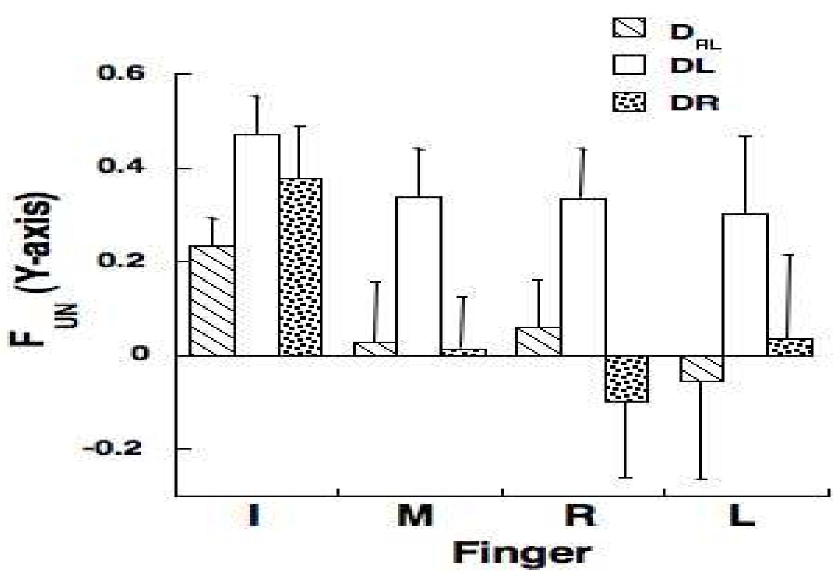

Figure 7: The index of unintended force production F_{UN} within-a-finger along Y axis for the four fingers, in 3 different pressing tasks involving X axis. Averaged values across subjects with standard error bars are shown. For abbreviations see Figure 5.

In contrast, Task-direction had no significant effect on F_{UN} for the *X*-axis. But the *Finger* × *Task-direction* interaction was significant. In addition, the main effect of *Finger* was also significant ($F_{1.2,\ 8.45} = 5.14$, $p < 0.05$). Tukey comparisons of the *Finger* × *Task-direction* interaction showed that F_{UN} in the *X*-direction during DB task was significantly less during the Index finger tasks as compared to the Ring and Little finger tasks. ($p < 0.05$).

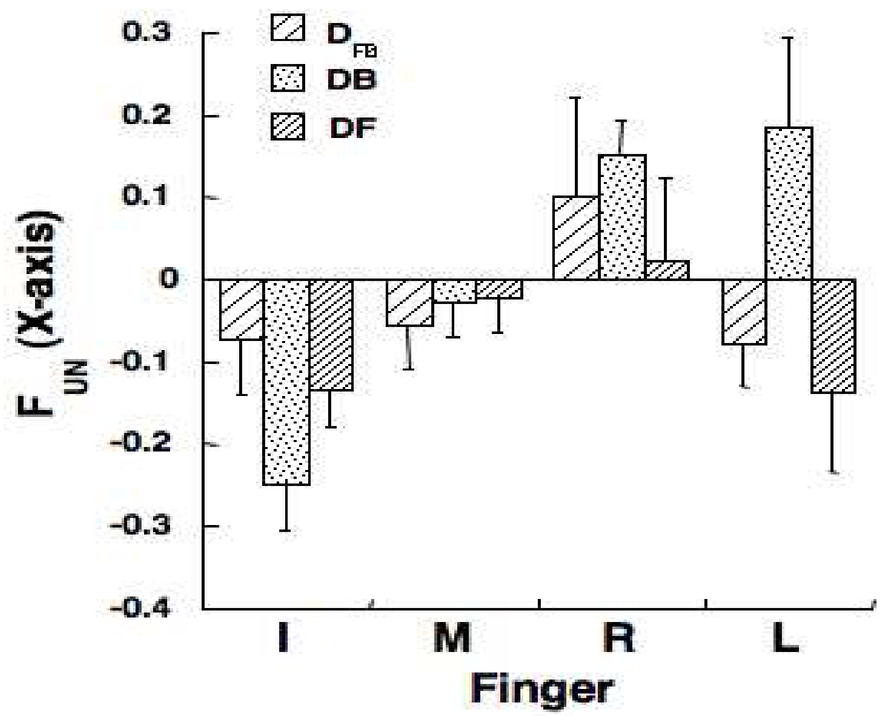

Figure 8: The index of unintended force production FUN within-a-finger along X axis for the four fingers, in 3 different pressing tasks involving Y axis. Averaged values across subjects with standard error bars are shown. For abbreviations see Figure 5.

Analysis of Multi-Finger Synergies

In order to analyze multi-finger synergies stabilizing the total force magnitude and force direction, we used the framework of the uncontrolled manifold (UCM) hypothesis. The variance across trials was measured at each time sample and quantified as two components – V_{UCM} and V_{ORT}. V_{UCM} gave a measure of the variance per DOF, which did not have any effect on the performance variable. V_{ORT} gave a measure of the variance per DOF orthogonal to UCM, which affected the performance variable. A normalized difference between V_{UCM} and V_{ORT}, ΔV was used as the index of synergy. Positive ΔV would indicate a synergy stabilizing the performance variable for which ΔV was quantified, while zero or negative ΔV would mean no such synergy.

Across all the task conditions, V_{UCM} was higher than V_{ORT}, and ΔV was positive for both magnitude and direction of the force vector (Figure 9 and 10). The grand average of ΔV across all conditions was 0.933 for force magnitude stabilization and 0.811 for force direction stabilization. Hence, we conclude that strong multi-finger synergies stabilized both force magnitude and direction.

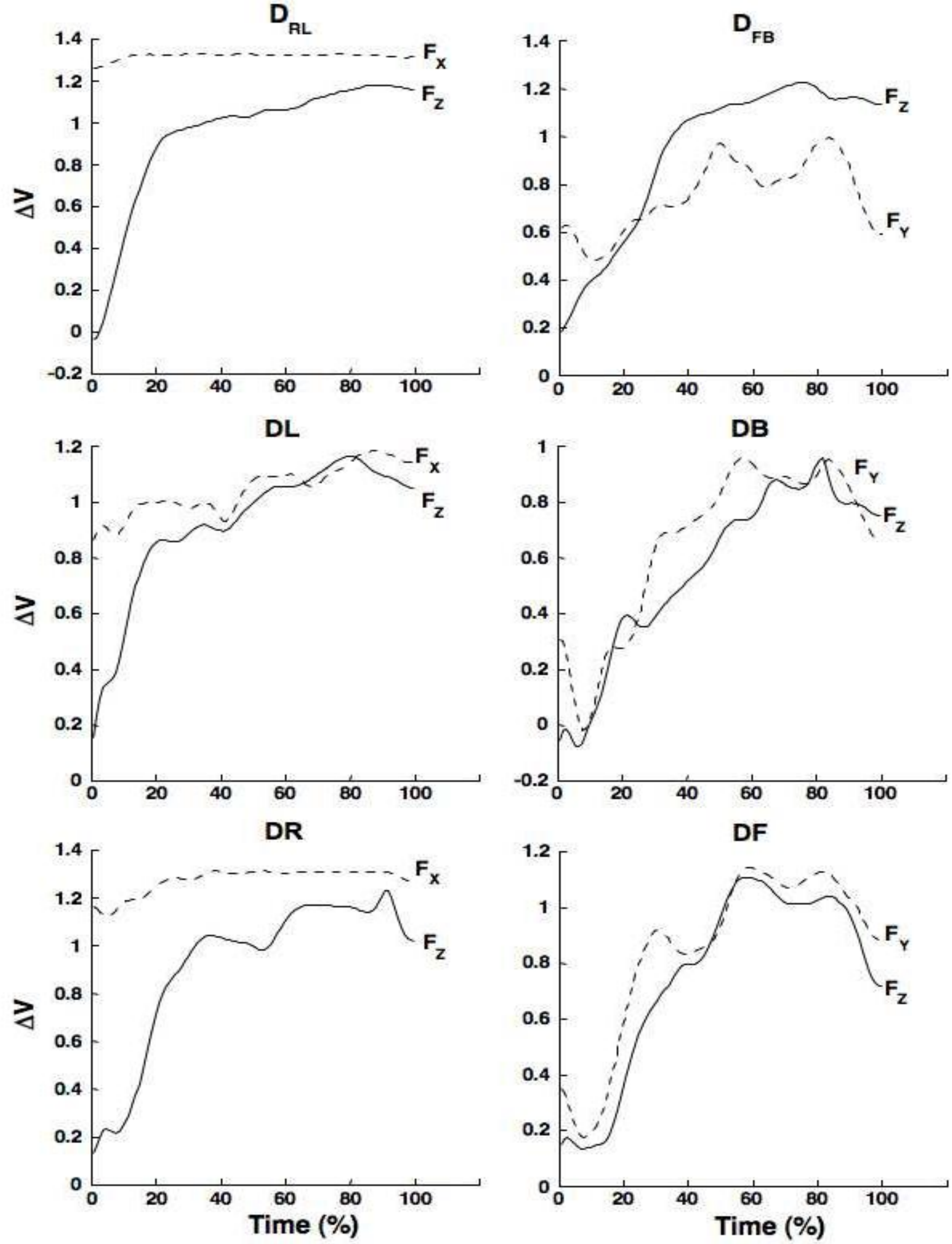

Figure 9: Time changes of the index of multi-finger synergy (ΔV) stabilizing force magnitude for different task conditions and different force directions. Averages across subjects are shown. For abbreviations see Figure 5.

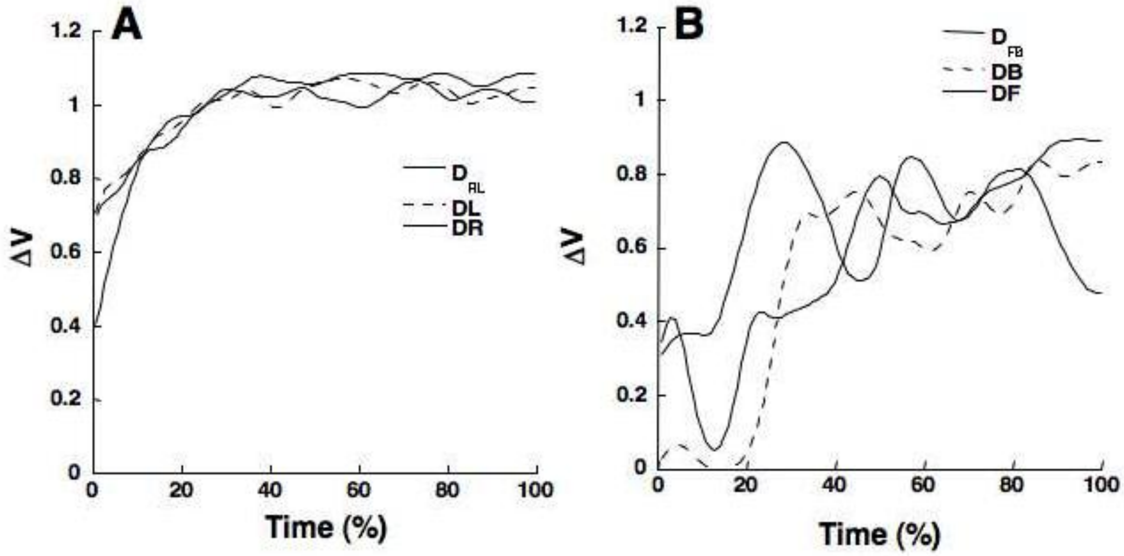

Figure 10: Time changes of the index of multi-finger synergy (ΔV) stabilizing force direction for different task conditions involving force production in the right-left direction (A) and in the forward-backward direction (B). Averages across subjects are shown. For abbreviations see Figure 5.

Force magnitude stabilization

The index of synergy (*ΔV*) showed a dependence on both the task and the axis along which the force magnitude was computed. In addition, the *ΔV* index increased with time early in the trial duration and then reached a plateau.

Two-way ANOVA with repeated measures on z-transformed *ΔV* values averaged over the whole time interval was performed with *Condition* (6 levels, D_{RL}, D_{FB}, DR, DL, DF and DB) and *Axis* (two relevant axes for each condition – *Z* and *X* or *Y*) as factors. There were significant effects of *Condition* ($F_{5,\,77} = 12.50$; $p < 0.0001$) and of *Axis* ($F_{1,\,77} = 19.68$, $p < 0.0001$). Tukey comparisons revealed that *ΔV* was higher for the D_{RL} task as compared to the DL, D_{FB}, DF and

DB tasks. Also it was higher for the DR as compared to the DL, DF and DB tasks. The synergy index was smaller for force components along *Z*-axis as compared to force components along the other relevant axis (*X* or *Y*) ($p < 0.01$).

Time changes in ΔV happened mostly over the first 30% of the task interval: The value of ΔV increased from 0.474 (in the 10% time interval) to 0.873 (in the 30% time interval), with small changes afterwards (the values ranging from 0.93 to 1.11). However, ΔV remained significantly greater than zero throughout the task, right from the task initiation. A two-way ANOVA with repeated measures on z-transformed ΔV values with *Condition* (6 levels) and *Time* (10 levels) as factors was run for ΔV values computed for forces along *Z*-axis. *Condition* had significant effect ($F_{5, 413} = 17.78$, $p < 0.001$ for *Condition*) without a significant *Condition* × *Time* interaction. Tukey's comparisons showed that ΔV was greater for the D_{RL} than for the DB and DF tasks and it was greater for the DR and D_{FB} as compared to the DL, DB and DF tasks ($p < 0.01$).

For ANOVA on z-transformed ΔV values along the other relevant axis (*X* or *Y*), both *Condition* and *Time* had significant main effects ($F_{5,413} = 136.39$, $p < 0.001$ for *Condition*; and $F_{3.22,22.55} = 38.12$, $p < 0.0001$ for *Time*) without a *Condition* × *Time* interaction. Tukey comparisons showed the following order for ΔV values: D_{RL} > DR > DL, D_{FB} > DB, DF ($p < 0.01$).

Force Direction Stabilization

While the subjects, on average, produced force in the instructed direction, individual finger force vectors could point at substantial angles from the required direction. This is illustrated in Figure 9 that shows finger force vectors averaged for one trial direction (task D_{RL}) and then over a set of trials performed by a representative subject. Note the visible deviations of finger force vectors from the required direction (set at 90° in Fig. 11), while total finger force points rather precisely in the task direction. The insert in Fig. 11 shows standard deviations of the force direction computed across trials for the same data set. Note the much smaller standard deviation of the total force vector direction as compared to the standard deviations for the individual finger force directions. Such results were typical of all subjects. This suggests existence of multi-finger synergies stabilizing total force direction, a hypothesis tested using the framework of the UCM hypothesis (see Methods).

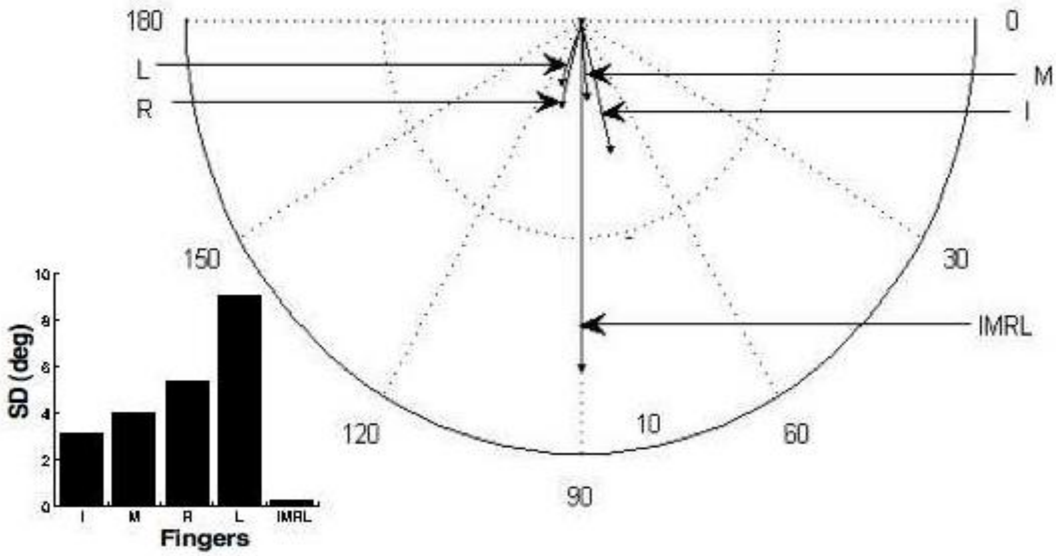

Figure 11: Individual finger force vectors for a typical four-finger trial for the Down with feedback on the X-axis (right-left) force task (D_{RL}) performed by a representative subject. The arrows show the magnitude and the direction of force. The instructed direction corresponds to 90° angle. The insert graph (left, bottom corner) shows standard deviation of force direction computed for the same data set. We used standard deviations rather than circular statistics because of the relatively small variation in the finger force directions. IMRL: total force produced by all four fingers; I, M, R and L: forces produced by the Index, Middle, Ring and Little fingers.

Though the ΔV values computed for force direction were greater than zero for all tasks, they were significantly greater for the tasks involving force production along the *X*-axis than for the tasks involving force production along the *Y*-axis (in addition to *Z*-axis forces). This was supported by one-way ANOVA with repeated measures done on z-transformed ΔV with *Condition* (6 levels, D_{RL}, D_{FB}, DR, DL, DF and DB) as the factor (main effect, $F_{5,35} = 21.47$, $p < 0.0001$). Tukey comparisons revealed that ΔV values for force direction stabilization for D_{RL}, DL and DR conditions were significantly greater than that for D_{FB}, DF and DB without differences within each of the two groups of tasks.

The value of ΔV gradually increased at the beginning of the task (from 0.496 in the 10% time interval to 0.828 in the 30% time interval), with small changes afterwards (ΔV ranging from 0.82 to 0.91). A two-way ANOVA with repeated measures on z-transformed ΔV values with *Condition* (6 levels) and *Time* (10 levels) as factors showed significant effects of both factors ($F_{5,413} = 86.46$, $p < 0.0001$ for *Condition*; and $F_{3.34,23.37} = 56.485$, $p < 0.0001$ for *Time*) without an interaction. The value of ΔV increased significantly from the 10% time interval to the 30% time interval ($p < 0.0005$), but the changes after 30% time interval were not statistically significant.

4.6 Discussion

Two main hypotheses were tested in the experiments. The first was that shear force components may show features such as unintended force produced by a non-task finger in the direction opposite to the instructed force and also unintended force in a direction orthogonal to the instructed direction. The second hypothesis was that strong multi-finger synergies would be observed stabilizing both magnitude and direction of the total force vector. Both of these hypotheses have been supported by the findings. In particular, we observed strong multi-finger synergies stabilizing both magnitude of the total force (as in Latash et al. 2002a; Shim et al. 2005) and direction (as could be expected based on an earlier study by Gao et al. 2005). This study is the first to show simultaneous stabilization of force magnitude and direction. It is also the first to document force magnitude and direction stabilizing synergies for shear forces. Indices of involuntary force production showed more complex patterns as compared to earlier reports on finger interdependence during pressing tasks (Li et al. 1998a; Zatsiorsky et al. 1998, 2000). In particular, intentional force production by a finger parallel to the surface of contact could result in unintentional force production by other fingers in the same or in the opposite direction (cf. Pataky et al. 2007). Further, we discuss implications of these and other findings for issues of finger interaction and stabilization of combined finger action in everyday tasks.

Finger Force Interdependence in Three Dimensions

Limitations in the control of individual fingers has been studied in both movement and force production tasks (Schieber 1991; Kilbreath and Gandevia 1994; Li et al. 1998a, 2004; Zatsiorsky et al. 2000; Shim et al. 2007; Ingram et al. 2008). In all these studies, finger motion or force production in a given direction was accompanied by unintentional motion (or force production) by other digits of the hand. Kinematic and kinetic variables were linked in a study showing that motion of a finger is accompanied by force production by other fingers of the hand if they are acting against a stop (Kim et al. 2006). All the mentioned studies reported regular features of these phenomena addressed as enslaving, enslavement, or lack of individuation. In particular, higher enslaving (lower individuation) was reported for fingers that are anatomical neighbors of the task finger as compared to more distant fingers of the hand. The index finger was reported to be most independent while the ring finger typically showed highest enslaving indices.

These phenomena have been discussed as resulting from two groups of factors (reviewed in Schieber and Santello 2007). The first group includes anatomical links among the fingers provided by connective tissues and multi-digit extrinsic muscles with several compartments (Kilbreath and Gandevia 1994; Leijsne et al. 1993, 2008). The second group involves the neural organization of the control of the hand including the overlapping cortical projections of the digits (Rouiller 1996; Latash et al. 2002b; Reilly and Hammond 2006; Schieber et al 2009).

In our study, enslaving showed more complex patterns for the non-vertical force vector components. In particular, **E** matrices along the *X* and *Y* axes contained a substantial number of negative entries (Table 3). Note that the values in Table 3 are out of 12 non-diagonal entries (the diagonal entries of the 4×4 matrices are, by definition, +1). So, the average values of about 5 out of 12 suggest that nearly 50% of the forces produced by the non-task fingers were directed opposite to the force produced by the task finger. These observations cannot be easily explained by peripheral factors such as multi-finger muscles and connective tissue links. They very strongly favor a neural factor playing a dominant role in the finger force interdependence patterns.

Asymmetry of enslaving indices has been reported by Shim et al. (2007) who studied finger force production into flexion and into extension. In particular, Shim and colleagues documented higher enslaving indices in extension tasks. In our experiments, significant asymmetry of the enslaving index ($|E|$) was seen in the left-right direction but not in the forward-backward direction (Table 4). This result is in contrast to a study by Pataky et al. (2007) who reported no asymmetry in MVC tasks involving radial and ulnar finger deviation efforts. Note, however, that in the experiment by Pataky and colleagues the fingers were placed in rigid slots such that radial-ulnar efforts could be produced without a change in the downward force. In our experiments, this was impossible: The downward pressing force had to be sufficient to allow the production of shear forces given the friction. Besides, we studied sub-maximal force production in contrast to the cited Pataky study.

As mentioned earlier, most studies reported highest enslaving indices for the ring finger and lowest indices for the index finger. This result was also confirmed in the study of maximal ulnar and radial efforts (Pataky et al. 2007). In our study, we analyzed the enslaving matrix in more detail and quantified separately two indices: E_j – how strongly a finger enslaves other fingers and E_i – how strongly a finger is enslaved by other fingers. The results were similar to the ones mentioned in the earlier studies for the former index but not for the latter. Indeed, the index finger induced the least enslaving in other fingers reflected by the smallest E_j, while the ring and the little fingers showed the highest E_j values. However, the finger that was least enslaved by other fingers was the little finger, while the three other fingers showed similar E_i indices. These results suggest that enslaving is a more complex phenomenon than previously thought, and reducing it to a single index may be too crude for meaningful analysis.

The complex pattern of unintentional force production suggests an interaction of at least two factors, enslaving and synergic effects. Both factors are expected to lead to co-varied forces in digits that are and are not instructed to produce force. Synergic effects in multi-digit prehensile tasks have been discussed with respect to stabilization of the combined digit action on the hand-held object (Santello and Soechting 2000; reviewed in Zatsiorsky and Latash 2008; Latash and Zatsiorsky 2009). In our one-finger tasks, we did not ask the subjects to stabilize any variable produced by all the fingers together. However, it is possible that the central nervous system tried to bring such variables as the total shear force and the total moment of force acting on the hand to zero without any explicit instruction (cf. the principle of minimization of secondary moments, Li et al. 1998a, 2000). Synergic effects related to stabilization of the mentioned variables may be hidden in the computed enslaving matrices (contributing, in particular, to the large number of negative entries) and to large force changes produced by the strongest and most independent finger such as the index finger when another finger performed the task. Taken together, our results suggest that both enslaving and synergic effects play a major role in defining patterns of unintentional force production.

Unintended Force Production Orthogonal to the Task Direction

To our knowledge, only one study reported unintentional force components orthogonal to the direction of the required action (Pataky et al. 2007). In that study, downward pressing tasks were associated with force vectors that deviated from the vertical direction, on average, by about 8°. Much larger deviations were observed for force production tasks in the radial-ulnar direction (right-left), by over 20°. These phenomena were seen both in task fingers and in non-task (enslaved) fingers. The authors of that study introduced the notion of “preferred direction” and tried to link it to the anatomical architecture of tendon attachments resulting in certain directions of muscle lines of action (Li et al. 2005).

We would like to emphasize a few features of unintended force production orthogonal to the intended action (F_{UN}) found in our experiments. Unexpectedly, the index finger, which has been described as most independent and best controlled (Zatsiorsky et al. 2000; Shim et al. 2007; Gorniak et al. 2008), produced the largest F_{UN} along the *Y*-axis (forward-backward direction). In contrast, along the *X*-axis (left-right), the index finger showed the smallest F_{UN} values. These results cannot be easily mapped on the hand muscle anatomy. Rather, they may be related to everyday function of the human hand, in particular to the different roles of the fingers in prehensile tasks involving holding a load and simultaneously counteracting an external torque (Zatsiorsky et al. 2003a,b).It should be noted however that the constraints of this task, in particular the requirement to keep all fingers on the transducers, and the horizontal placement of the force transducers, may limit its applicability to more ecological situations where these constraints are not found.

Accuracy of Performance and Multi-Finger Synergies

Some of our results on directional force vector errors are expected and some are unexpected. On the one hand, the observations of smaller directional errors in four-finger tasks as compared to one-finger tasks are in line with the earlier publication by Gao et al. (2005) and with a general observation that motor redundancy helps produce more accurate performance (Latash et al. 2001; Sosnoff et al. 2005; reviewed in Latash et al. 2007). On the other hand, we did not find differences among the one-finger tasks. In fact, the index finger that was expected to be most accurate showed, on average, larger directional errors as compared to the other three fingers, although the differences were not statistically significant. Note that Vaillancourt et al.

(2002) described a negative correlation between the degree of inter-digit individuation and force variability. Based on these results, we expected the most independent index finger to be most accurate. This was not the case, at least not with respect to directional accuracy.

Analysis of multi-finger synergies performed within the framework of the UCM hypothesis showed very strong synergies in the space of finger modes (Latash et al. 2001; Danion et al. 2003) that stabilized both the magnitude and direction of the total force vector. In other words, variance in the space of finger modes was consistently higher within the sub-space (UCM) compatible with the average across trials magnitude and direction of the force vector as compared to the sub-space that led to changes in these variables.

The observation of strong force amplitude stabilizing synergies is not novel (reviewed in Latash et al. 2007; Latash and Zatsiorsky 2009), although earlier studies addressed only magnitude of the pressing force, normal to the surface of contact. Our observations show that such synergies exist for shear force components too. Indeed, the index of synergy (ΔV) was significantly higher for the shear force components as compared to the normal force component.

To our knowledge, this study is the first to apply the framework of the UCM hypothesis to analysis of force vector direction. The values of ΔV were highly positive across all tasks showing that individual finger force vectors co-varied across trials such that direction of the resultant force vector showed relatively low variance as compared to what could be expected without such co-variation. We found higher synergy indices stabilizing force vector direction in tasks that involved force production in the ulnar-radial (left-right) direction as compared to tasks involving force production in the forward-backward direction. This observation may be a consequence of practicing typical everyday tasks, such as taking a drink from a glass, that require accurate control of the moment of force in the plane of digit contacts. Note that this moment of force gets significant contribution from shear forces in the ulnar-radial direction.

Both synergy indices, computed for force vector magnitude and for force vector direction, showed similar time profiles: They both started with relatively low (although significantly positive!) values, these values increased over the first one-third of movement time and then reached a plateau. These results are similar to earlier reports on time profiles of synergy indices during multi-finger pressing tasks that required accurate ramp force production (Shim et al. 2003, 2005). In earlier studies, such results were interpreted as suggesting that the relative amount of variance parallel to the UCM increases with the total force magnitude. However, this explanation obviously does not work with respect to force vector direction, which remained constant over the trial duration. So, time from the trial initiation may be a more important factor defining the synergy index magnitude as suggested in earlier studies of multi-finger synergies (Shim et al. 2003, 2005).

Implications for Finger Coordination in Prehensile Tasks

The human hand is an amazingly versatile instrument for object manipulation. It is feasible that, during the lifetime, the central nervous system develops control mechanisms that use a handful of parameters to tune the descending signals to adjust hand action to such commonly varied characteristics of external objects as mass, friction, and external torque (Schieber and Santello 2004; Latash et al. 2010). This may be done, in particular, by uniting distributed sets of cortical neurons into functional groups (Poliakov and Schieber 1999; Schieber and Santello 2004). Patterns of peripheral variables recorded in experiments are reflective of both the specific experimental tasks and the pre-existent coupling patterns defined by neural adaptations to common everyday tasks.

In our experiment, despite the non-involvement of the thumb, the observed patterns of finger interaction could be defined by the experience with everyday prehensile tasks. In particular, a recent study has shown that shear finger forces co-vary negatively across trials to stabilize the total shear force applied to the hand-held object (Gorniak et al. 2009). Such synergic mechanism could contribute to the apparent negative enslaving observed in our experiments with shear force production. Earlier, a hypothesis was suggested that the rotational action of the hand could be stabilized by pointing the vectors of individual finger forces at the point of the thumb contact (Li et al. 1998b). This obviously requires the shear forces of the radial fingers to be directed against the shear forces of the ulnar fingers potentially contributing to the apparently negative enslaving indices.

Another major phenomenon typical of object manipulation is the load-grip force coupling documented in many studies (Johansson and Westling 1984; Flanagan and Wing 1993; Gysin et al. 2003; Jaric et al. 2005). This mechanism allows to produce feed-forward grip force adjustments to ensure adequate friction to expected shear force changes during object manipulation. The proportional shear and normal force changes typical of the load-grip force coupling might have contributed to the very high indices of multi-finger synergies stabilizing force vector direction in our experiments. Neural mechanisms responsible for such scaling could be reflected in the documented synchronizarion of motor units across muscles involved in different finger actions (Santello and Fuglevand 2004; Winges et al. 2008; Johnston et al. 2009).

To summarize, this study reports, for the first time, indices of unintentional finger forces during one-finger tasks involving force production in all three dimensions. We also report, for the first time, indices of multi-finger synergies stabilizing force vector magnitude and direction in four-finger accurate force production tasks in three dimensions. The results suggest that synergic force adjustments, likely conditioned by everyday experience with prehensile tasks, play a major role in indices of finger force interaction quantified in experiments.

CHAPTER – 5

AGE RELATED CHANGES IN THE FINGER FORCE INTERACTIONS

5.1 Introduction

Aging leads to changes at the neural level and muscular level. One consequence is high motor variability. It was mostly studied in one-element task such as, for example, index finger abduction. Multi-element tasks allow less variable performance even if elements are highly variable.

Many tasks require accurate production not only of force magnitude but also of force direction. Recently, we quantified performance of young healthy subjects in one-finger and multi-finger tasks that required accurate force production. Those studies documented and quantified multi-finger synergies stabilizing force vector direction. They also introduced a novel index for unintentional force production in directions orthogonal to the instructed direction.

Earlier studies of finger interaction showed that aging is associated with changes in enslaving and in indices of multi-finger synergies stabilizing force and moment of force. These studies have been limited to one direction of force production, normal to the contact surface.

The goal of this study was to extend the analysis of indices of finger interaction and multi-finger synergies to three-dimensional tasks. At this stage, we limited the study to pressing tasks, which allow to standardize tasks and quantify finger force components in three directions.

Based on earlier studies, we hypothesized that elderly participants will show lower enslaving not only for normal forces but also for shear forces. We also hypothesized that the similar Fun phenomenon will also be lower in elderly. We expected the elderly to be less accurate in both force magnitude and direction. We expected the higher motor variability to be associated with lower indices of synergies stabilizing those variables.

5.2 Participants

Eight elderly subjects (four males and four females) volunteered to participate in the study. Their age was 76.4 ± 2.5 years (mean ± standard deviation), height 166.69 ± 13.58 cm, weight 159.5 ± 34.8 lbs, hand length from the proximal palmar crease to the tip of the middle finger, 18.84 ± 2.36 cm and hand width, at the level of metacarpal heads, 8.33 ± 0.84 cm. All subjects were healthy, right-handed according to their hand usage during writing and eating, and none of them had any diagnosed neurological or peripheral musculoskeletal pathology that could significantly affect the right hand function. None of them reported to had been professionally engaged in any activity that might affect hand dexterity (such as being a professional typist or piano player). The elderly subjects were recruited from a local retirement community and passed a screening process that involved a cognition test (mini-mental status exam ≥ 24 points), a depression test (Beck depression inventory ≤ 20 points), a quantitative sensory test (monofilaments ≤ 3.22) and a general neurological examination. Prior to the study, all subjects gave informed consent according to the procedures approved by the Office for Research Protections of The Pennsylvania State University.

5.3 Methods

The methods have been explained in the chapter on Common Methodology (Chapter – 3). This chapter presents the original data collected in the group of elderly participants. We compare this data with the data from the study of young, healthy participants (Kapur et al 2010). The Young study used the same numbers of male and female subjects, the same set-up, and the same methods of data processing. The only difference was in a larger number of conditions (trials) performed by the young participants. In the Elderly study, we reduced the number of conditions to ensure that no fatigue effects happened in the elderly participants who are known to be more fatigueable as compared to younger persons (Luff, 1998). Only three conditions – D_{RL}, DL and DB were used in the Elderly study. The particular conditions were selected to be able to explore age-related changes in the significant effects that were seen across the conditions in the young participants.

5.4 Statistics

For all the repeated measures ANOVAs, the assumptions of sphericity were checked using Mauchly' sphericity test. We used the Greenhouse-Geisser epsilon corrections wherever the assumption of sphericity was violated. *Group* was a between subject factor while others were within subject factors.

To explore the effects on aging on MVC produced by the subjects, we did repeated measures two-way ANOVA on MVC with *Group* (Elderly, E and Young, Y) and *Finger* (I, M, R, L, IMRL) as factors.

To explore the effects of aging on differences in performance between one-finger and four-finger pressing tasks, three-way ANOVA with repeated measures was done on the *RMS* errors of the force vector angle with *Group* (E and Y), *Finger* (I, M, R, L, IMRL) and *Condition* (D_{RL}, DL and DB) as factors. Two similar ANOVAs were run on the *RMS* errors of force magnitude in *Z* direction and for *RMS* errors of force magnitude in non-*Z* direction. In these ANOVAs, only the first three trials of the four-finger tasks were included to avoid any effects of practice.

To explore the trend of E_j and E_i across different groups, fingers and conditions, three-way ANOVAs with repeated measures were done with *Group* (E and Y), *Finger* (I, M, R, L) and *Condition* (3 levels –D_{RL}, DL and DB) as factors.

Another three-way ANOVA with repeated measures was done on the index of unintended force production in the non-instructed direction (F_{UN}) with factors *Group* (E and Y), *Finger* (I, M, R, L) and *Condition* (3 levels –D_{RL}, DL and DB), to explore the effects of aging on F_{UN}.

For comparing the synergies stabilizing force direction in the two subject groups, three-way ANOVA was done on ΔV with *Group* (E and Y), *Condition* (3 levels –D_{RL}, DL and DB) and *Time* (10 levels: 10%, 20%, 30%, 40% , 50%, 60%, 70%, 80%, 90% and 100%) as factors. To test the effect of aging on the synergies stabilizing force magnitude, three way ANOVA was done on ΔV with *Group* (E and Y) and *Condition* (3 levels –D_{RL}, DL and DB) and *Axis* (*Z* and non-*Z*) as factors. To compare the trend of ΔV across time in the two subject groups, another three-way ANOVA was run on ΔV with *Group* (E and Y), *Axis* (*Z* and non *Z*) and *Time* (10 levels: 10%, 20%, 30%, 40% , 50%, 60%, 70%, 80%, 90% and 100%) as factors.

To explore the effects of aging on variance in force magnitude in the two subspaces (V_{UCM} and V_{ORT}), three-way ANOVA with repeated-measures was done on V_{UCM} for magnitude with the factors- *Group* (E and Y) , *Axis* (*Z* and non *Z*) and *Condition* (D_{RL}, DL and DB). A similar ANOVA was done for V_{ORT}.

To explore the effects of aging on variance in force direction in the two subspaces (V_{UCM} and V_{ORT}), a three way ANOVA was run on the two components of Variance computed for force direction stabilization with the factors- *Group* (E and Y), *Variance* (V_{UCM} and V_{ORT}) and *Condition* (D_{RL}, DL and DB).

Significant effects were further explored with Tukey's pairwise comparisons. The level of significance was set at $p < 0.05$.

5.5 Results

<u>Maximal Force Production</u>

Maximal voluntary contraction (MVC) force along *Z* axis was recorded for each of the individual fingers and for the IMRL task. MVC values for Elderly were lower as compared to Young, though the difference was significant only for the IMRL task (see Figure 12). This was confirmed using a two-way ANOVA with *Group* (Elderly, E and Young, Y) and *Finger* (I, M, R, L, IMRL) as factors. *Finger* had a significant main effect ($F_{1.42,\ 19.92} = 91.3$, $p < 0.0001$). Also, *Group* and *Finger* interaction was significant ($F_{4,56} = 6.53$, $p < 0.001$). Tukey comparison revealed that MVC was significantly less for Elderly as compared to Young for the IMRL tasks ($p < 0.05$). However, the MVC was not significantly different between the two groups for the individual finger tasks.

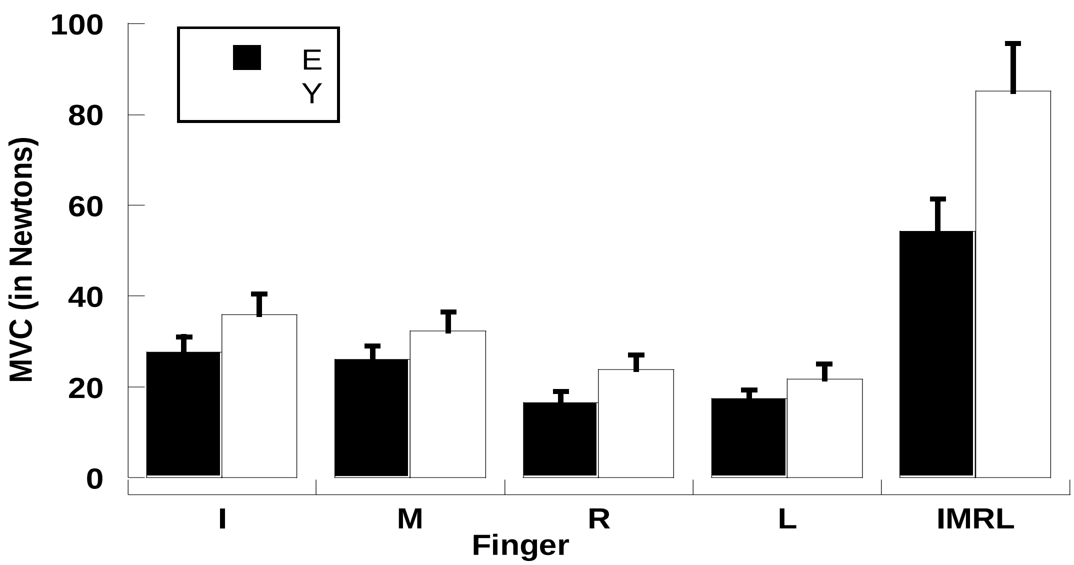

Figure 12: MVC for one finger and IMRL tasks for elderly and young.

Values have been averaged across all subjects (with standard error bars). I: Index, M: Middle, R: Ring, L: Little, IMRL: Four-finger task.

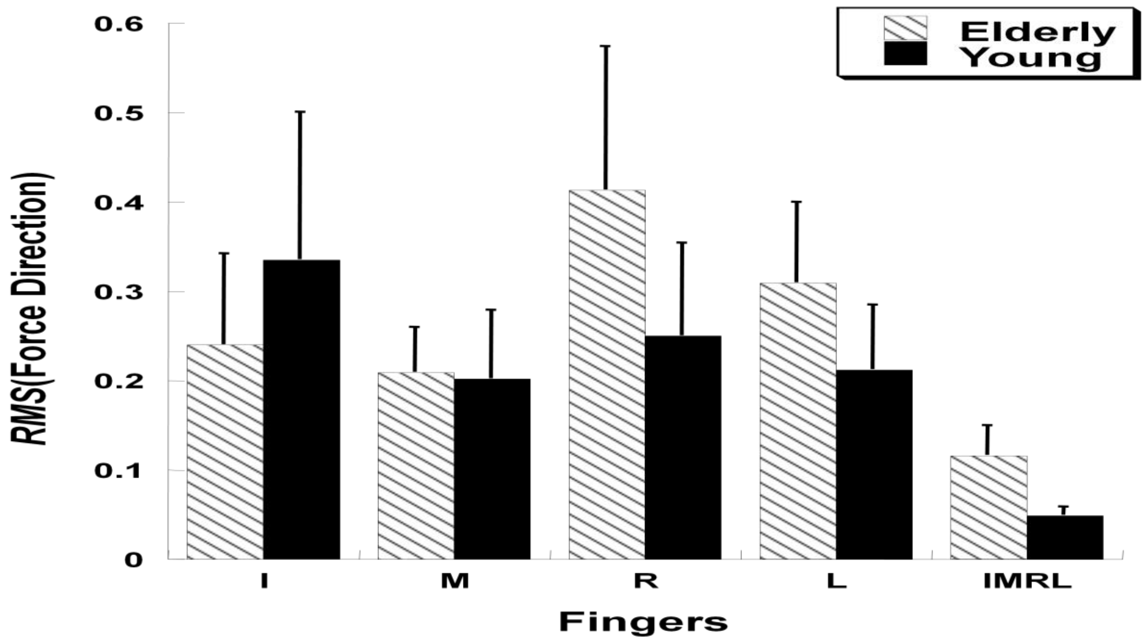

Figure 13A: *RMS* error of force direction for one-finger and IMRL tasks.
Values have been averaged across all subjects (with standard error bars). I: Index, M: Middle, R: Ring, L: Little, IMRL: Four-finger task.

Accuracy of Performance

To study how accurately the subjects followed the task direction of force, *RMS* of force vector angle was computed with respect to the task force direction for both one-finger and four-finger tasks over time. The *RMS* indices were averaged across trials for each subject, and then compared across the two groups and tasks. Directional errors were less for IMRL tasks as compared to the one-finger tasks for both Young and Elderly, as shown in Figure 13A. The trend across different conditions was also similar for Elderly and Young as illustrated in Figure 13B.

This was confirmed by a three-way ANOVA with repeated-measures on the *RMS* errors of the force vector angle with *Group* (E and Y), *Finger* (I, M, R, L, IMRL) and *Condition* (D_{RL}, DL and DB) as factors. There was a significant main effect of *Condition* and *Finger* ($F_{2,28} = 7.93$, $p < 0.01$ for *Condition*; $F_{2.29,32.12} = 3.89$, $p < 0.05$ for *Finger*). Neither *Group* effect nor any of the interactions were significant. The effect of finger reflected lower *RMS* errors for the IMRL task as compared to one-finger tasks. The differences were significant between IMRL and I, R and L fingers ($p < 0.05$). This was consistent in both Elderly and Young. Also, the *RMS* error was larger for DB condition than for D_{RL} ($p < 0.05$). The trend of *RMS* error for force direction was similar in Elderly and Young, both across conditions and across fingers.

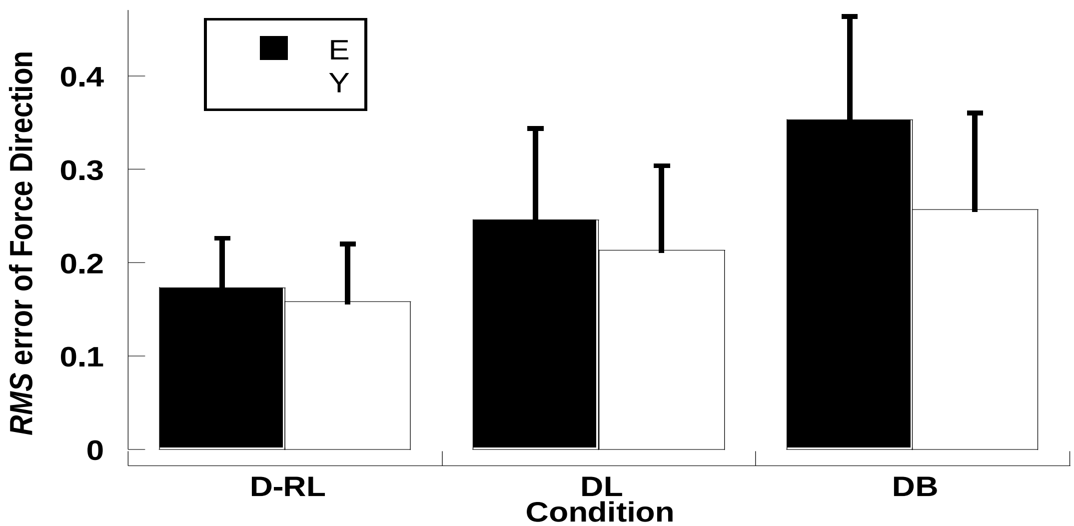

Figure 13 B: *RMS* error of force direction for different conditions.

Values have been averaged across all subjects (with standard error bars). D_{RL}: Down – feedback on the right-left force changes, DL: Down left, DB: Down backward.

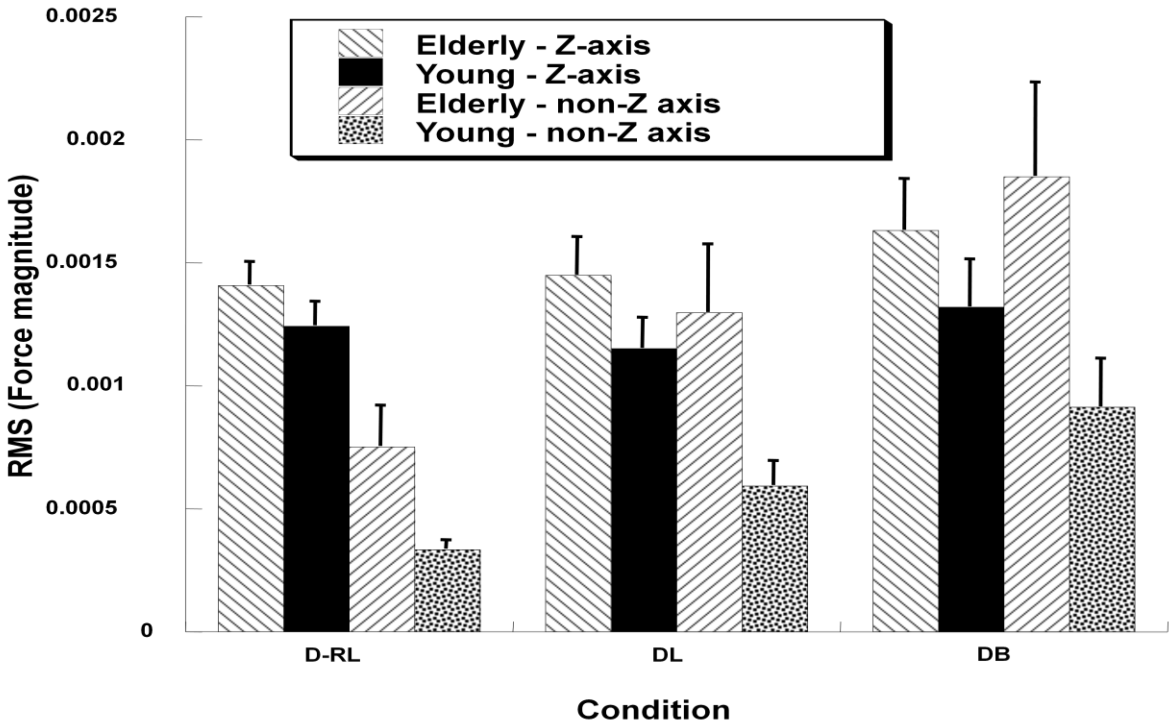

Figure 14: RMS error of Force magnitude for different conditions.

Values have been averaged across all subjects (with standard error bars). D_{RL}: Down – feedback on the right-left force changes, DL: Down left, DB: Down backward.

RMS error of force magnitude along *Z* axis was similar between the IMRL and one-finger tasks. In Figure 14, *RMS* error of force magnitude along *Z* axis and along non *Z* axis is shown for different conditions for both Elderly and Young. Note the similar *RMS* indices for both Elderly and Young for accuracy of downward force magnitude. However, the *RMS* indices of shear force magnitude were larger for Elderly across all the conditions. Also, *RMS* indices of both downward and shear force magnitude were larger for DB condition as compared to the other two conditions, for both Elderly and Young.

A three-way ANOVA with repeated-measures was done on the *RMS* errors of the force magnitude along *Z* axis with *Group* (E and Y), *Finger* (I, M, R, L, IMRL) and *Condition* (D_{RL}, DL and DB) as factors. *Condition* had a significant main effect ($F_{2,28} = 5.21$, $p < 0.05$). Tukey's comparisons revealed that *RMS* error was greater for the DB condition as compared to the D_{RL} and DL conditions ($p < 0.05$). None of the other factor effects or interactions was significant. Thus both Elderly and Young had similar trend of *RMS* error of the force magnitude along *Z* axis across conditions (see Figure 14). Though the main effect of *Group* approached significance ($F_{1,14} = 4.16$, $p = 0.06$), with *RMS* errors greater for Elderly than for Young group.

ANOVA done on *RMS* error of the force magnitude along non-*Z* axis revealed that both *Group* and *Condition* had a significant main effect ($F_{1,14} = 9.74$, $p < 0.01$ for *Group*; $F_{1.15,16.22} = 30.08$, $p < 0.001$ for *Condition*). *RMS* error of Force magnitude along the non-*Z* axes was greater for the Elderly as compared to the Young group ($p < 0.01$). Tukey comparison revealed that, for both Young and Elderly, *RMS* error was greater for the DB condition as compared to the D_{RL} and DL ($p<0.05$).

<u>Indices of Finger Interaction</u>

Enslaving

Enslaving across fingers was defined as the involuntary force production by non-task fingers. For each condition, enslaving matrices (**E**) and indices of enslaving, |E|, were calculated separately for the forces produced along the three axes (see Methods). To compute entries of the **E** matrix, the forces produced by non-instructed fingers were regressed on the force produced by the task finger over the whole trial duration. Different columns correspond to different task fingers and different rows correspond to different enslaved fingers. A typical **E** matrix along *Z*-axis for the DB task for a typical elderly subject looked as follows:

$$\begin{bmatrix} 1.0000 & 0.1120 & 0.3424 & 0.0764 \\ 0.0357 & 1.0000 & 0.7450 & 0.0192 \\ 0.0342 & 0.1390 & 1.0000 & 0.1239 \\ 0.0001 & 0.0388 & 0.4787 & 1.0000 \end{bmatrix}$$

It should be noted that this matrix is strongly non-symmetric, i.e. there are large differences between indices of how a finger enslaves another finger and how it is enslaved by that finger.

Enslaving matrices along non-*Z* axis could have negative entries meaning that non-task fingers produced force in a direction opposite to the force produced by the task finger. Here follows an example of the **E** matrix along the *X*-axis for the DL task (a typical elderly subject):

$$\begin{bmatrix} 1.0000 & -0.0501 & -0.3361 & -0.3416 \\ 0.1451 & 1.0000 & -0.2039 & -0.3712 \\ 0.0611 & 0.2971 & 1.0000 & -0.1497 \\ -0.0959 & 0.0652 & 0.2051 & 1.0000 \end{bmatrix}$$

The number of negative entries found in the **E** matrices across the non-D force production tasks was similar for the Elderly and Young groups. It was 5.1 ± 1.8 (mean ± standard deviation) for Elderly and 5 ± 1.2 for Young. Thus, there were on an average 5 negative entries (out of the 12 non diagonal entries) in both Elderly and Young.

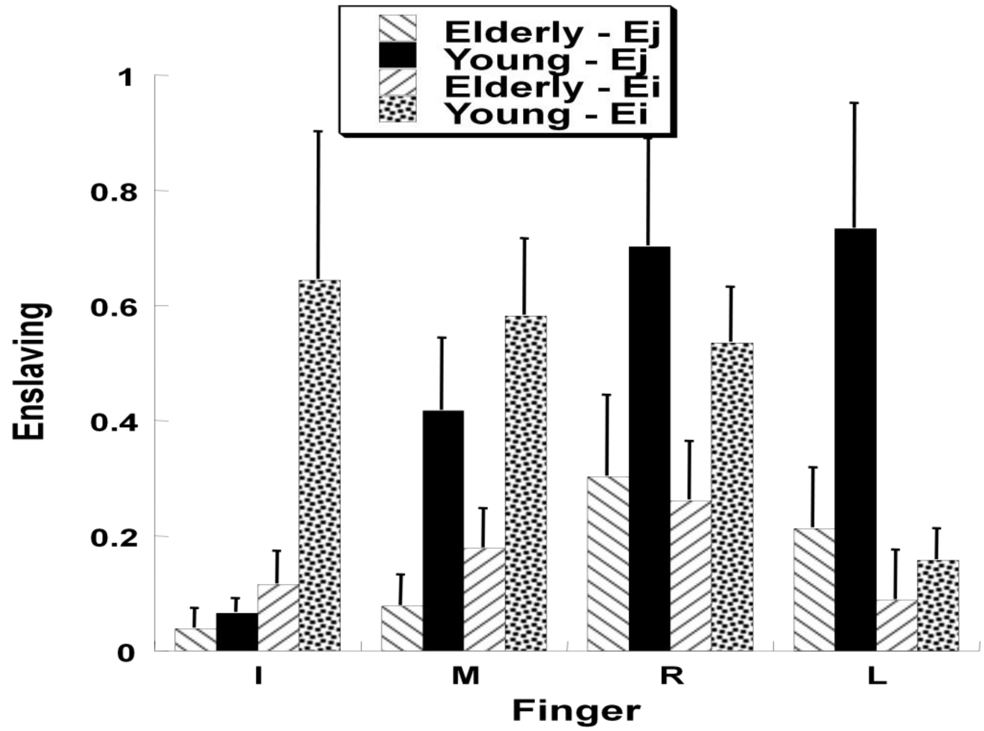

Figure 15: Enslaving Indices (Ej and Ei) for Elderly and Young.

Values have been averaged across all subjects and across all conditions (with standard error bars). I: Index, M: Middle, R: Ring, L: Little, IMRL: Four-finger task.

E_j was used as the measure of how a finger enslaves the other fingers in the Z-direction (it is the sum of entries over a column of the **E** matrix minus 1). E_i was used as a measure of how a finger is enslaved by other fingers in *Z*-direction (it is the sum of entries over a row of the **E** matrix minus 1). Figure 15 illustrates that both the indices of Enslaving, E_j and E_i were lesser for Elderly as compared to Young. Note that this trend was consistent across all the fingers. A three-way ANOVA with repeated measures done on E_j with *Group*, *Finger* (I, M, R, L) and *Condition* as factors confirmed this. Both *Group* and *Finger* showed significant effects ($F_{1,14}$ = 5.67, p < 0.05 for *Group*; $F_{3,42}$ = 12.04, p< 0.001 for *Finger*). Also, the interaction between *Finger* and *Condition* was significant ($F_{2,84}$ = 2.45, p < 0.05). Neither *Condition* nor any of the other interaction effects were significant. Thus, E_j was smaller for Elderly as compared to Young and this was consistent across all the fingers and conditions. Also, Tukey's comparisons revealed that E_j was less for the Index and Middle finger as compared to the Ring and Little finger ($p < 0.05$).

A similar ANOVA was done on E_i. Both *Group* and *Finger* had significant effects ($F_{1,14} = 5.67$, $p < 0.05$ for *Group*; $F_{3,42} = 5.96$, $p < 0.01$ for *Finger*). Also, the interaction between *Group* and *Finger* was significant ($F_{3,42} = 2.96$, $p < 0.05$). Neither *Condition* effect nor any of the other interactions was significant. E_i was smaller for Elderly as compared to Young and this was consistent across all the conditions. Tukey's comparisons revealed that E_i was less for Elderly as compared to Young only for I and M finger. ($p < 0.05$). Also, E_i was least for Little finger as compared to other fingers ($p < 0.05$), and this was consistent across both Elderly and Young.

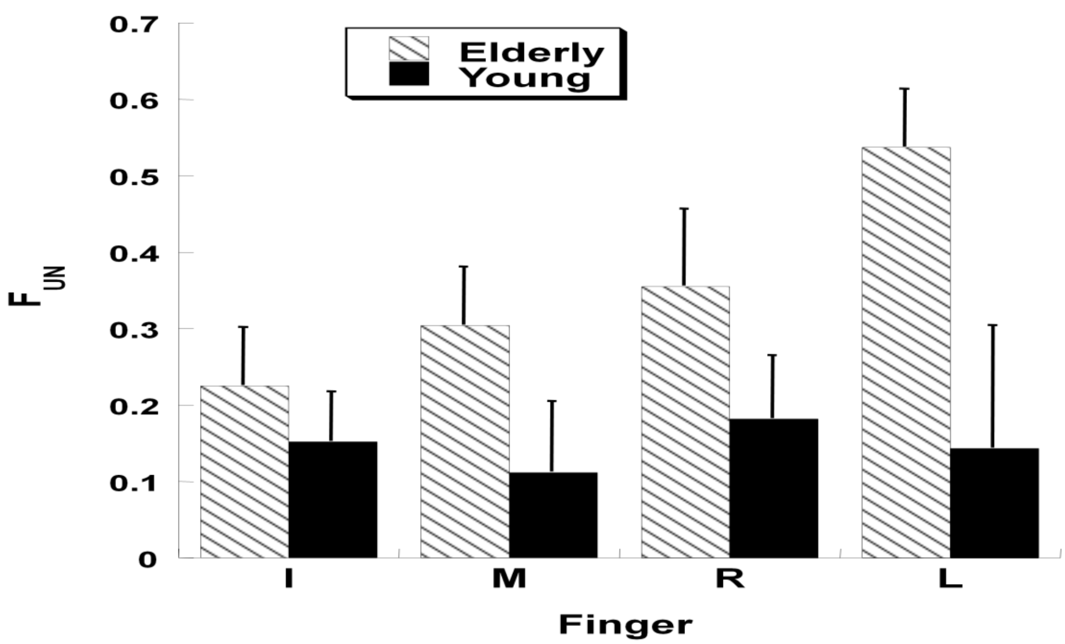

Figure 16 A: Unintended Force Production (F_{UN}) by different fingers for Elderly and Young. Values have been averaged across all subjects (with standard error bars). I: Index, M: Middle, R: Ring, L: Little, IMRL: Four-finger task.

Unintended force production by a finger across directions

An index of unintended force production in a direction orthogonal to the instructed direction, F_{UN} was defined as a measure of the amount of force produced by the task finger in a non-instructed direction (X or Y) while pressing downward (along the Z axis). In Figure 16, unintended force production by different fingers is shown for different fingers (in Figure 16A) and for different conditions (in Figure 16B). Note the greater magnitude of F_{UN} for Elderly as compared to Young. This was tested using a three-way ANOVA on F_{UN} with factors *Group*, *Finger* (I, M, R, L) and *Condition*. *Group* and *Condition* had significant main effects ($F_{1,14} = 7.23$, $p < 0.05$ for *Group* ; $F_{2,28} = 26.66$, $p < 0.0001$ for *Condition*). Effect of *Finger* was close to significant ($F_{1.92,\ 26.98} = 3.20$, $p = 0.05$). Also, all the two-factor interactions were significant ($F_{3,42} = 3.07$, $p < 0.05$ for *Group* x *Finger*; $F_{2,28} = 10.11$, $p < 0.001$ for *Group* x *Condition*; $F_{6,84} = 8.88$, $p < 0.0001$ for *Finger* x *Condition*). Overall, Elderly had higher F_{UN} as compared to Young. Among conditions, F_{UN} was least for DB, for both Elderly and Young. Tukey's comparisons revealed that Elderly had higher F_{UN} as compared to Young only for the D_{RL} condition and for the Little finger ($p < 0.05$).

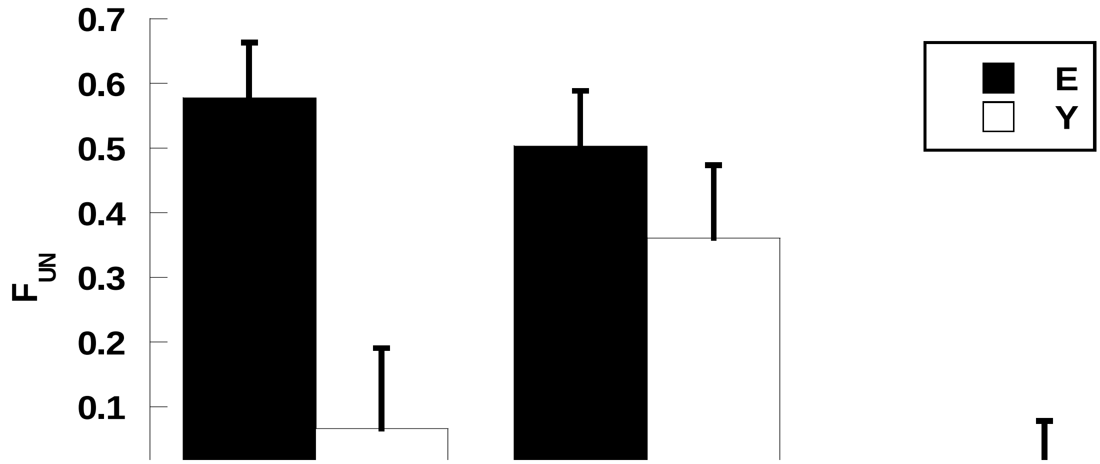

Figure 16 B: Unintended Force Production (F_{UN}) in different conditions for Elderly and Young. Values have been averaged across all subjects (with standard error bars). D_{RL}: Down – feedback on the right-left force changes, DL: Down left, DB: Down backward.

Analysis of Multi-Finger Synergies

In order to analyze multi-finger synergies stabilizing the total force magnitude and force direction, we used the framework of the uncontrolled manifold (UCM) hypothesis. The variance across trials was measured at each time sample and quantified as two components – V_{UCM} and V_{ORT}. V_{UCM} gave a measure of the variance per DOF, which did not have any effect on the performance variable. V_{ORT} gave a measure of the variance per DOF orthogonal to UCM, which affected the performance variable. A normalized difference between V_{UCM} and V_{ORT}, ΔV was used as the index of synergy. Positive ΔV indicated a synergy stabilizing the performance variable for which ΔV was quantified, while zero or negative ΔV would mean no such synergy.

Across all the task conditions, V_{UCM} was higher than V_{ORT}, and ΔV was positive for both magnitude and direction of the force vector. Hence, we conclude that strong multi-finger synergies stabilized both force magnitude and direction in both subject groups.

Force magnitude stabilization

Figure 17 illustrates the time profile of Z transformed ΔV values for stabilizing force magnitude for Elderly and Young. Note the smaller indices of synergy (ΔV) stabilizing force magnitude for Elderly as compared to Young and the similar trend across time for Elderly and Young. The trend across different conditions and along different axes (Z and non-Z) was also similar for both Elderly and Young.

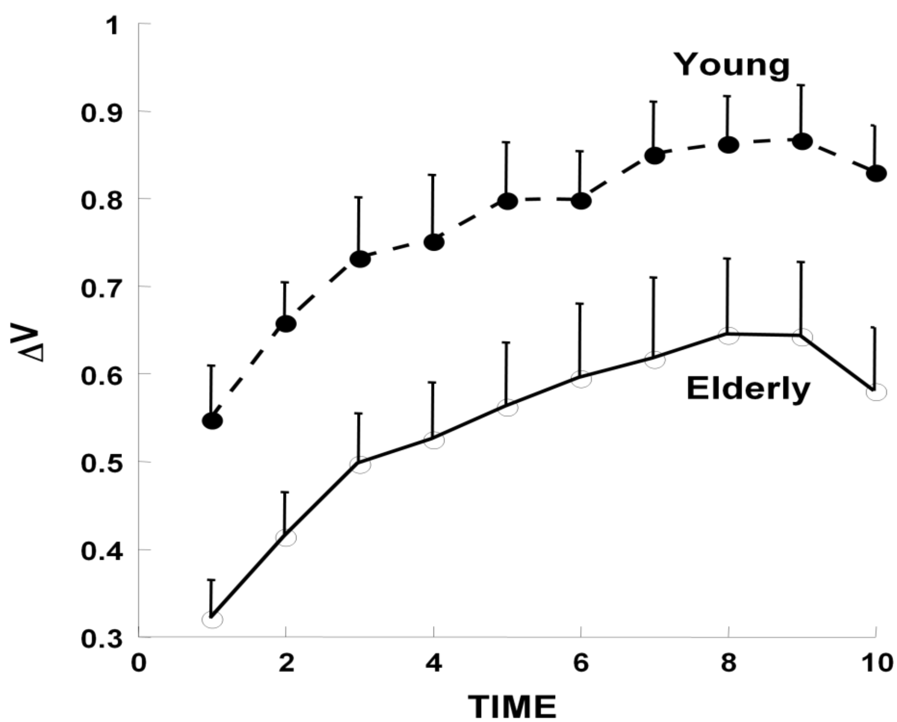

Figure 17: Time profile of Z transformed Δ V values for stabilizing Force magnitude for elderly and young. Values have been averaged across all subjects (with standard error bars).

To explore the effect of aging on the synergies stabilizing force magnitude, a three-way ANOVA was done on ΔV averaged across the whole trial with *Group*, *Condition* and *Axis* (*Z* and non *Z*) as factors. There was a significant main effect of *Group* and *Axis* ($F_{1,14} = 4.86$, $p < 0.05$ for *Group*; $F_{1,14} = 8.07$, $p < 0.05$ for *Axis*). However, neither the *Condition* effect nor any of the interactions were significant. Both Elderly and Young had higher ΔV along the relevant non-*Z* axis than along the *Z* axis ($p < 0.05$). The results reflected that the synergy stabilizing the shear force magnitude was stronger than the one stabilizing the magnitude of downward force.

As there was no significant main effect of *Condition* on ΔV related to force magnitude stabilization, ΔV values were averaged across the three conditions. Further, a three-way ANOVA was run with a new factor, *Time* (10 levels: 10%, 20%, 30%, 40% , 50%, 60%, 70%, 80%, 90% and 100%) to compare the trend of ΔV stabilizing force magnitude with time for Elderly and Young. For that factor, ΔV magnitudes were averaged across ten equal time intervals over the trial duration. . The three-way ANOVA, *Group* x *Axis* x *Time* showed main effects of *Axis* and *Group*. Also, *Time* emerged as a significant factor ($F_{3.07,\ 42.93} = 41.89$, $p < 0.0001$). Tukey comparison revealed that the value of ΔV increased till 30% time and after that the differences were not significantly different from the next higher time level The interaction *Group* x *Time* was not significant. Thus both Elderly and Young showed similar time trends of ΔV computed for force magnitude stabilization along both *Z* and non-*Z* axes.

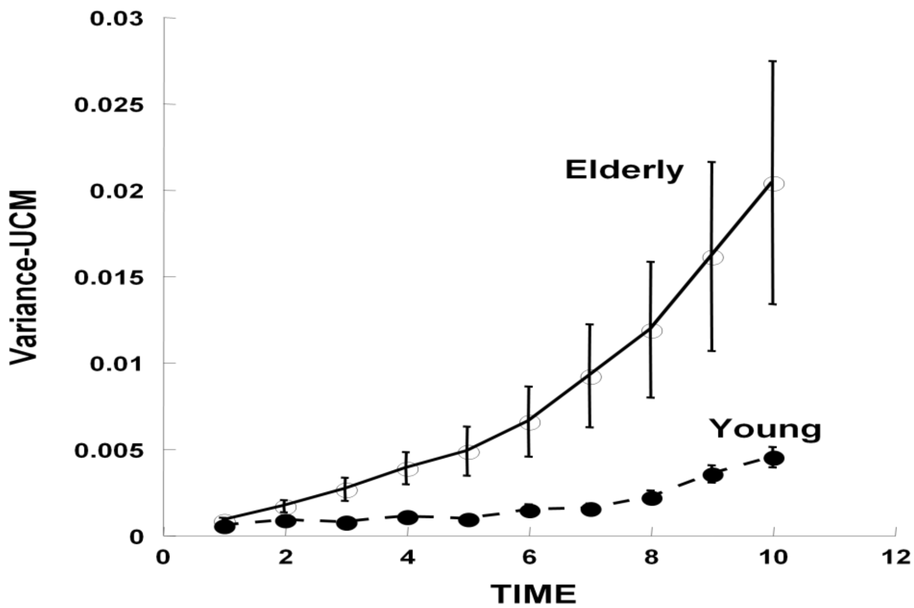

Figure 18: Time profile of V_{UCM} values for stabilizing Force magnitude for Elderly and Young. Values have been averaged across all subjects (with standard error bars).

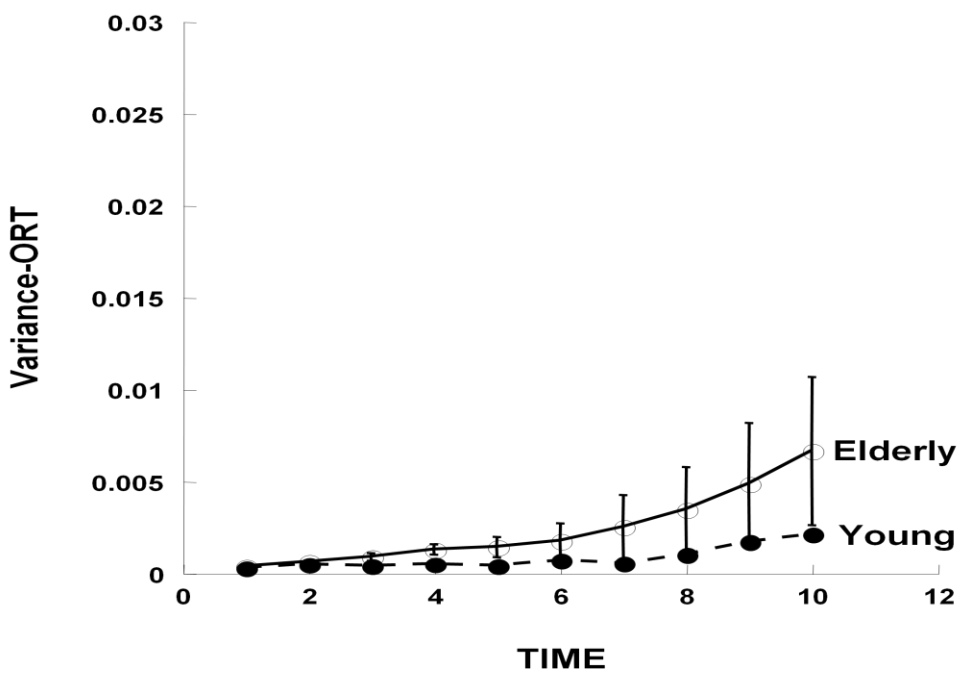

Figure 19: Time profile of V_{ORT} values for stabilizing Force magnitude for Elderly and Young. Values have been averaged across all subjects (with standard error bars).

The analysis of variance for force magnitude in two subspaces (V_{UCM} and V_{ORT}) showed that V_{ORT} was higher in Elderly as compared to Young without a significant difference in V_{UCM}. Figure 18 and 19 illustrate the time profiles of V_{UCM} and V_{ORT} for Elderly and Young. Note the huge difference in the values of V_{UCM} and V_{ORT}, indicating strong synergies. Also, note the significantly higher values of V_{ORT} in Elderly. A three-way ANOVA done on V_{UCM} computed for force magnitude stabilization, *Group* x *Axis* x *Condition* showed that *Axis* had a significant main effect ($F_{1,14} = 14.37$, $p < 0.01$). V_{UCM} was greater for non-*Z* axes as compared to *Z* axis, and this was consistent across both groups. Also, two-way interaction *Group* x *Condition* was significant ($F_{2,28} = 5.04$, $p < 0.05$). Three-way interaction was significant ($F_{2,28} = 5.43$, $p< 0.05$) as well. Tukey's comparisons revealed that V_{UCM} was greater for D_{RL} as compared to DL and DB, only along the non-Z axes and only for the Young group ($p < 0.05$). No such differences across conditions were found in the Elderly group. *Group* was not found to be a significant factor. A similar ANOVA done on V_{ORT} for force magnitude showed that *Group* had a significant main effect ($F_{1,14} = 6.48$, $p < 0.05$). V_{ORT} was greater for Elderly than Young. In addition, *Axis* was nearly significant ($F_{1,14} = 4.58$, $p= 0.05$). V_{ORT} was greater along the non-*Z* axes as compared to *Z* axis, and this was consistent across both Young and Elderly. Also, the two-way interaction between *Axis* and *Condition* was significant ($F_{2,28} = 3.83$, $p < 0.05$). Tukey's comparisons revealed that V_{ORT} was greater along the non-*Z* axis than *Z* axis, only for the DB condition.

Force Direction Stabilization

The index of synergy (*ΔV*) stabilizing force direction was lower for Elderly as compared to Young. The trend across time was similar for both groups. Figure 20 shows the time profile of Z transformed *ΔV* values for stabilizing force direction for Elderly and Young. Note the smaller synergy indices for Elderly and similar trend across time for both Elderly and Young.

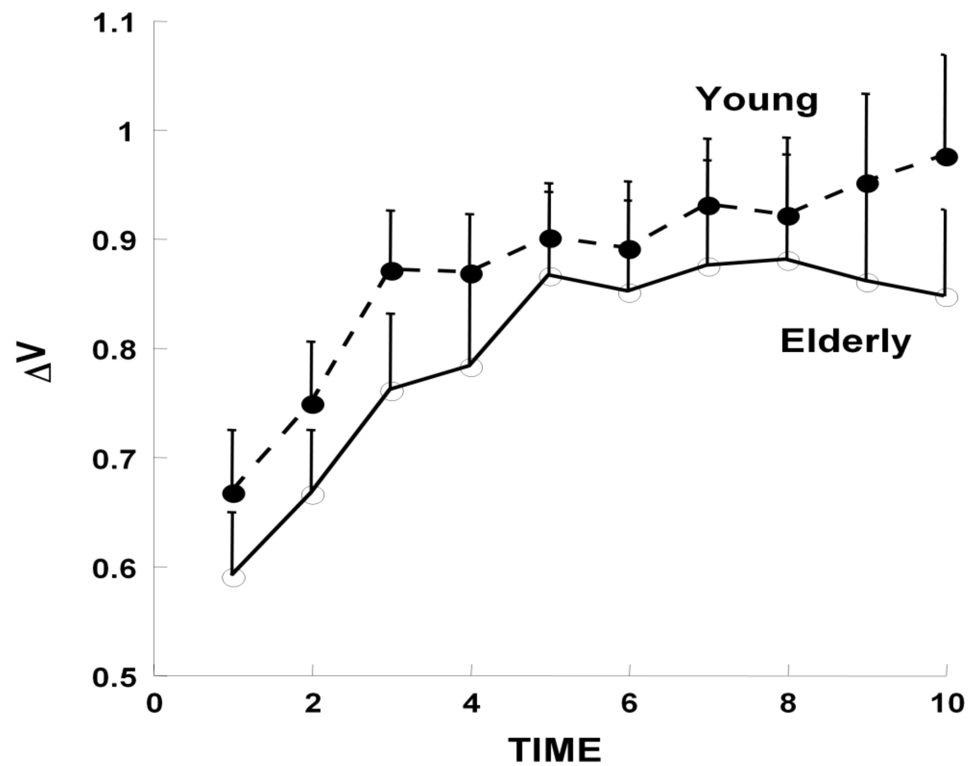

Figure 20: Time profile of Z transformed *Δ V* values for stabilizing Force direction for Elderly and Young. Values have been averaged across all subjects (with standard error bars).

For comparing the synergies stabilizing force direction in the Elderly and Young groups, three-way ANOVA was done on *ΔV*, *Group* x *Condition* x *Time*. Main effects of *Condition* and *Time* were significant ($F_{2,28} = 20.67$, $p < 0.001$ for *Condition*; $F_{3.39,47.54} = 24.79$, $p < 0.0001$ for *Time*). Also, the *Group* x *Condition* interaction was significant ($F_{2,28} = 5.07$, $p < 0.05$). However, the main effect of *Group* and all the other interactions were not significant. Thus the trend of *ΔV* stabilizing direction across time was similar for Elderly and Young. Tukey's comparisons revealed that ΔV magnitude was greater for Young as compared to Elderly only for the D_{RL} condition ($p < 0.05$). The ΔV index was significantly lower for the DB condition as compared to the DL for both Young and Elderly ($p < 0.05$). Also, the ΔV index for DB was significantly less than for either DL or D_{RL} for Young, while for Elderly the significant difference was only between the DB and DL conditions ($p < 0.05$). Overall, ΔV(DB) < ΔV(D_{RL}) < ΔV(DL); for Young ΔV(DB) < ΔV(DL, D_{RL}), and for Elderly ΔV(DB) < ΔV(DL).

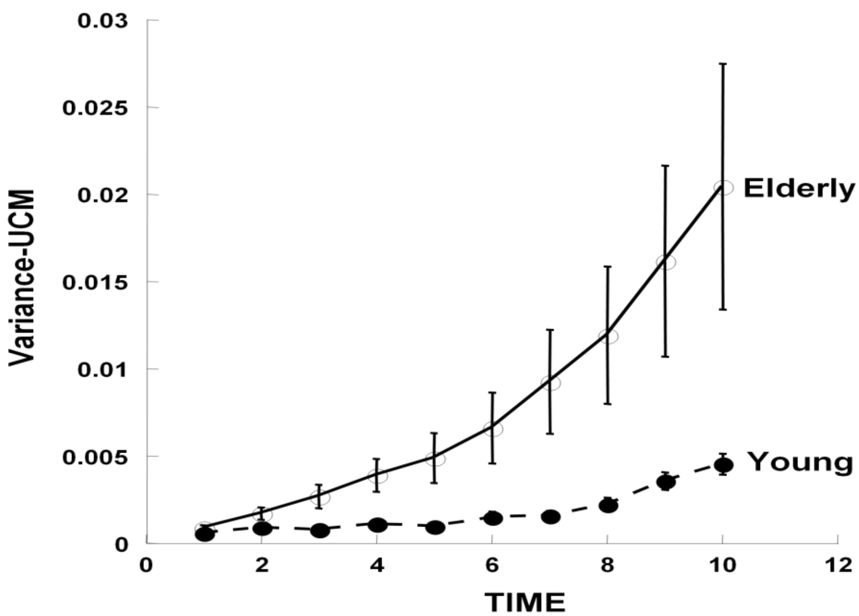

Figure 21: Time profile of V_{UCM} values for stabilizing Force direction for Elderly and Young. Values have been averaged across all subjects (with standard error bars).

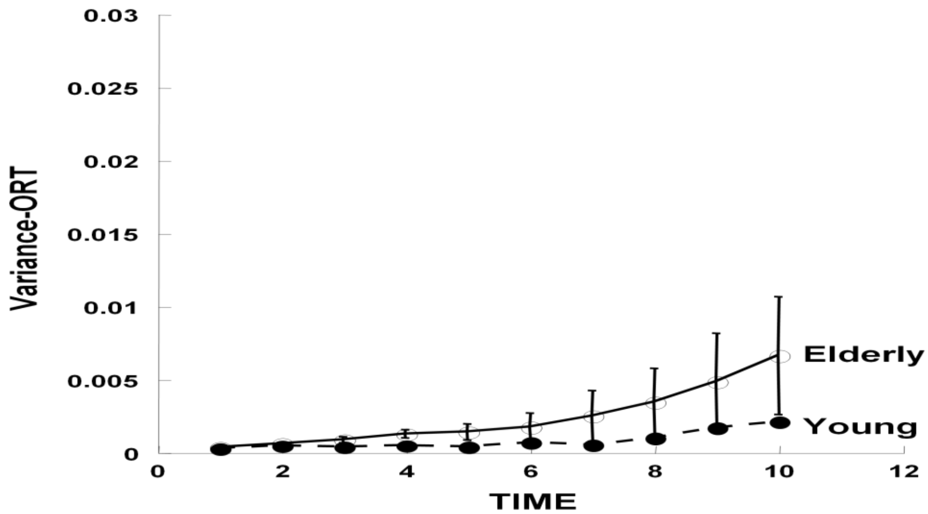

Figure 22: Time profile of V_{ORT} values for stabilizing Force direction for Elderly and Young. Values have been averaged across all subjects (with standard error bars).

The analysis of the two variance components (V_{UCM} and V_{ORT}) showed that, though both V_{UCM} and V_{ORT} were higher in Elderly as compared to Young, the V_{UCM} had about three-fold increase while the increase in V_{ORT} was about six-fold. Figure 21 and 22 shows the time profiles of V_{UCM} and V_{ORT} for both Elderly and Young. Note the huge difference in the values of V_{UCM} and V_{ORT}, indicating strong synergies. Also, note that both V_{UCM} and V_{ORT} were higher in Elderly as compared to Young, however the magnitude of increase varies. A three way ANOVA was done on the two components of Variance computed for force direction stabilization with the factors *Group*, *Variance* and *Condition*. *Group* and *Variance* had significant main effects ($F_{1,14}$ = 6.96, p< 0.05 for *Group*; $F_{1,14}$ = 19.53, p< 0.001 for *Variance*). Variance was significantly more for Elderly as compared to Young. The V_{UCM} was significantly greater than V_{ORT}, for both Elderly and Young. The interaction between *Variance* and C*ondition* was also significant ($F_{2,28}$ = 4.49, p< 0.05). Tukey comparison revealed that V_{UCM} was greater than V_{ORT} for all the conditions (p< 0.05). The interaction between *Variance* and *Group* was approaching significance ($F_{2,28}$ = 4.20, p= 0.059). Neither *Condition* nor any other interaction was significant.

5.6 Discussion

This study explored the changes in the indices of finger interaction that occur as a result of aging. MVC values for Elderly were lower as compared to Young, though the difference was significant only for the IMRL task. We had expected the elderly to be less accurate in both force magnitude and direction. Though Elderly were less accurate in shear force magnitude as compared to Young. But the differences between Elderly and Young in the accuracy of downward force magnitude and force direction were not significant. Directional errors were less for IMRL tasks as compared to the one-finger tasks for both Young and Elderly. The trend of *RMS* error for force direction was similar in Elderly and Young, both across conditions and across fingers.

We had hypothesized that elderly participants will show lower enslaving not only for normal forces but also for shear forces. Both the indices of Enslaving, E_j and E_i were lesser for Elderly as compared to Young. This trend was consistent across all the fingers. We had also hypothesized that the similar F_{UN} phenomenon will also be lower in elderly. However, we found that the magnitude of F_{UN} for Elderly was greater as compared to Young.

We had expected the higher motor variability to be associated with lower indices of synergies stabilizing those variables. We found smaller indices of synergy (ΔV) stabilizing force magnitude and the ones stabilizing force direction for Elderly as compared to Young and the similar trend across time for Elderly and Young. The trend across different conditions and along different axes (*Z* and non-*Z*) was also similar for both Elderly and Young. The synergy stabilizing the shear force magnitude was stronger than the one stabilizing the magnitude of downward force for both Elderly and Young.

CHAPTER – 6

GENERAL DISCUSSION

Hand serves as a valuable tool in almost all the activities of daily life. Accurate control of forces produced by the fingers is essential for performing varied manipulations of everyday objects. In pressing tasks, the vectors of force produced by human fingers vary in both magnitude and direction within a broad range. Until now, most studies of pressing tasks have focused only on normal force production. Our goal was to extend the analysis of indices of finger interaction and multi-finger synergies to three-dimensional tasks. At this stage, we limited the study to pressing tasks, which allow us to standardize tasks and quantify finger force components in three directions.

The first study done on young participants tested two main hypotheses. The first was that shear force components may show features such as unintended force produced by a non-task finger in the direction opposite to the instructed force and also unintended force in a direction orthogonal to the instructed direction. The second hypothesis was that strong multi-finger synergies would be observed stabilizing both magnitude and direction of the total force vector. Both of these hypotheses have been supported by the findings. We observed strong multi-finger synergies stabilizing both magnitude of the total force and direction. This study is the first to show simultaneous stabilization of force magnitude and direction. It is also the first to document force magnitude stabilizing synergies for shear forces. Indices of involuntary force production showed more complex patterns as compared to earlier reports on finger interdependence during pressing tasks. In particular, intentional force production by a finger parallel to the surface of contact could result in unintentional force production by other fingers in the same or in the opposite direction.

Unexpectedly, the index finger, which has been described as most independent and best controlled (Zatsiorsky et al. 2000; Shim et al. 2007; Gorniak et al. 2008), produced the largest amount of unintended shear force along the forward-backward direction. In contrast, along the left-right axis, the index finger showed the smallest amount of unintended shear force. These results cannot be easily mapped on the hand muscle anatomy. Rather, they may be related to everyday function of the human hand, in particular to the different roles of the fingers in prehensile tasks involving holding a load and simultaneously counteracting an external torque (Zatsiorsky et al. 2003a,b).

Many studies have reported a decrease in manual dexterity and general strength of hands with increasing age. The second study explored the changes in the indices of finger interaction that occur as a result of aging. Based on earlier studies, we hypothesized that elderly participants will show lower enslaving not only for normal forces but also for shear forces. We also hypothesized that the amount of unintended force production orthogonal to the instructed direction will also be smaller in elderly. We expected the elderly to be less accurate in both force magnitude and direction. We expected the higher motor variability to be associated with lower indices of synergies stabilizing those variables.

There were certain similarities and certain differences between the elderly and young participants in indices of finger interaction. Strong multi-finger synergies stabilizing both force magnitude and direction were found in the elderly as well as in the young participants. In both groups, synergic adjustments of individual finger involvement significantly improved directional accuracy. The trend of the index of synergy across time was similar for both groups. Synergies stabilizing the shear force magnitude were characterized by greater indices than the ones stabilizing the magnitude of downward force.

We found that enslaving across fingers was smaller for the elderly as compared to the young participants. However, the unintentional force produced by the task finger in a non-instructed direction (F_{UN}) was greater in the elderly. The elderly exhibited less strong synergies stabilizing force magnitude as compared to the younger participants along all axes and across all conditions. However, the difference between the two groups in the index of synergy stabilizing force direction was smaller and significant only for one condition (D_{RL}).

The results show that unintentional force production by a finger in a non-instructed direction (F_{UN}) and unintentional production of force by a non-instructed finger (enslaving) are phenomena of different origin. In particular, they show opposite changes with age. As discussed earlier, enslaving may get contributions from a variety of peripheral factors (such as inter-finger connective tissue links), the participation of multi-tendon muscles in finger force production, and neural factors such as overlaps of cortical finger representations. Individual finger force direction is not directly affected by the former two factors. It may reflect the coordination of intrinsic and extrinsic hand muscles serving that particular finger. As such, F_{UN} may be viewed as an index defined primarily by neural factors. Its increase in the elderly participants suggests impaired multi-muscle synergies and strengthens the current findings of weaker multi-finger synergies stabilizing total finger force magnitude and direction.

To summarize, the two studies presented in this thesis report, for the first time, indices of unintentional finger forces during one-finger tasks involving force production in all three dimensions. They also report, for the first time, indices of multi-finger synergies stabilizing force vector magnitude and direction in four-finger accurate force production tasks in three dimensions in both young and elderly participants. Also, the changes in the indices of multi-digit interaction in a three dimensional pressing task, as a result of aging, have also been reported for the first time.

These results may have implications for several areas. First, they introduce new indices (E_i, E_j, and F_{UN}) that describe finger interaction and that are sensitive to age-related changes in the control of the hand. These indices may be useful for future studies of populations with impaired hand function due to a variety of reasons, such as atypical development and neurological disorders. Second, the studies expand the applicability of the UCM hypothesis to synergies stabilizing direction of vector variables produced by a set of elements. This is a relatively novel field of application of the UCM method. Finally, the studies contributed to the knowledge of age related changes in the multi-finger synergies.

APPENDIX

Table 1: *RMS* error of the force vector angle

Condition	**Four-finger task**	**One-finger tasks**			
		Index Finger	**Middle Finger**	**Ring Finger**	**Little Finger**
D_{LR}	2.20 ±2.17	15.58 ± 8.04	8.65 ± 2.33	9.63± 2.74	9.58 ± 4.14
D_{FB}	4.25 ± 2.04	14.80 ± 6.85	9.24 ± 2.04	6.30 ± 0.40	13.77 ± 3.76
DL	3.39 ± 2.92	20.33 ± 9.85	11.55 ± 5.58	14.18± 5.02	11.16 ± 4.91
DR	3.16 ± 1.31	19.58 ± 8.05	14.12 ± 5.10	12.17 ± 2.90	12.61 ± 3.63
DF	5.78 ± 1.78	12.09 ± 3.68	8.70 ± 3.99	10.34 ± 3.66	8.23 ± 2.58
DB	8.60 ± 2.92	21.64 ± 10.50	14.47 ± 5.25	19.09±10.07	15.65 ± 3.39

Means and standard errors across subjects have been presented in degrees.

D_{LR} : Down – feedback L/R, D_{FB}: Down – feedback F/B, DL: Down left, DR: Down right, DF: Down forward, DB: Down back.

Table 2A: ***RMS*** **error of force magnitude for the four-finger task**

Condition	***RMS*** **F_X ($\times 10^{-3}$)**	***RMS*** **F_Y ($\times 10^{-3}$)**	***RMS*** **F_Z ($\times 10^{-3}$)**
D_{LR}	0.24 ± 0.03	------	1.2 ± 0.08
D_{FB}	-----	0.33 ± 0.08	1.1 ± 0.08
DL	0.43 ± 0.09	------	1.1 ± 0.07
DR	0.52 ± 0.10	------	1.3 ± 0.10
DF	-------	0.66 ± 0.16	1.1 ± 0.08
DB	-------	0.79 ± 0.12	1.3 ± 0.15

Table 2B: ***RMS*** **error of force magnitude for a one-finger task (Index Finger)**

Condition	***RMS*** **F_X ($\times 10^{-3}$)**	***RMS*** **F_Y ($\times 10^{-3}$)**	***RMS*** **F_Z ($\times 10^{-3}$)**
D_{LR}	0.31 ± 0.04	------	1.2 ± 0.08
D_{FB}	-----	0.3 ± 0.05	1.1 ± 0.09
DL	0.55 ± 0.30	------	1.1 ± 0.12
DR	0.62 ± 0.29	------	1.1 ± 0.10
DF	-------	0.5 ± 0.07	0.8 ± 0.08
DB	-------	1.1 ± 0.25	1.3 ± 0.21

The forces were divided by the total task magnitude before calculating RMS (so that RMS can be compared across different directions). The data were first averaged across all repetitions for one condition, then averaged across all subjects. Means and standard errors across subjects are presented. D_{LR} : Down – feedback L/R, D_{FB}: Down – feedback F/B, DL: Down left, DR: Down right, DF: Down forward, DB: Down back. Only index finger data (from one finger tasks) has been shown for comparison, and this is representative of the data for all one-finger tasks.

Table 3: Number of negative entries in enslaving matrices for different non-down tasks.

Condition	**Axis**	**Number of negative entries**
DB	Y	4.9± 1.6
DF	Y	1.6 ± 2.1
DL	X	5.1 ± 0.8
DR	X	4.1 ± 2.0

The numbers are averages across all subjects. DL: Down left, DR: Down right, DF: Down forward, DB: Down back.

Table 4: $|E|$ **(enslaving index) for different task conditions.**

Condition	$\mathbf{\vert E\vert_X}$	$\mathbf{\vert E\vert_Y}$	$\mathbf{\vert E\vert_Z}$
D	----	----	1.43 ± 0.29
D_{LR}	----	----	2.19 ± 0.61
D_{FB}	----	----	2.65 ± 0.78
DR	4.30 ± 2.30	----	2.47 ± 0.68
DL	0.11 ± 0.29	----	1.68 ± 0.44
DF	----	1.80 ±0.42	2.23 ± 0.57
DB	----	1.22 ± 0.35	1.88 ± 0.42

Averages across all subjects are presented with standard errors.

D_{LR} : Down – feedback L/R, D_{FB}: Down – feedback F/B, DL: Down left, DR: Down right, DF: Down forward, DB: Down back.

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