AGE RELATED DIFFERENCES IN
MULTI-DIGIT COORDINATION

A Thesis in
Kinesiology

by
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Abstract

This dissertation addresses differences in multi-finger coordination related to aging. It attempts to identify some of the processes that may facilitate the observed decrease in dexterity with advancing age and investigates the effects of strength training on some of these changes.

The experiment on the effects of aging on multi-finger coordination in a moment of force production task showed that elderly individuals had a reduced ability to produce synergies that stabilize the total moment and the total force. This suggests that elderly individuals have a decreased ability to coordinate commands to the fingers in order to stabilize action, and in particular rotational action.

The two experiments that addressed anticipatory synergy adjustments (ASAs) showed that elderly individuals are not able to manipulate synergies in preparation to a predictable change in the force output to same extent as the younger people. Combined, the results of these studies suggest that aging is associated with a decreased ability to use feed-forward adjustments in preparation for an anticipated change in the performance variable and provide further support for feed-forward nature of ASAs.

The experiment on the effects of repetitive testing on indices of finger interaction displayed that repeated testing is not sufficient to generate changes in these indices. These results can be used to support the argument that the training induced changes observed in the last experiment were truly due to training and not familiarity with the experimental setup.

The final experiment, investigated the effects of site specific strength training on maximal voluntary force, enslaving and performance on an accurate force production task and functional clinical tests in the elderly. This study showed that strength training has general improving effects on force produced at both sites of both hands regardless if they received training or not but these effects were most prominent at the trained proximal sites whose force is mostly generated by the intrinsic hand muscles. This suggests that focused training of the intrinsic
muscles may result in an improved ratio between the intrinsic and extrinsic muscles and allow the extrinsic muscles to be activated to a larger degree.

When taken together, this series of studies has enhanced our knowledge of changes in finger interaction and coordination in aging. These studies may carry a negative message of impaired multi-finger synergies in the elderly but also a positive message that such changes may be counteracted or even reversed with appropriately designed exercise.
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HBO
CHAPTER 1 Introduction

1.1 Problem Statement

The human hand is a very versatile tool, capable of performing both tasks that require power such as opening jars and tasks of fine control. Many tasks of daily living require considerable prestidigitation. Picking up small objects, buttoning buttons, tying shoe laces, pouring from a bottle and even eating with chopsticks are all fairly frequent human tasks and all necessitate a coordinated action of the digits of the hand. The ability to carry out simple tasks as these may be a crucial factor in determining one’s ability for unassisted living.

Aging is associated with a well documented decline in both manual dexterity and strength (Boatright et al. 1997; Francis and Spirduso 2000; Rantanen et al. 1998; Ruiz et al. 2007; Smith et al. 1999) that has been attributed to both changes in peripheral structures (Campbell et al. 1973; Doherty and Brown 1997; Macaluso et al. 2002) as well as in the central command (Cole et al. 1998, 1999; Shinohara et al. 2003a).

This thesis addresses differences in multi-digit coordination related to age with specific focus on the following aspects: rotational hand action, feed forward adjustments of digit interaction and effects of strength training on digit interaction.

Most studies of digit coordination in the elderly have focused on force production during pressing (Cole, 2006; Shinohara et al. 2003b, 2004) and grasping tasks (Cole, 1991; Cole et al. 2001; Cole and Rotella, 1999; Edin et al. 1992; Flanagan et al. 1999; Quaney et al. 2004). Much less attention has been paid to the ability to produce an accurate rotational hand action, that is, the control of moment of force which is essential for many daily activities such as drinking from a glass, writing with a pen and using a hand held tool. For clarification it should be noted that here the term “finger” refers to index, middle, ring and little finger while the term “digit” includes the four fingers and the thumb.
Considerable experimental evidence has been collected in support of the hypothesis of hierarchical control of prehension (Santello and Soechting, 1997; Baud-Bovy and Soechting, 2001, 2002; Zatsiorsky et al. 2003a, 2004b; Shim et al. 2003b). This hypothesis suggests that control of prehension is hierarchical and includes at least two levels. At the higher level a given task is distributed between the thumb and virtual finger (VF, an imaginary finger whose mechanical action is equivalent to the summed action of index, middle, ring and little fingers) while at the lower level the action of the VF is distributed among individual fingers.

Previous studies of multi-digit accurate moment production tasks in young subjects have established the following: (a) at the level of individual fingers, subjects show co-variation of commands to fingers across trials that stabilizes the total moment of force, that is, they produce a moment stabilizing synergy (Zhang et al. 2006). A synergy is a negative co-variation of elemental variables that stabilizes an important performance variable (such as total moment); (b) at the level of thumb and VF, individual performance variables are divided into two subsets which are associated with two aspects of the prehension task, control of grasp (preventing an object from slipping out of the hand) and control of moment (maintaining the desired orientation of the object) (Shim et al. 2003b, 2005a; Zatsiorsky et al. 2002).

Multi-digit coordination during a rotational task in the elderly has only been addressed by one study, which did so at the thumb – VF level (Shim et al. 2004b). The results of the study showed that elderly subjects are less accurate in the production of total moment; produce larger antagonist moment (moment of force generated by digits that oppose the desired direction of moment production) and show lower indexes of both total force and total moment stabilization.

Thus, age related differences in the production of moment stabilizing synergies at the level of individual fingers have not been addressed.

Feed-forward control of movements means in essence that the controller supplies the signal independently of the output. The role of feed-forward control is to prepare the system for expected changes that will perturb it. In human movements feed-forward control can be seen at multiple levels of analysis.
an object is lifted using the fingertips of thumb and index finger, gripping force changes in anticipation of the weight (Johansson and Westling, 1988; Gordon et al. 1993) and when a person applies force to the bottom of a hand-held object with the other hand, gripping force changes in a feed-forward fashion (Scholz and Latash, 1998). The feed-forward mechanism appears to be affected by advancing age. Anticipatory postural adjustments, (APA’s), another example of a feed-forward control (rev. in Massioni, 1992), have been reported to be both delayed and of reduced magnitude in elderly individuals (Inglin and Woollacott, 1988; Rogers et al. 1992; Woollacott et al. 1988).

Recently a novel phenomenon, anticipatory synergy adjustments, (ASA’s) has been described in relation to multi-digit pressing and prehension tasks (Kim et al. 2006; Olafsdottir et al. 2005b; Shim et al. 2005c, 2006). During a multi-digit force task, the generation of a steady level of force is associated with the production of a multi-finger force stabilizing synergy. When the task requires the total force output to change rapidly in a predictable manner, an anticipatory drop in the index of synergy has been observed, starting 100 – 150 ms prior to the change in force (Kim et al. 2006; Olafsdottir et al. 2005b; Shim et al. 2005c, 2006). It has been suggested that ASA’s have the functional importance to weaken synergies that would otherwise counteract the planned action and reflect a feed-forward mechanism of similar nature as APA’s. Age related differences in ASA’s have previously not been studied. Showing that elderly individuals display a decreased ability to produce ASA’s in a similar manner as APA’s would both provide further support for the commonality of these two phenomena as well as the idea that the elderly may have a reduced capacity of feed-forward control.

The fingers are controlled by two groups of muscles, intrinsic muscles which are located inside the hand and extrinsic muscles that are located in the forearm. Due to the difference in tendon attachment sites of these two muscle groups, pressing down on an object with the fingertips activates mostly the extrinsic muscles (Harding et al., 1993; Z-M Li et al. 2000) whereas the intrinsic muscles are the focal force generators when the proximal phalanges are used (Chao and An, 1978). Comparisons of maximal force generating abilities of
young and elderly subjects have revealed that elderly subjects lose disproportionately more of their muscle strength in the intrinsic hand muscles (Shinohara et al. 2003a). It has been speculated that this imbalance may contribute to the impaired ability of elderly individuals to produce synergies that stabilize the total force and total moment of force in multi-finger tasks that require accurate force production (Shinohara et al. 2003a, 2004, Shim et al. 2003a).

Strength training has been shown to be an effective way to improve the force producing capacity of muscles in the elderly (Narici et al. 2004, Reeves et al. 2004, 2006) and reverse some of the changes observed in the muscles architecture with increased age (Reeves et al. 2004; Narici et al. 2004; Reeves et al. 2006) as well as to influence the neural command (Akima et al. 1999, Carolan et al. 1992, Connelly et al. 2000, Enoka, 1997, Hakkinen et al. 1998, Kornatz et al. 2005 Moritani et al. 1980, Ranganathan et al. 2001). However, the effect of site specific strength training on indices of finger interaction has not been investigated.

1.2 Study Objectives

This thesis explores the following hypotheses:

**Hypothesis 1** Aging is associated with a decreased ability to produce moment of force stabilizing synergies during rotational hand action at the level of individual fingers.

**Hypothesis 2** Aging is associated with a decreased ability to adjust synergies in preparation to a planned quick action or a predictable perturbation.

**Hypothesis 3** Repeated testing without additional intervention does not induce improvements in the maximal strength of fingers or indices of finger interaction.

**Hypothesis 4** Strength training that targets specifically intrinsic hand muscles in elderly individuals improves the balance between the maximal force generating abilities of intrinsic and extrinsic hand muscle groups. Enslaving increases in parallel to an increase in maximal force and facilitates positive co-variation among finger forces. This may cause a worsened performance on the multi-finger ramp task and a decline in dexterity measured by clinical functional tests.
1.3 Organization of Dissertation

The dissertation is composed of 10 chapters. Chapter 1 is an introduction to the dissertation. Chapter 2 reviews the literature related to the topic of the dissertation. Chapter 3 describes general methodology of the experiments described in Chapters 4 to 8.

Chapters 4 and 5 are based on the following published papers:


   Young and elderly subjects pressed down on force sensors with index, middle, ring and little fingers of the right hand and followed an inverted trapezoid template on a computer screen by producing a time profile of the total moment of force with respect to a pivot between the middle and ring fingers. Index and middle finger forces produced a positive (pronation) moment, and ring and little fingers produced a negative (supination) moment. Total force and its variance and total moment of force and its variance were calculated across trials for each time point and averaged across subjects. The framework of the Uncontrolled Manifold (UCM) hypothesis was used to compute indices of synergies stabilizing the total moment of force of total force. Young subjects were able to produce total moment of force stabilizing synergies while the elderly subjects failed to do so. Elderly subjects also displayed a larger variance of the total moment of force and total force than young subjects.


   Young and elderly subjects produced quick force pulses by pressing down on force sensors with index, middle, ring and little fingers of the right hand. Prior to force pulse, the subjects produced a constant low level of the total force. The
force pulse was initiated either in response to an auditory signal (reaction time trials, RT) or in a self-paced fashion (self-paced trials, SP) by the subjects themselves. The framework of the UCM hypothesis was used to compute an index of synergy stabilizing the total force. In SP trials all subjects showed anticipatory drop in the synergy index (ASA’s) prior to the change in total force but in the elderly subjects these changes started later and were of smaller magnitude.

Chapter 6: Anticipatory synergy adjustments in preparation to self-triggered perturbations in elderly individuals.

Elderly subjects produced a steady state of force by pressing down on force sensors with all four fingers. All fingers were placed through loops that were attached to loads via a pulley system, so subjects had to produce flexion force with all fingers in order to touch the sensors. In each trial, the middle finger was perturbed by releasing the load attached to it, either by the experimenter (unknown to subjects, EXP) or by the subjects themselves (SELF). Forces produce by the each of the four fingers were measured. For each subject, first all trials were aligned using the time of load release and then the variance of the total force (VarF_{tot}) and sum of the variances of individual finger forces (\sum VarF_i) were calculated across them. Co-variation of finger forces was estimated by comparing these two variables. \sum VarF_i > VarF_{tot} corresponds to a negative co-variation among finger forces and can be interpreted to reflect a synergy that stabilizes the total force. Prior to the perturbation all subjects were able to successfully produce force stabilizing synergies. In SELF trials the synergy index showed an anticipatory drop (ASA’s) prior to the time of unloading while in EXP trials no such drop was seen. The ASA’s observed in this study were both smaller in magnitude and delayed compared to a previous similar study of young subjects.

Chapter 7: The effects of repetetive testing on indices of finger interaction in elderly individuals.
The purpose of this study was to test the effects of repetitive testing on maximal force (MVC) and indices of finger interaction and provide background information in support of the training study (Chapter 8). Elderly subjects produced maximal force by individual fingers (I, M, R, L) or by all fingers together by pressing down on force sensors. Each subject was tested on 3 separate occasions over a period of 5 weeks but did otherwise not receive any training. The vertical forces produced by each finger were measured. For each subject, peak force, enslaving, force deficit and sharing were calculated. Multiple testing did not induce improvements in subjects’ performance of the calculated measures.

Chapter 8: The effects of resistance training on manual strength and dexterity in elderly individuals.

The study involved 4 testing sessions over a period of 6 weeks. During each testing session elderly subjects produced (a) MVC by individual fingers or by all fingers together and (b) individual finger or four-finger sub-maximal ramps by pulling down on loops that were attached to force sensors. The loops were placed either at the proximal phalange or the distal phalange which changed the relative contribution of intrinsic and extrinsic hand muscles. Both sites and both hands of each subject were tested in each session. Between testing sessions subjects trained their hand muscles, in one hand their extrinsic muscles and the other one the intrinsic muscles. To quantify functional abilities of the hands, subjects performed two tests (the Grooved Pegboard test and the Jebsen-Taylor hand function test) and filled out a questionnaire on hand function (the ABILHAND questionnaire) in the first and last testing sessions (pre- and post-training tests). For each subject, hand and site peak force and enslaving were calculated. To quantify performance on the ramp task, the root mean square (RMS) of the difference between the target (template) ramp and the actual ramps was calculated. The framework of the UCM hypothesis was used to compute and index of synergy (ΔV), stabilizing the total force. We also calculated the change in ramp performance between the pre- (test 1) and post-training (test 4) sessions (ΔRMS); the change in the synergy index
from the pre- to post-training sessions ($\Delta \Delta V$) and investigated the relationship between those two variables.

To quantify functional abilities of the hands, subjects performed two tests (the Grooved Pegboard test and the Jebsen-Taylor hand function test) and filled out a questionnaire on hand function (the ABILHAND questionnaire) in the first and last testing sessions (pre- and post-training tests).

Strength training improved the maximal total force produced by both proximal and distal sites of both hands. This increase in strength was particularly prominent at the proximally trained sites. Enslaving had also increased after the training period, causing enslaving values to be more similar to what has been seen in young subjects. Due to increased enslaving, we had expected the performance on the ramp task to worsen following the training. This prediction was not supported and RMS improved moderately even though the change was not significant. The synergy index, $\Delta V$, showed a small, non-significant increase after the training and a linear regression revealed that subjects that improved their performance after the training (smaller RMS), tended to increase their value of the synergy index (larger $\Delta V$). After the training, subjects performed significantly better on the grooved pegboard test while their performance on the Jebsen-Taylor test and the ABILHAND questionnaire remained unchanged.

Chapter 9 summarizes the experimental conclusions and Chapter 10 is a general discussion.
CHAPTER 2 Background and Literature Review

2.1 Motor Redundancy/Abundance

The human body is a complex system, with multiple segments, joints and muscles which allows us to interact with the world in a very flexible manner. During a voluntary movement, such as reaching out for an object in space, the system is confronted with the problem of redundant degrees of freedom. At every level of analysis (joints, muscles, motor units, etc.), more elements participate in the task than are necessary to complete it successfully and an infinite number of solutions exist. In mathematical terms this is similar to having to solve a set of equations when the number of unknown variables is larger than the number of equations. The question is; how does the brain choose a solution from the vast of seemingly equal options? This problem, first formulated by Nikolai Bernstein (Bernstein, 1947, 1967) has been termed the Problem of Motor Redundancy or Bernstein’s problem (Turvey, 1990). Bernstein (1947, 1967) considered the elimination of redundant degrees of freedom a central issue in motor control and saw coordination as the art of mastering the many degrees of freedom involved in a movement (Turvey, 1990).

In a seminal study, Bernstein observed the kinematics of blacksmiths hitting a chisel with a hammer. He noticed that the variability of the end point of the hammer was less than the variability of individual joints and concluded that the joints were not acting independently but compensated for each others errors and by that decreased the degrees of freedom (Bernstein, 1947, 1967). Later an alternative approach to the degree of freedom problem, appropriately named “The principle of abundance” was developed by Gelfand and Latash (1998, Latash, 2000). According to this approach the numerous degrees of freedom should not be considered a “burden” that the controller has to deal with but more as a luxury that allows the controller to ensure both stability and flexibility in the performance of the motor system (Latash et al. 2004, Gelfand and Latash, 2002).
2.2 Synergies and the Uncontrolled Manifold Hypothesis

The notion of synergies can be traced back to the seminal work of Hughlings Jackson (1899), Babinski (1899) and Sherrington (1910). Hughlings Jackson wrote in 1899, “The central nervous system knows nothing about muscles, it only knows movements”. He was by that questioning the then prominent views that the body was controlled in a string puppet like fashion, by hardwired pathways from the brain to individual muscles.

The term “synergy” originates in the work of Babinski, who in 1899 suggested that muscles are united into groups or “synergies” that the controller activates simultaneously, but it is most commonly associated with Nicola Bernstein. Bernstein hypothesized that the mechanical degrees of freedom were reduced by muscle linkages or synergies and that the control system was a hierarchical one (Bernstein, 1947, 1967; Gelfand and Latash, 2002; Turvey, 1990). Today the idea of the synergy is still very much alive but its definition has changed considerably.

In 1966, Gelfand and Tsetlin further developed the synergy idea by proposing two principles of motor control, the principle of non-individualized control and the principle of minimal interaction. According to the principle of non-individualized control, the elements of a complex system are not controlled individually but joined into flexible, task-specific structural units, organized by the controller for purposes that can be called synergies. The purpose or the synergy of a structural unit and external conditions define the external behavior the structural unit produces (Gelfand and Tsetlin, 1966). The principle of minimal interaction (PMI) states that interactions among elements at a lower level of the hierarchy are organized in such a way that the external input to each of the elements is minimized (Gelfand and Tsetlin 1966; cf. Latash et al. 2004). This principle was later further developed by Gelfand and Latash (1998) and split into two levels, PMI1 that is at the level of interaction among elements or local and PMI2 that is at the level of interaction between individual elements and the higher level of hierarchy or global. PMI1 and PMI2 describe two key features of a synergy, stable sharing pattern and error compensation. These features can be
described in general terms by saying that the elements within a synergy interact in such a way that each one of them tries to maintain a stable performance (stable sharing pattern) but at the same time to maintain their common functional output at the desired level without any intervention from higher levels of the hierarchy, even when one or more of the elements change their contribution (error compensation) (c.f. Latash et al, 2004).

Multi-finger pressing tasks provide a good example. If subjects are asked to gradually increase the total force produce by four fingers (index, middle, ring and little), the relative contribution of each finger stay stable, that is a certain sharing pattern is established in the beginning of the task and is maintained throughout it. By comparing the variance of the total force and the sum of the variances of individual finger forces across trials, it can be seen that the system compensates for errors, i.e., the sum of the variances of individual fingers exceeds the variance of the total force. This indicates that the fingers are negatively correlated; when one finger produces more or less force the other fingers adjust their output accordingly to maintain the common output stable (Li et al, 1998b). Synergies are both task specific and depend on the performance variable (Li et al, 1998b). Sharing pattern has for example been shown to be different in two, three, four and five digit tasks (Li et al. 1998b; Olafsdottir et al. 2005a). Li et al. (1998b) proposed a possible explanation for the force-sharing pattern, the hypothesis of minimization of secondary moments. During static tasks the hand is in equilibrium, that is, the sum of all forces and the sum of all moments is equal to zero. Imagine the transverse plane of the hand that that divides it into dorsal and palmar sides and a longitudinal axis that lies perpendicular to that plane. When the fingers press down, any force that does not pass though the axis produces a moment about it (the location of the axis depends on the number of active fingers). When multiple fingers press simultaneously they produce a certain total moment and in order to maintain the hand in equilibrium this “secondary” moment has to be counterbalanced by additional muscle action. For isometric pressing tasks, the secondary moment is unnecessary and the controller attempts
to minimize it by using the easiest method possible, maintaining a stable sharing pattern independent of the total force (Li et al. 1998b).

In recent years the Uncontrolled Manifold (UCM) Hypothesis, introduced by Scholz and Schöner in 1999 has further advanced the synergy concept. The UCM hypothesis is in essence a tool to test if the structure of the trial-to-trial variability of elemental variables indicates that the controller is stabilizing certain performance variables. This method has been used to identify synergies in studies of finger coordination (Latash et al. 2001; Scholz et al. 2003; Kang et al. 2004; Olafsdottir et al. 2005b; Zhang et al. 2006, 2007), multi-joint coordination (Scholz et al. 2000, Tseng et al. 2002, de Freitas et al. 2007), postural control at the level of EMG (Krishnamoorthy et al. 2003, 2004; Wang et al. 2005, 2006; Danna-Dos-Santos et al. 2007) and kinematics (Freitas et al. 2006; Hsu et al. 2007) and locomotion (Auyang and Chang, 2007; Yen et al. 2007).

According to the UCM hypothesis, for a given task, the controller selects a variable or a set of variables, named performance variables, whose value or values it wants to stabilize at each moment in time. The trial-to-trial variance of elemental variables can be decomposed into two components; one that affects and one that does not affect the output of the performance variable in question. A null space of the Jacobian, (a matrix of partial derivatives that describe how small changes in each elemental variable effect the value of the performance variable) and a orthogonal subspace, range space, are computed. Each data point is projected onto the null and range spaces and the variance of the projections obtained. The variance of the null space is called \( \text{Var}_{UCM} \) and variance of the range space \( \text{Var}_{ORT} \). The variance of the elemental variables within the null space \( \text{Var}_{UCM} \) reflects to what extent flexible combinations of the elemental variables can produce equivalent values of the performance variable while the variance within the range space \( \text{Var}_{ORT} \) reflects on the other hand combinations of the elemental variables that lead to changes in the performance variable. Thus \( \text{Var}_{UCM} > \text{Var}_{ORT} \) indicates that the elemental variables are negatively correlated and organized into flexible combinations that produce a stable performance of the performance variable (Latash et al. 2004a; Latash et al. 2007). In some studies the
\( \Delta V \) is computed as:

\[
\Delta V = \frac{\text{Var}_{\text{UCM}} \cdot \text{dof} - \text{Var}_{\text{ORT}} \cdot \text{dof}}{\text{Var}_{\text{Total}} \cdot \text{dof}}, \text{ where } \text{Var}_{\text{Total}} = \text{Var}_{\text{UCM}} + \text{Var}_{\text{ORT}}.
\]

Thus, negative co-variation of elemental variables results in positive \( \Delta V \) while positive co-variation results in negative \( \Delta V \).

In multi-finger pressing tasks, synergies have been described as co-variations of force modes that stabilize either the total force or total moment of force. The proposed elemental variables are modes (hypothetical independent central commands to the fingers that correspond to the desired involvement of individual fingers in the task (Danion et al. 2003)) rather than individual finger forces due to the phenomenon of enslaving [when one finger produces force other fingers will also produce force without being instructed to do so (Kilbreath and Gandevia 1994; Zatsiorsky et al. 2000)], which makes the fingers not independent. Figure 2.1.A shows the pattern of data distribution of a force stabilizing synergy (\( \text{Var}_{\text{UCM}} > \text{Var}_{\text{ORT}} \) and \( \Delta V > 0 \); negative co-variation of modes that stabilizes the total force output) in a two finger task; figure 2.1.B no synergy (\( \text{Var}_{\text{UCM}} = \text{Var}_{\text{ORT}} \) and \( \Delta V = 0 \)), figure 2.1.C a synergy that stabilizes the total moment of force but not the total force. Force stabilizing synergies and moment of force stabilizing synergies are in competition because the former favors negative co-variation of finger modes, while the second one favors positive co-variation among subgroups of fingers that produce moment in the opposite direction in reference to a pivot point. Force stabilizing synergies have been seen in multiple pressing experiments where subjects received visual feedback on the total force (Latash et al. 2002; Scholz et al. 2003; Shim et al. 2005c). However, some experiments of fast force production, the total moment was stabilized better than the total force, even though the subjects did not receive any feedback on the total moment (Latash et al. 2001; Scholz et al. 2002) and it was proposed that
activities of daily living such drinking from a glass constrain the rotational action of the hand more than its gripping action. A later experiment where subjects received visual feedback on the total moment showed that subjects stabilized the total moment but the total force to less extent (Zhang et al. 2007).

![UCM analysis](image)

**Figure 2.1 An example of UCM analysis during a two finger pressing task.**

Studies with older individuals have revealed that they are able to produce force stabilizing synergies, but to a lesser degree than young subjects (Shinohara et al. 2003a, 2003b, 2004).

Recently UCM analysis has been used to identify a novel phenomenon, anticipatory synergy adjustments (ASA’s) that appear in preparation to a predictable change in the performance variable (Olafsdottir et al. 2005b; Kim et al. 2006). When a steady level of force is produced in pressing tasks, negative co-variation of finger forces prevails, quantified by a positive index of co-variation ($\Delta V$). In conditions where subjects could not predict the occurrence of perturbation or initiation of change in total force, $\Delta V$ stayed stable until the change in total force occurred while in conditions where subjects initiated the change in total force themselves, $\Delta V$ started to drift downwards (indicating destabilization of the total force) prior to any force changes were observed. It was suggested that these anticipatory changes reflect a feed-forward mechanism of similar nature as anticipatory postural adjustments.
2.3 Anatomy of the Hand

2.3.1 Bones and Joints of the Hand, Wrist and Forearm

In common language, the hand is defined as the area of the upper extremity that is distal to the wrist, meaning the joint between the two forearm bones, radius and ulna, and the carpal bones. Anatomically, however, the carpal bones belong to the wrist. In this discussion the common definition will be used when describing the hand and anatomical position (palms forward) assumed.

The human hand has 27 bones, 8 carpal, 5 metacarpal and 14 phalangeal. The 8 carpal bones are arranged in two rows; the scaphoid, lunate, triquetrum and pisiformis bones (seen lateral to medial) forming the proximal row and the trapezium, trapezoideum, capitate and hamate bones (lateral to medial) the distal row. The two rows of carpal bones as well as individual bones are connected by the intercarpal joint but the distal row is connected to the five metacarpal bones via the carpometacarpal (CMC) joint. Each digit has three phalangeal bones except the thumb which has two. The metacarpophalangeal (MCP) joint connects the metacarpal bones and the proximal phalanges; the proximal interphalangeal (PIP) joint the proximal and middle phalanges and the distal interphalangeal (DIP) joint the middle and distal phalanges. The thumb, having only two phalanges has only one interphalangeal (IP) joint. Figure 2.2 shows the bones and joints of the hand.
Two bones, ulna and radius form the forearm, figure 2.3. In a supinated position the ulna is medial and the radius lateral but when the forearm is pronated the radius rotates about an axis passing from the proximal head of the radius to the distal head of the ulna so its distal end moves medial to the ulna (figure 2.3). Proximally the forearm bones connect to the bone of the upper arm, the humerus via the elbow joint. It is comprised of three parts, the joint between the ulna and the humerus; the joint between the radius and humerus, and the proximal radio-ulnar joint. Distally the wrist joint connects the hand and the forearm. The distal head of the radius connects to three of the bones in the first row of the carpal bones, the scaphoid, lunate and triquetrum.

Figure 2.2 Bones and joints of the hand.
2.3.2 Movements of the Hand, Wrist and Elbow

The interphalangeal joints of the fingers are uni-axial hinge joints that permit only flexion and extension. The range of motion (ROM) of joint flexion is about 60°-70° in the DIP and 100°-110° in the PIP. The MCP joints are condyloid joints that allow flexion, extension, abduction, adduction and circumduction. Their ROM is approximately 90° in flexion and 20°-30° extension (from neutral position), but the ROM differs between the fingers, i.e. the index finger has the smallest ROM (70°) but the little finger the largest (95°). The ROM of ab- and adduction are about 60° for the index finger, 45° for the middle and ring fingers and 50° for the little finger. The CMC joints are plane synovial joints that allow only gliding movements. The articulations of the thumb are quite different from the other digits. The thumb has only one interphalangeal joint, a uni-axial hinge joint that has ROM of 15°-20° in (hyper) extension and 80° in flexion. The thumb’s MCP joint is unique among the joints of the hand. It is a ball and socket joint with 3 degrees of freedom but when it is flexed, collateral ligaments tighten.
and limit rotation, ab- and adduction, so the joint acts like a hinged joint with
ROM of 10° extension and 55° flexion (Eaton, 1997). The CMC of the thumb is a
saddle joint and permits flexion, extension, abduction, adduction and opposition.
It’s ROM ranges from 60° extension until the thumb touches the palm and 45°
abduction until it touches the index finger. Figure 2.4 shows the moments of the
thumb.

Figure 2.4 Movements of the thumb (Smith 1996)

The wrist joint is a condyloid joint formed by the distal head of the radius
and the distal surface of the articular discus on one side and three carpal bones
(scaphoid, lunate and triquetrum) on the other side. The joint has three degrees of
freedom, allowing flexion, extension, abduction (radial deviation), adduction
(ulnar deviation) and circumduction (Gray, 2000). The ROM of the wrist is 75°
flexion, 70° extension, 20° abduction and 35° adduction. The elbow is a hinge
type joint. The trochlea fovea of the humerus sits in the semilunar notch of the ulna and the capitulum of the humerus also connects to the fovea on the radial head (Gray, 2000). The ROM of the joint is 0° extension and 145° flexion. The rotation of the radius about the ulna has ROM of 70° pronation and 85° supination (Eaton, 1997).

### 2.3.3 Muscles of Hand and Forearm

The muscles that serve hand are divided into extrinsic (originating in the fore- or upper arm) and intrinsic (originating within the hand) muscles. The extrinsic muscles are connected to the hand bones by long tendons that run through tendon sheaths. Of the 33 muscles that control the hand, 18 are intrinsic and 15 extrinsic. The extrinsic muscles are generally larger and generate most of the force of the hand while the intrinsic muscles are smaller and are associated with fine movements of the fingers (Freivalds, 2004). The extrinsic muscles are both functionally and structurally divided into two groups, anterior and posterior, the anterior muscles being flexors of the fingers and the posterior muscles the extensors. Flexor digitorum superficialis (FDS) and profundus (FDP) are the main flexors of the fingers. FDS originates on humerus and ulna and splits into four tendons that attach to the middle phalanx of the index to little fingers. The FDP also has origins at the ulna and splits into four tendons but they insert at the distal phalanx of the four fingers and have to pass through a split in the FDS in order to do so. In addition to FDS and FDP, the lumbricales and interossei muscles flex the fingers about the MCP joint but extend at the interphalangeal (IP) joint. That enables the IP joints to be extended while the MCP joints are flexed (make a “roof”). Figure 2.5 illustrates some of the intrinsic hand muscles and figure 2.6 some of the extrinsic flexor muscles.
Figure 2.5 Intrinsic hand muscles of the right hand. A. Dorsal interossei. B. Palmar interossei (Drake et al. 2005)
Figure 2.6 Extrinsic flexor muscles of the right forearm. A. Intermediate layer B. Deep layer. (Drake et al, 2005).

The mechanism by which the fingers are extended is slightly more complicated. The main extending muscle is extensor digitorum communis (EDC). It is aided by the lumbricales and interossei but in addition to that, extension is mediated by several non-contractile structures that in fact are elaborate extension
of the EDC tendon. Figure 2.7 illustrates the extensor mechanism of the fingers. The EDC tendon crosses the MCP joint and attaches to the base of the proximal phalanx by a lax tendinous slip and extends the joint. Above the proximal phalanx, the EDC tendon divides into three bands: a central band and two lateral bands. The central band proceeds to the base of the middle phalanx where it attaches and produces extension of the PIP joint. Extension in the DIP joint is produced by tension in the lateral bands that course on either side of the PIP joint before rejoining over the middle phalanx and attaching to the base of the DIP.

The interossei muscles attach to the sides of the fingers in numerous places. They insert into the base of the middle phalanx, contribute to the lateral bands and to the tendons that attach to the base of the middle phalanges. The lumbricals attach to the lateral bands of the EDC. Therefore, the extension of the PIP and DIP joints is produced by input from at least four muscles, the EDC, a lumbrical and two interosseous muscles that all connect to the lateral bands. In addition to that, the extensor indicis and extensor digitii minimi produce extension in respective digits (Smith et al. 1996).

![Figure 2.7 Finger extensor mechanism (Drake et al. 2005).](image)

The main flexors of the wrist are flexor carpi ulnaris and radialis while extension is produced mostly by extensor carpi radialis longus and brevis and extensor carpi ulnaris.

Pronator quadratus and pronator teres pronate the forearm but the supinator muscle supinates it. Elbow flexion is produced by biceps brachi, brachialis and radiobrachialis and triceps brachi extends it.
Tables 2.1, 2.2 and 2.3 describe the intrinsic muscles of the hand, the extrinsic muscles of the hand and the muscles that control the movements of elbow and forearm, their origin, insertion and main functions (Brand, 1985; Moore, 1992, Richardson et al. 2000, Eaton, 1997).

**Table 2.1 Intrinsic muscles of the hand.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metacarpal</td>
<td>Palmar interossei (3)</td>
<td>Metacarpal bones (except the middle)</td>
<td>Bases of proximal phalanges (except of middle finger)</td>
<td>Flexion and adduction of fingers at MCP</td>
</tr>
<tr>
<td></td>
<td>Dorsal interossei (4)</td>
<td>Metacarpal bones</td>
<td>Bases of proximal phalanges and extensor tendons of digits</td>
<td>Abduction and flexion of fingers 2-4 at MCP, extension at IP</td>
</tr>
<tr>
<td></td>
<td>Lumbricales (4)</td>
<td>Tendons of flexor digitorum profundus</td>
<td>Lateral sides of tendons of extensor digitorum on the proximal phalanx of each finger</td>
<td>Flexion of MCP joints, extension at IP</td>
</tr>
<tr>
<td>Thenar</td>
<td>Abductor Pollicis brevis</td>
<td>Scaphoid and trapezium and surrounding area</td>
<td>Base of the 1st proximal phalanx</td>
<td>Abduction of thumb, aids in opposition</td>
</tr>
<tr>
<td></td>
<td>Flexor pollicis brevis</td>
<td>1st metacarpal, trapezium, radial side of carpus</td>
<td>Base of the 1st proximal phalanx</td>
<td>Flexion of thumb, aids in opposition</td>
</tr>
<tr>
<td></td>
<td>Adductor pollicis</td>
<td>Capitate &amp; 2nd &amp; 3rd metacarpals</td>
<td>Base of the 1st proximal phalanx</td>
<td>Adduction and flexion of thumb</td>
</tr>
<tr>
<td></td>
<td>Opponens pollicis</td>
<td>Trapezium &amp; surrounding area</td>
<td>1st metacarpal</td>
<td>Opposition of thumb, rolls it towards midline</td>
</tr>
<tr>
<td>Hypothenar</td>
<td>Abductor digiti minimi</td>
<td>Pisiform &amp; surrounding area</td>
<td>Medial aspect of the 5th proximal phalanx (little)</td>
<td>Abduction and flexion of little finger at MCP</td>
</tr>
<tr>
<td></td>
<td>Flexor digiti minimi brevis</td>
<td>Flexor retinaculum &amp; hamate</td>
<td>Medial side of the proximal phalanx of the little finger</td>
<td>Flexion of little finger at CP and MCP</td>
</tr>
<tr>
<td></td>
<td>Opponens digiti minimi</td>
<td>Hamate &amp; adjacent region</td>
<td>Medial side of the 5th proximal phalanx</td>
<td>Opposition of little fingers</td>
</tr>
</tbody>
</table>
Table 2.2 Extrinsic hand muscles.

<table>
<thead>
<tr>
<th>Group</th>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial anterior</td>
<td>Flexor carpi radialis</td>
<td>Medial epicondyle of humerus</td>
<td>2nd and 3rd metacarpals</td>
<td>Flexion and radial abduction at wrist</td>
</tr>
<tr>
<td></td>
<td>Flexor carpi ulnaris</td>
<td>Medial epicondyle of humerus &amp; sup post border of ulna</td>
<td>Pisiform, hamate &amp; base of 5th MC</td>
<td>Flexion and ulnar abduction of wrist</td>
</tr>
<tr>
<td></td>
<td>Palmaris longus</td>
<td>Medial epicondyle of humerus</td>
<td>Flexor retinaculum &amp; palmar aponeurosis</td>
<td>Weak flexion of wrist</td>
</tr>
<tr>
<td>Deep anterior</td>
<td>Flexor digit. superficialis</td>
<td>Medial epicondyle of humerus, coronoid process of ulna</td>
<td>Splits into 4 tendons that insert on the distal phalanges of digits 2-5</td>
<td>Strong finger flexion; flexes wrist, MCPs and PIPs</td>
</tr>
<tr>
<td></td>
<td>Flexor digit. profundus</td>
<td>Antero-medial proximal ulna, interosseous membrane</td>
<td>Splits into 4 tendons that insert on the distal phalanges of digits 2-5</td>
<td>Strong finger flexion; flexes: wrist, MCPs, PIPs and DIPs</td>
</tr>
<tr>
<td></td>
<td>Flexor pollicis longus</td>
<td>Ant surface of proximal radius &amp; interosseous membrane</td>
<td>Distal phalanx of thumb</td>
<td>Thumb: Flexion of: Wrist, CMC,MCP, DIP; Adduction of CMC</td>
</tr>
<tr>
<td>Radial</td>
<td>Ext carpi rad brevis</td>
<td>Lat epicondyle of humerus</td>
<td>3rd MC</td>
<td>Extension and abduction at wrist</td>
</tr>
<tr>
<td></td>
<td>Ext carpi rad longus</td>
<td>Lat supracondylar ridge of humerus</td>
<td>2nd MC</td>
<td>Extension and abduction at wrist</td>
</tr>
<tr>
<td>Superficial posterior (Ulnar)</td>
<td>Extensor carpi ulnaris</td>
<td>Lat epicondyle of humerus &amp; post border of ulna</td>
<td>5th MC</td>
<td>Extension and adduction at wrist</td>
</tr>
<tr>
<td></td>
<td>Extensor digitorum</td>
<td>Lat epicondyle of humerus</td>
<td>Splits into 4 tendons that insert on the distal phalanges of digits 2</td>
<td>Finger extension; extends wrist, MCPs, PIPs and DIPs</td>
</tr>
<tr>
<td></td>
<td>Extensor indicis</td>
<td>Distal aspect of dorsal ulna &amp; interosseous membrane</td>
<td>Joins tendon of ED, inserts into the distal phalanx of the index finger</td>
<td>Extension of index finger; MCP,PIP,DIP</td>
</tr>
<tr>
<td></td>
<td>Extensor digitii minimi</td>
<td>Lateral epicondyle of humerus &amp; proximal radius</td>
<td>Distal phalanx of little finger</td>
<td>Extension of little finger</td>
</tr>
<tr>
<td>Deep posterior</td>
<td>Abd pollicis longus</td>
<td>Dorsal radius, ulna &amp; interosseus membrane</td>
<td>Base of 1st MC</td>
<td>Thumb: Extension and abduction at MCP</td>
</tr>
<tr>
<td>Group</td>
<td>Muscle</td>
<td>Origin</td>
<td>Insertion</td>
<td>Function</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------</td>
<td>------------------------------------------------------------------------</td>
<td>-----------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Anterior</td>
<td>Pronator Quadratus</td>
<td>Distal ¼ anterior surface of ulna</td>
<td>Distal ¼ ant surface of radius</td>
<td>Pronation of forearm</td>
</tr>
<tr>
<td></td>
<td>Pronator Teres</td>
<td>Medial epicondyle of humerus and coronoid process of ulna</td>
<td>Middle of lateral surface of radius</td>
<td>Pronation of forearm</td>
</tr>
<tr>
<td></td>
<td>Biceps Brachi</td>
<td>Supraepiglenoid turbercule of scapula (long head)</td>
<td>Tuberosity of radius</td>
<td>Flexion of elbow and supination of forearm.</td>
</tr>
<tr>
<td></td>
<td>Brachialis</td>
<td>Lower ½ of front of humerus</td>
<td>Tuberosity of ulna</td>
<td>Flexion of elbow</td>
</tr>
<tr>
<td></td>
<td>Brachioradialis</td>
<td>Lateral supracondylar ridge of humerus</td>
<td>Lateral part of radius above styloid process</td>
<td>Flexion of elbow and supination of forearm.</td>
</tr>
<tr>
<td></td>
<td>Supinator</td>
<td>Lateral epicondyle of humerus, radial col-lateral and annular ligaments, supinator fossa and crest of ulna</td>
<td>Lateral, posterior and anterior surfaces of proximal 1/3 of radius</td>
<td>Supination of forearm</td>
</tr>
<tr>
<td>Posterior</td>
<td>Anconeus</td>
<td>Lateral epicondyle of humerus</td>
<td>Lateral surface of olecranon and superior part of post. surface of ulna</td>
<td>Extension of elbow.</td>
</tr>
<tr>
<td></td>
<td>Triceps Brachi</td>
<td>Long head: Infra-glenoid tuberosity of scapula; Lat. head: Post. surface of humerus above rad groove; Med. head: Post surface of humerus below rad groove.</td>
<td>Olecranon process of ulna</td>
<td>Extension of elbow and adduction of arm.</td>
</tr>
</tbody>
</table>

Table 2.3 Muscles of elbow and forearm.
2.4 The Central Nervous System and the Hand

The concept of a somatotopic organization of the primary motor cortex (M1) has been around for quite a long time. Hughlings Jackson (1958) hypothesized in the 1870’s that cortical regions were systematically organized to control movements of different body parts. He based this idea on his observations of epileptic patients whose spasmic movements traveled systematically between parts of the body.

Later, improvements in electrical stimulation techniques facilitated more knowledge on the organization of the cortex and in 1950 Penfield and Rasmussen published their famous notion of the homunculus (Penfield and Rasmussen, 1950), see figure 2.8

Within the homunculus, M1 is systematically organized and different physical parts correspond to different parts of the body. In the most elaborate format of the homunculus, M1 was divided so accurately that each digit was represented by separated areas (Schieber, 2001). Recent data; do however, argue against this intricate point-to-point organization of the M1 (Hepp-Reymond, 1988; Porter, 1993; Schieber, 1999; Schieber, 2001) even though it is clear that the head, upper- and lower extremities are represented by different areas of the M1. Humans seem, however, to possess greater somatotopic representation of digits than other primates (Beisteiner et al. 2001; Kim, 2001; Kleinschmidt et al. 1997; Schieber, 1999; Schieber and Poliakov, 1998). In humans lateral lesions have been seen to have more effect on movements of thumb and index finger while medial lesions impair more little and ring fingers but this kind of segregation is not evident in Macaque monkey (Kim, 2001; Schieber, 1999; Schieber and Poliakov, 1998). As of now the notion of well-ordered within-limb somatotopic organization of the M1 has not been refuted by one experiment but cumulative data suggest that it is not as simple as observed in the homunculus (Schieber, 2001). Several factors constrain to what degree the control of finger movements can be explained by somatotopic organization of the M1 (Schieber, 2001). a) Outputs from a large M1 area converge to control a particular part of the body. b) The output of a single M1 neuron often diverges and innervates the
motoneuronal pool of more than one muscle. c) Horizontal connections interlink the cortex throughout a major body part region. d) Activation of a small body part, such as a finger, induces a widely distributed activity in its larger body part area (the arm). e) A partial inactivation of a major region affects multiple smaller body parts at the same time. Stimulation of a small area causes movements in thumb and index fingers but lesion of that area causes impairment of the whole hand. f) The M1 is very plastic. A variety of changes, such as peripheral lesions, central lesions and motor skill learning causes M1 to undergo plastic reorganization. In rats that were trained to reach and grab food, the representation of digits and wrist movements increased but the area responsible for elbow and shoulder movements decreased (Schieber, 2001).

In spite of all these constraints, humans are able to produce both movements that require individual control of fingers as well as synchronized control. Population analysis has shown that the discharge of M1 neurons transmits information that specifies which finger movement will be performed (Ben Hamed et al. 2001; Georgopoulos et al. 1999; Schieber and Santello, 2004) and it has been suggested that M1 is organized in such a way that similar neurons that control particular movements or subsets of movements are clustered into groups but the members of each group are spatially distributed throughout the M1 hand representation (Schieber and Santello, 2004).

Poliakov and Schieber (1999) used cluster analysis to search for populations of M1 neurons that were functionally similar during hand and finger movements in monkeys. From this study they hypothesized that the connections from M1 to motoneuronal pool act as a highly distributed network. Within this network, activity of a selected subset of M1 neurons would induce activation of the motoneuronal pool needed for the desired movement (Schieber and Santello, 2004).
2.5 Coordination of Fingers in Pressing Tasks

2.5.1 Indices of Finger Interaction

Voluntary flexion of one finger induces involuntary flexion of other fingers, that is, the fingers are not independent to one another. This is caused both by peripheral factors such as common tendons and muscles to the fingers and central factors such as overlapping cortical representations of the fingers (Schieber 2001). Studies on finger interaction during force production tasks have shown to be represented by three major indices: sharing, enslaving and force deficit (Li et al. 1998a, b; Zatsiorsky et al. 1998, 2000).

Sharing (S) is the phenomenon that the relative share of a finger to the total force in a multi-finger task is stable over a wide range of forces (Ohtsuki 1981; Kinoshita et al. 1995). Enslaving (E) describes the involuntary force production of
fingers in tasks where they are not the specifically instructed fingers (Kilbreath and Gandevia 1994; Schieber 2001) and force deficit (FD) addresses the fact that the maximal force a finger produces in a multi-finger task is less than the maximal force it produces when acting alone (Ohtsuki 1981; Kinoshita et al. 1995). Quantitatively sharing, enslaving and force deficit have been defined as:

\[ S_i = \frac{100}{\%} \frac{F_{i,\text{task}}}{F_{\text{Tot,task}}} \quad E_{i,j} = \frac{100}{\%} \frac{F_{i,j}}{F_{i,i}} \quad FD_{i,\text{task}} = \frac{100}{\%} \frac{(F_{i,j} - F_{i,\text{task}})}{F_{i,i}} \]

where S, E, and FD refer to sharing, enslaving and force deficit, subscripts i and j refer to fingers (index I, middle: M, ring: R and little: L), Tot stands for total and task indicates a multi-finger task.

In studies with young healthy subjects sharing, enslaving and force deficit have been observed to behave in a fairly regular manner. Typically in a four finger task, index and middle fingers produce about 30% of the total force each while the ring finger produces 25% and the little finger 15% (Li et al. 1998a; Li et al. 2000; Zatsiorsky et al. 1998). The sharing pattern can change if external mechanical conditions are altered (Zatsiorsky et al. 1998). When the thumb is included in a task, the sharing pattern that results depends on its position relative to the fingers. When the thumb acted in opposition, its share doubled compared to when it acted parallel to the fingers (Olafsdottir et al. 2005a). Enslaving effects are stronger between adjacent fingers (i.e. proximity rule) and the index finger is the most independent finger, that is, it induces the least enslaving in other fingers and is the least enslaved one while the ring and little fingers are both highly enslaved (Zatsiorsky et al. 2000). Enslaving is on average 2.1 times larger when the thumb opposes the fingers than when it is parallel to them but is not dependent on whether the thumb is a task finger or not (Olafsdottir et al. 2005a). Force deficit increases with the number of explicitly involved fingers and is, on average, 38% in two-finger tasks, 48% in three-finger tasks and 54% in four-finger tasks (Li et al. 1998a), but decreases again when the thumb is included (Olafsdottir et al. 2005a).
The fingers of the hand are controlled by both extrinsic (located in the forearm) and intrinsic (located in the hand itself) muscles. During normal usage of the hand, both groups of muscles are activated but their relative involvement may differ from task to task (Darling et al. 1994; Maier and Hepp-Reymond 1995a, b). The extrinsic and intrinsic muscles attach to the fingers in different anatomical sites which enables their relative involvement in a task to be manipulated by changing the point of force application (Danion et al. 2000; Li et al. 2000). When pressing down using the fingertips, most of the force is produced by the extrinsic flexor muscles but the intrinsic muscles mostly work to balance moments at the MCP joints (Li et al. 2000). On the other hand, when the force is generated by pressing down the proximal phalanges, holding the distal phalanges in an intermediate position, the focal force generators are the intrinsic muscles while the extrinsic muscles balance out the action of the extensor mechanism at the IP joints (An et al. 1985; Chao et al. 1976). During a peak force generation using the fingertips, extrinsic muscles are producing their maximal output while intrinsic muscle produce only about 10-30% of their maximum (Harding et al. 1993; Li et al. 2000) and maximal effort at the proximal phalanges is generated by close to maximal force production of the intrinsic muscles and about 20% of the maximal output of the two main extrinsic muscles (FDP and FDS) (Chao and An 1978; Harding et al. 1993; Landsmeer and Long 1965; Smith 1974). Studies of the indices of finger coordination at the two sites, distal (fingertips) and proximal, have shown that when young healthy subjects produce force at the proximal phalanges, maximal force, enslaving and force deficit are all larger (Li et al. 2000; Danion et al. 2000; Latash et al. 2002; Shinohara et al. 2003a). Various factors, for example, age, gender and fatigue can affect the difference between the two sites in these indices (Li et al. 2000; Danion et al. 2000; Latash et al. 2002; Shinohara et al. 2003a).

Studies on the indices of finger interaction have provided evidence in support of the hypothesis that these indices reflect the central organization of control as well as the anatomical design of the hand (Leijnse et al. 1993; Kilbreath and Gandevia 1994; Roullier 1996; Latash et al. 1998; reviewed in Schieber and
Enslaving has been seen to be larger when force is produced at the proximal phalanges. When intrinsic muscles produce the majority of the force and elderly individuals show less enslaving in spite of having both larger amount of connective tissue and enlarged motor units (Larsson and Ansved 1995; Zimmerman, 1993). If enslaving resulted only from the biomechanics of the hand, in both cases the opposite results would be expected (Li et al. 2000; Danion et al. 2000; Latash et al. 2002a; Shinohara et al. 2003a, b).

Fatigue induces a drop in the maximal force production of the fingers and changes in sharing, enslaving and force deficit. When all four fingers were fatigued, peak force dropped by about 43% but the sharing pattern changed minimally. Enslaving did not change in magnitude but force deficit increased by 122% (Danion et al. 2000). The effects of fatigue were more pronounced at the site it was applied to. When only the index finger was fatigued, its maximal force dropped by 33% but the peak force of other fingers dropped as well, though to a lesser degree. When applied to the proximal phalange of the index finger, fatigue induced a loss only in fingers close the index finger but when applied to the distal phalange all fingers showed equal drop in maximal force produced. Fatiguing only the index finger caused it to be less enslaved by other fingers while its enslaving effects on other fingers remained unchanged. Force deficit of index finger increased but other fingers showed no change (Danion et al. 2001).

2.5.2 The Force Mode Hypothesis

When one finger produces force, other fingers involuntarily also produce force. This phenomenon, called enslaving, results both from peripheral factors such as shared muscles (Moore, 1992) as well as central factors such as overlapping cortical areas of individual fingers (Schieber 2001). Thus, the forces the fingers produce are not independent variables. The notion of force modes, hypothetical independent central commands to the fingers were first introduced by Zatsiorsky et al. (1998) in relation to the neural network model. Later force modes were used for a formal description of finger force generation (Danion et al. 2003) and within the framework of the Uncontrolled Manifold Hypothesis to identify
synergies that stabilize an important performance variable such as total force or total moment in finger coordination tasks (Latash et al. 2001, Scholz et al. 2002, Olafsdottir et al. 2005b).

Within this description, during a given task where one or more of the four fingers are instructed to produce force, the total force output is the result of a force mode vector, generated by the central nervous system, that is transformed by a matrix of inter-finger connections (enslaving matrix) and a factor ”k” that reflects the phenomenon of force deficit and depends on the number of task fingers (Danion et al. 2003). The force mode hypothesis is depicted in figure 2.9. More formally, the force produced by the four fingers of the hand are modeled as a four-dimensional vector $f = [F_I, F_M, F_R, F_L]$ that is the product of a $4 \times 4$ enslaving matrix $[E]$ obtained in single-finger MVC or ramp tests and a four-dimensional input vector of force modes $m = [m_I, m_M, m_R, m_L]^T$, where subscripts refer to individual fingers and the superscript T refers to transpose. The result is attenuated by an empirically defined factor, $k$, that reflects the force deficit and depends on the number of explicitly involved (master) fingers, $n$:

$$ f = k(n) [E] m $$

In MVC tasks, the force mode vector is a row of zeros (for slave fingers) and ones (for master fingers) so that a task where index and ring fingers are task or master fingers will have input $m = [1,0,1,0]^T$. The factor reflecting force deficit, $k$, was found by fitting datasets to the function $k = 1/N_y$ using the least squares algorithm in MatLab. The best fit was found with the exponent $y = 0.712$, accounting for 99.9% of the variance.

With the force mode hypothesis enslaving, force deficit and sharing are integrated in a simple manner. Sharing patterns in multi-finger tasks are seen to arise simply from a linear superposition of modes and the different magnitudes of the sharing of different fingers to arise from different enslaving patterns during single-finger tasks. Force deficit is represented by a gain factor $k$ that has been shown to depend on the number of task fingers but not the exact fingers being used.
2.5.3 Force and moment stabilizing synergies during pressing

The notion of synergies has been used quite extensively to investigate and quantify finger coordination in multi-finger force production tasks. Synergies were introduced in section 2.2 but are in general terms a set of elemental variables that interact in such a way that they stabilize the output of a common important performance variable chosen by the central nervous system. In studies with multi-finger pressing tasks, the elemental variables have been defined as being either forces produced by the fingers or modes (hypothetical independent elemental variables, see section 2.4.2) and the performance variables either total force or total moment of the force.

To identify force or moment stabilizing synergies two methods have been predominantly used, the uncontrolled manifold (UCM, see section 2.2) and a method nicknamed “Poor man’s UCM”. The latter method is based on the argument that synergies can be defined as covariations of forces or moments produced by individual fingers that reduce the variance of the total force or total moment across trials. Operationally this method compares the variance of the total force ($\text{VarF}_{\text{tot}}$) or total moment ($\text{VarM}_{\text{tot}}$) to the sum of the variances of individual finger forces ($\sum \text{VarF}_i$) or moments ($\sum \text{VarM}_i$) and a conclusion of predominantly negative covariation of individual finger forces or moments that stabilize total force or total moment is found when $\Delta V = (\sum \text{VarF}_i - \text{VarF}_{\text{tot}}) > 0$. 

$$G = F(\text{number of Modes}) \leq 1$$
(see Bienaymé equality theorem, Loève 1977). This method will, however, inherently underestimate the strength of synergies due to the phenomenon of enslaving (finger forces and moments are not independent variables).

When young healthy subjects produce a steady state of force or increase the magnitude of force gradually (force ramp) they are typically able to successfully produce force stabilizing synergies (Latash et al. 2002a; 2002d; Olafsdottir et al. 2005b; Shim et al. 2003a, 2005c; Shinohara et al. 2003b, 2004) but only after a certain subject and task dependent time delay that ranges from 130 – 800 ms (Shim et al. 2003a, 2005c). The time delay may reflect the time needed to adjust the finger force using sensory-feedback and is in agreement with results of studies on sensory feedback for control of finger forces in grasping (Burstedt et al. 1997; Johansson 1996). In force tasks where a pair of fingers on each hand was used, a between-hands synergy was seen but not a within-hand synergy. When the task was performed using only one hand, within-hand synergies appeared that were independent of both hand dominance and which finger pair was used (Gorniak et al. 2007). Similarly, in a bimanual force task where unusual finger combinations were used (index and ring on left hand and middle and little fingers on right hand), within-hand force stabilizing synergies were seen but when each hand performed the task on their own, total force was not stabilized but total moment was (Kang et al. 2004). Following a 2 day practice within-hand force stabilizing synergies appeared and stabilization of total moment remained unchanged (Kang et al. 2004).

Studies with elderly individuals have shown that they are able to produce force stabilizing synergies but to a much lesser degree than young subjects (Shinohara et al. 2003b, 2004). Similarly, individuals with Down’s syndrome have impaired ability to produce force stabilizing synergies and typically favor positive co-variation among finger forces or a “fork strategy” (Latash et al. 2002d). However, following training over 3 days, their performance improved drastically and the pattern of co-variation of finger forces became closer to what was observed in typical control subjects (Latash et al. 2002d).
Recent studies on finger coordination in force pressing tasks have introduced novel phenomena, anticipatory synergy adjustments, ASA’s. As described before, a steady force production with multiple fingers is accompanied by a negative co-variation of finger forces that stabilize the total force output. When the task requires the total force output to change in a manner that is predictable to the subject, anticipatory drop in the synergy index, $\Delta V$, has been observed, starting 100-150 ms prior to any change in the total force (Kim et al. 2006; Olafsdottir et al. 2005b; Shim et al. 2005c). Anticipatory synergy adjustments have been observed in a task that involved a controlled decrease in total force from a certain level (Shim et al. 2005c), prior to a quick pulse to a target that was initiated in a self-paced manner (Olafsdottir et al. 2005b) and prior to a self-induced perturbation of one of the fingers (Kim et al. 2006).

Most of previous studies on finger coordination have used the total force produced by the task fingers as visual feedback. In several studies, unexpectedly, the subjects stabilized the total moment produced by the fingers about a longitudinal axis of the hand better than the total force in spite of not receiving any instructions or feedback about the total moment (Latash et al. 2001; Scholz et al. 2002). These results lead the authors to hypothesize that in everyday tasks, control of total moment may be more important than control of total force. This issue was investigated further in a study where subjects were requested to produce a time profile of total moment (about an axis located between middle and ring fingers) using four fingers where two fingers were assigned to produce “negative” moment and the other two “positive” moment and a feedback on the total moment was provided. The results were in agreement with the hypothesis that stabilization of rotational action may be a default strategy conditioned by everyday experience, subjects showed a pattern of co-variation of commands to the fingers that stabilized the total moment but not or to a very little extent the total force (Zhang et al. 2006).
2.5.4 The Mechanical Advantage Hypothesis

The mechanical advantage hypothesis states that when several effectors, for example, fingers or muscles, produce a common rotational action in the same direction, the effectors with the longer moment arm produce a relatively larger share of the total moment because less force is needed to produce each unit of the total moment (Buchanan et al. 1989, Prilutsky 2000, Zatsiorsky et al. 2002, Zhang et al. 2006). Figure 2.10 describes the mechanical advantage hypothesis. Forces $F_1$ and $F_2$ are of equal size but moment arm $r_1$ is twice the size of moment arm $r_2$, thus, $M_1$, the moment of $F_1$ about the axis, is larger than $M_2$. Several studies on multi-finger pressing and prehension tasks, have addressed the mechanical advantage hypothesis, the results of some supporting it fully (Shim et al. 2005a) while others only partially (Gao et al. 2005; Shim et al. 2004a,b; Zatsiorsky et al. 2002; Zhang et al. 2006). This has led to the suggestion that the mechanical advantage hypothesis reflects an intrinsic self-imposed tendency to minimize the total amount of finger force produced but is of a limited applicability because other factors also contribute to the definition of effector involvement. It may, for example, be applicable to a set of effectors that produce action in the required direction (agonist) but not those that produce action in the direction that opposes the movement (antagonist) (Zhang et al. 2006).
Figure 2.10 A simple example of the mechanical advantage hypothesis: The two forces that produce moments are equal in size but the moment arm of F₁ is twice the moment arm of F₂. Therefore the moment produced by F₁ (M₁) is twice the magnitude of M₂.

2.6 Coordination of Fingers in Prehension

2.6.1 Classification and hierarchical control of Prehension

Prehension has be defined as “the act of grasping or seizing” or in a slightly more elaborate manner as “the application of functionally effective forces by the hand to an object for a task, given numerous constraints” (c.f. McKenzie & Iberall, 1994). Researches from various fields such as anthropology, medicine, biomechanics, robotics and occupational medicine have made multiple attempts to classify hand postures (Table 2.4).
Table 2.4 Examples of classifications of prehension from the literature.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Posture names</th>
<th>Posture names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutkosky 1989</td>
<td>Power grasps</td>
<td>Precision grasps</td>
</tr>
<tr>
<td></td>
<td>Large diameter heavy wrap</td>
<td>5-finger precision grasp</td>
</tr>
<tr>
<td></td>
<td>Small diameter heavy wrap</td>
<td>4-finger precision grasp</td>
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<td></td>
<td>Medium wrap</td>
<td>3-finger precision grasp</td>
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<td></td>
<td>Adducted thumb wrap</td>
<td>2-finger precision grasp</td>
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<tr>
<td></td>
<td>Disk power grasp</td>
<td>Disk precision grasp</td>
</tr>
<tr>
<td></td>
<td>Spherical power grasp</td>
<td>Spherical precision grasp</td>
</tr>
<tr>
<td></td>
<td>Lateral pinch</td>
<td>Tripod precision grasp</td>
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<tr>
<td></td>
<td>Hook, platform, push</td>
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</tr>
<tr>
<td>Iberall et al. 1986</td>
<td>Palm opposition</td>
<td>Side opposition</td>
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<td></td>
<td>Pad opposition</td>
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<tr>
<td>Jacobson et al. 1976</td>
<td>A coding system for fingers,</td>
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<td></td>
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<td>finger positions, finger joint</td>
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<td></td>
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<td>positions, contact surfaces</td>
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<td>and orientation of object’s</td>
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<td>longitudinal axis with</td>
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<td>respect to the hand</td>
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<td>Kamakura et al. 1980</td>
<td>Power grip-standard</td>
<td>Parallel extension grip</td>
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<tr>
<td></td>
<td>Power grip-index extension</td>
<td>Tripod grip</td>
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<td>Power grip-distal</td>
<td>Tripod grip-var. 1</td>
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<tr>
<td></td>
<td>Power grip-extension</td>
<td>Tripod grip-var. 2</td>
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<tr>
<td></td>
<td>Parallel Mild flexion grip</td>
<td>Lateral grip</td>
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<tr>
<td></td>
<td>Tripprehension</td>
<td>Power grip-hook</td>
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<td></td>
<td>Surrounding mild flexion grip</td>
<td>Adduction grip</td>
</tr>
<tr>
<td>Landsmeer 1962</td>
<td>Power grasp</td>
<td>Precision handling</td>
</tr>
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<td>Napier 1956</td>
<td>Power grip</td>
<td>Combined grip</td>
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<tr>
<td></td>
<td>Precision grip</td>
<td>Hook grip</td>
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<tr>
<td>Schlesinger 1919</td>
<td>Open fisted cylindrical grasp</td>
<td>Cylindrical w/add. Thumb</td>
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<tr>
<td></td>
<td>Close fisted cylindrical grasp</td>
<td>Flat/thin (2 finger) pincer</td>
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<td></td>
<td>Spherical prehension</td>
<td>Large (5 fingered) pincer</td>
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<td></td>
<td>Palmar prehension</td>
<td>Three-jaw chuck</td>
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<td></td>
<td>Tip prehension</td>
<td>Nippers prehension</td>
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<td></td>
<td>Lateral prehension</td>
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<td></td>
<td>Hook prehension</td>
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<tr>
<td>Seimiya et al. 2003</td>
<td>Analyzed the number and the</td>
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<td></td>
<td>position of force vectors</td>
<td></td>
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<td></td>
<td>required in handling 444 tools</td>
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<td></td>
<td>used in the evaluation of</td>
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<td></td>
<td>ADL and classified the hand</td>
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<td></td>
<td>movement into 35 types of</td>
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<td></td>
<td>operation</td>
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</table>
Schlesinger designed a system to classify prehension for prosthetic hands that were developed because of injuries from World War I. Schlesinger emphasized the functional aspect of prehension in his system and described six basic hand postures: cylindrical, tip, hook or snap, palmar, spherical and lateral (Schlesinger, 1919). Figure 2.11 depicts Schlesinger’s six postures of prehension. In spite of being quite extensive, Schlesinger’s system does not address task requirement, that is, a bag is picked up differently if it has fragile objects in it versus smelly garbage. Napier (1956) proposed a system that integrates better the functional and anatomical description of the hand during prehension. He classified prehension into two categories: precision grip and power grip. The power grip is defined as: “The thumb is in the plane of the palm; its metacarpophalangeal and carpometacarpal joints are adducted. The fingers are flexed, laterally rotated, and inclined towards the ulnar side of the hand. The fingers flex in opposition to the palm, with the degree of flexion depending on object dimensions. The wrist is positioned with ulnar deviation, neutral between extension and flexion” (cf. McKenzie and Iberall, 1994). The position of the thumb defines the amount of precision the power grip has and ranges from some precision when it is adducted and contacts the object (figure 2.12a) to no precision when the thumb is abducted and power is maximized as in “coal hammer grip” (figure 2.12c).
The precision grip involves the thumb to be adducted and medially rotated at the metacarpophalangeal and the carpometacarpal joints. The fingers are flexed and abducted at the metacarpophalangeal joints, producing a degree of axial rotation in them. The wrist is extended, positioned between ulnar and radial deviation. Objects are pinched between the finger pads and the opposing thumb. For very fine control thumb and index finger are used (figure 2.12b). Cutkosky et al. (1989) extended Napier’s classification by subdividing the power grip into nine grips and the precision grip into seven grips (see table 2.4). In their classification system the power grip is a grip where stability and security are emphasized whereas dexterity is the focal point of the precision grip. Other researches, focusing on other aspects of prehension have designed different systems of classifications. Landsmeer (1962) highlighted the dynamic aspect of movements during precision grip and redefined it as precision handing. Kamakura (1980) described four basic postures by focusing on the multiple surfaces the human hand has while Iberall et al. (1986) described three postures: pad opposition, palm opposition and side opposition after observing the direction of the two opposing forces that are applied to objects during prehension.

Jacobson and Sperling (1976) developed a detailed coding system that describes the configuration of the hand qualitatively and more recently Seimiya et al. (2003) analyzed the number and position of force vectors required in handling 444 tools and described 35 types of hand postures to use as an evaluation tool for individuals with functional disorders of the hands.

The idea of the virtual finger (VF) was proposed by Arbib et al. (1985) after they observed how the grasp of subjects varied when they grasped mugs of
different sizes. They noticed that the number of fingers placed inside the handle depended strongly on its length while the task remained practically unchanged and suggested that the task was being performed by virtual fingers. A virtual finger is a fictional finger that represents a functional unit, a collection of individual fingers and hand surfaces that applies opposing forces to another VF (McKenzie and Iberall, 1994). Mechanically speaking, the VF generates the same mechanical effects as the sum of the individual fingers that it is composed of (Aoki et al. 2006; Arbib et al. 1985; Baud-Bovy and Soechting, 2001; Cutkosky, 1989; Cutkosky and Howe, 1990; Gao et al. 2005; Gentolucci et al. 2003; Iberall, 1987, 1997; McKenzie and Iberall, 1994; Santello and Soechting, 1997, 2000; Shim et al. 2003b, 2006; Zatsiorsky et al. 2004a, b, 2006).

The tripod grasp (three-digit task) has been investigated quite often, most likely because it has rather broad applicability and is fairly simple to set up experimentally. The grip involves the thumb and two fingers which have been shown to act as one functional unit even though they may not be located close to one another (Baud-Bovy and Soechting, 2001). Other authors have suggested that the tripod grasp is made up of three virtual fingers (Cutkosky and Howe, 1990).

In multi-finger prehension (multi-finger prismatic grasp) the forces and moments generated by the four fingers can be reduced to one wrench (force and a moment) or a VF that has the same mechanical effects as the actual fingers and oppose the thumb (Flanagan et al. 1999; Santello and Soechting, 2000; Shim et al. 2003b, 2004a, 2006; Zatsiorsky et al. 2004b, 2006). Analysis on both theoretical (Cutkosky and Howe, 1990; McKenzie and Iberall, 1994) and experimental (Baud-Bovy and Soechting, 2001, 2002; Santello and Soechting, 1997; Shim et al. 2003b, 2005b; Zatsiorsky et al. 2003a, 2004a, b) levels has suggested that prehension is controlled in a hierarchical fashion and includes at least two levels of control (figure 2.13). The hypothesis of hierarchical control is closely related to the idea of the virtual finger. At the higher level of the control the CNS coordinates the forces produced by the thumb and the virtual finger and at the lower level the forces produced by individual fingers are determined.
2.7 Aging and Finger Coordination

2.7.1 Age Related Differences in the Neuromuscular system

The decline in strength of skeletal muscles with aging has been documented by numerous studies, both cross-sectional (Hakkinen and Hakkinen, 1991; Macaluso et al. 2002; Young et al. 1984, 1985) and longitudinal (Aniansson et al. 1986; Frontera et al. 2000; Winegard et al. 1996). The magnitude of this loss varies, depending on the muscles estimated and type of contraction (concentric, eccentric, isometric, Vandervoort et al. 2002) but is on average 20-40% by the 7th and 8th decade of our lives (Aniansson et al. 1986; Frontera et al. 2000; Hakkinen and Hakkinen, 1991; Young et al. 1984, 1985).

The muscles of the lower limbs appear to lose more of their strength than upper limb muscles (Aniansson et al. 1996; Frontera et al. 2000) and some studies have reported a larger loss in distal muscles than proximal (Nakao et al. 1989; Shinohara, 2003a) while other studies failed to do so (Viitasalo et al., 1985).

Typically, the loss in muscle strength in the elderly is attributed to a loss in muscle mass due to fewer and smaller muscle fibers (Lexell, 1995). The loss in muscle mass with age, termed senile sarcopenia, is often quantified by the anatomical cross sectional area (ACSA) of the muscle (cross section at a right angle to the line of action of the muscle but not necessarily to the muscle fibers), using ultrasound, MRI and CT. Using this method, muscle mass is reported to
have decreased by 20-40% at the age of 80 (Klitgaard et al. 1990; Morse et al. 2004; Porter et al. 1995; Rice et al. 1989; Young et al. 1985). More recent work indicates that this method overestimates the actual contractile area of the muscle (Macaluso et al. 2002; Rev. in Macaluso and De Vito, 2004). With advancing age the amount of non-contractile elements, such as fat and connective tissue, within the muscle increases (Alnaqeeb et al. 1984; Kent-Braun et al. 2000; Macaluso et al. 2002; Rice et al., 1989) and the architecture of the muscles themselves changes (fascicles have been shown to be 10-16% shorter and pennation angles 7-16% smaller in the elderly) (Morse et al. 2005a, c; Narici et al. 2003). Both of these factors may lead to overestimation of the actual contractile area of the muscles. (Macaluso et al. 2002; Rev. in Macaluso and De Vito, 2004). The ratio of muscle strength and ACSA is commonly used to as an index to interpret changes in muscles based on the assumption that muscle size (estimated by ACSA) reflects the amount of contractile elements within it. Thus using the ACSA may give biased results. More recent studies have used the physiological cross sectional area (PCSA), which is the sum of cross sectional areas of all muscle fibers in a muscle and is calculated by measuring the muscle volume, fiber length and pennation angle. Using the PCSA may be especially relevant in pennated muscles such as the quadriceps where the muscle fibers run obliquely to the force generating axis of the muscle and it has been seen that muscle mass estimated by PCSA decreases by 15-16% in the elderly (Morse et al. 2005a,b; Narici et al. 2003). When muscle strength is normalized by the corrected muscle size, using PCSA, this ratio is still smaller in the elderly (Macaluso et al. 2002) which indicates that the traditional view that the decrease in muscle strength in the elderly is only caused by fewer and smaller muscle fibers can be disputed.

Muscle fibers both lose their size and number with age (Lexell, 1995) and earlier reports indicated that the fast twitch, type II fibers, were more affected (Tomonaga, 1977), thus that the ratio of slow twitch type I fibers was increased (Bemben, 1998). Improvements in techniques to identify fiber types in recent years have shown this process to be more complex than what was previously thought. This more recent work has showed that the proportion of type I and type
II fibers is generally maintained in the older muscles but the quantity of hybrid fibers of either type I/IIA or IIA/IIX is larger while the expression of the fastest isoform IIX is very low (Andersen et al. 1999, Andersen, 2003), that is, with age larger part of the muscle fibers become hybrid fibers that contain more than one isoform.

The excitation-contraction (E-C) coupling in the muscle is another factor that has been seen to change with age and may be a major cause of the decline in muscle force observed (Delbono, 2000). With age, the excitation-contraction processes stop working in synchrony due to a reduction in the number of both T-tubule dihydropyridine (DHPR) and sarcoplasmic reticulum membrane receptors. This causes the amount of sarcoplasmic reticulum calcium release channels and ryanodine receptors that are uncoupled to DHPR to become larger resulting in a failure in the transduction of sarcolemma depolarization into a calcium signal and a mechanical response (Delbono, 2000).

The decrease in muscle strength with age has also been attributed to changes in the motor unit. A motor unit (MU), which is comprised of a motoneuron and the muscle fibers it excites (Sherrington, 1929) exists in two types: fast twitch that have large and fast conducting motoneurons innerving 300-500 muscle fibers (McArdle, 1996) and slow twitch that have smaller and slower conducting motoneurons and innerve fewer fibers. With aging, the number of alpha motoneurons decreases and motor units increase in size but decrease in number (Brown et al. 1988; Campbell et al. 1973; Doherty and Brown, 1993; Doherty et al. 1993) and large motor units become as fatigable as small ones (reviewed in Luff, 1998).

Tendons act as force transmitters from muscles to the skeleton and by that facilitate movement. When a load, due to muscle contraction, is applied to tendons they both stretch and deform in ways defined by their mechanical properties (Dunn and Silver, 1983). Stiffness of tendons is of great importance to movements because it effects the time required to stretch it and therefore the rate of torque development as well as the electromechanical delay (Reeves et al. 2003). Multiple in vitro studies have shown that ageing is associated with a
decrease in tensile stiffness of tendons (Noyes and Grood, 1976; Tkaczuk, 1968),
while the results of others have been exactly opposite (Shadwick, 1990). More
recently, an ultrasound scanning technique has been used to estimate the
mechanical properties of tendons (Maganaris and Paul, 1999; Reeves, 2006). This
technique involves applying ultrasound scanning to the tendon in the saggital
plane to image the displacement of a reference point during isometric contraction
which can then be used to estimate the elongation of the tendon (Reeves, 2006).
The results of the in vivo experiments agree with the majority of in vitro studies,
concluding that tendons become more compliant with aging (Reeves, 2006).
Reeves (2006) estimated tendon elongation in young and elderly individuals. The
tendons of the elderly group elongated 10 % more even though the force applied
to them was less than half of the force applied to the tendons of the young
subjects. Even after the differences in size of tendons had been taken into account,
the tendons of the elderly subjects were more still compliant which indicates that
their material properties are intrinsically weaker (Reeves, 2006). Possible
implications of decreased stiffness of tendons in elderly individuals include a
decrease in force produced because muscle fibers shorten more (out of their
optimal range of force production), a slower transmission of contractile forces
from muscles to the skeleton which in turn may affect the time needed to
decelerate the body mass for example to prevent falls and increased likelihood of
tendon injury due to larger strains on the tendons at any given force (Reeves et al.
2003; Reeves, 2006).

2.7.2 Age Related Differences in Control of Hand and Fingers

Advancing age is accompanied by a decline in both dexterity and strength
of hands. These changes can greatly influence persons ability to perform activities
of daily living and be a crucial factor in determining ones ability of independent
living (Boatright et al. 1997; Francis and Spirduso, 2000; Giampaoli et al. 1999;
Hughes et al. 1997; Rantanen et al. 1999, 2002). These age related declines are
induced by changes both at the level of peripheral structures such as muscles,
tendons and joints and the central command and are often enhanced by underlying
diseases such as arthritis, Parkinson’s disease and osteoporosis (Carmeli et al. 2003).

Distal arm muscles have been seen to be more affected by advancing age than proximal ones (Christ et al. 1992; Era et al. 1992; Shinohara et al. 2003a). After the age of 60, thumb abduction strength, pinch strength and grip strength all decrease (Boatright et al. 1997). Reports on the magnitude of decrease in grip strength range considerably. Bassey and Harries (1993) reported 3-5% decrease per year after the age of 65, Rantanen (1998) 1% yearly decrease from the age of 45 while Kallman et al. (1990) found the decrease to be curvilinear and approximately 40% at the age of 90. Thenar muscles of older individuals have slower contraction time, decreased relaxation time, larger MU twitch tensions and the size of a single MU action potential is increased (Doherty and Brown 1997). Strength of abduction is decreased in the index finger while its force fluctuations are increased (Galganski et al. 1993). The discharge rate of the first dorsal interosseus muscle has been seen to be more variable and its peak values are reduced (Kamen et al. 1995) and its activity is accompanied by excessive co-activation of the second palmar interosseus muscle (Spiegel et al. 1996).

When gripping objects, elderly individuals use excessive force in comparison to their younger counterparts (Cole, 1991; Cole et al. 1999; Cole and Rotella, 2001; Danion et al. 2007; Gilles and Wing, 2003; Kinoshita and Francis, 1996). Several factors may contribute to this phenomenon and make it a wise choice of a strategy; skin slipperiness increases with age (Cole 1991; Cole and Rotella, 2001; Cole et al. 1999, Danion et al. 2007; Kinoshita and Francis, 1996), tactile and vibration sensitivity is reduced (Cole et al. 1998; Kenshalo, 1979), the capability to detect the slipping of an object is altered (Cole and Rotella, 2001) and safety margins are increased (Cole, 1991; Kinoshita and Francis, 1996).

Aging affects the predictive control of grip force during object manipulation (Danion et al. 2007) and causes a bias in the direction of fingertip force vector (Cole, 2006). The accuracy of force tracking is worse in the elderly than young, especially during force release phase but can be improved by training (Voelcker-Rehage and Alberts, 2005)
Variability of force increases with age (Galganski et al. 1993; Laidlaw et al. 1996; Vaillancourt and Newell, 2003), specifically when it is produced by the fingers of the hand (Christou and Tracy 2005; Enoka et al. 2003). Multiple studies have attempted to identify the mechanisms responsible for this change (Burnett et al. 2000; Galganski et al. 1993; Laidlaw et al. 1999, 2002; Semmler et al. 2000; Sosnoff et al. 2004; Vaillancourt et al. 2003; Rev. in Enoka, 2003). As of now, an increase in motor unit force, a decrease in number of motor units, a greater level of synchronization between pairs of motor units and a concurrent activation of agonist and antagonist muscles have not been supported as plausible causes for increased variability while results on increased single motor unit discharge variability have been unanimous (rev. in Enoka, 1997; Sosnoff et al. 2004; Vaillancourt et al. 2003). More recently, changes in the structure of the motor variability in aging have received increasing attention (rev. in Newell et al. 2006; Sosnoff et al. 2004; Vaillancourt et al., 2002, 2003; Vaillancourt and Newell, 2002, 2003). These studies have concluded that aging results in an increase in force variability but also changes the timing structure of the force signal. They suggest that aging results in a decline in the adaptive capability to coordinate the excitatory and inhibitory activity of multiple neural oscillators.

To date, observations suggest that the deterioration of manipulative performance in elderly is contributed by both peripheral and central neural factors.

2.7.3 Age Related Differences in Pressing Tasks

MVC, enslaving, force deficit and sharing.

The indices of finger interaction were described in section 2.4.1. Several studies have addressed age related differences in indices of finger interaction during MVC pressing tasks (Olafsdottir, 2004; Shinohara et al. 2003a, b, 2004). These studies have shown that elderly individuals produce in general smaller peak finger forces, are less enslaved but show larger force deficit than their younger counterparts.
The decrease in peak force is on average about 30% both in four-finger IMRL tasks and about 20% in individual finger (I,M,R,L) tasks (Shinohara et al. 2003a, b). When the thumb is added, the average difference between elderly and young individuals is about 40% in single-finger tasks but 30% in a five-digit TIMRL task (Olafsdottir, 2004). These results are in agreement with previous reports of a decrease in muscle force with increasing age (Frontera et al. 2000; Winegard et al. 1996, 1997).

Force deficit is, on average, 19% larger in elderly individuals in four-finger tasks. It has been proposed that force deficit is a consequence of an incomplete recruitment of motor units and a decrease of discharge rate when multiple fingers act together (Latash et al. 2003). The size of motor units increases with age (Doherty and Brown, 1997; rev. in Larsson and Ansved, 1995) and their discharge rate has been seen to decrease (Cooper and Eccles 1930; Shinohara et al. 2003a; Thomas et al. 1991; Vaillancourt et al. 2003), which both logically lead to an increase in the force deficit. Therefore it is likely that the increase in force deficit seen in elderly individuals has a neural origin.

Enslaving is on average 46% smaller in the elderly. Lower enslaving can be seen to reflect better control of individual finger forces, that is, more dexterity (Li et al. 2000). Several studies have shown tendon stiffness to increase with age (Shadwick et al. 1990; Tuite et al. 1997), even though others argue the opposite (Reeves et al. 2006) and within the muscle the amount of connective tissue increases (Macaluso et al. 2002; Zimmerman et al. 1993). It would be reasonable to expect the decrease in tendon compliance and the increase in the amount of connective tissue to increase enslaving due to “parallel” force transmission among the structures that serve individual fingers. The enlargement of motor units seen with aging should similarly also increase enslaving due to increased probability of simultaneous recruitment of fibers of the extrinsic muscles that serve multiple fingers. From this it can be concluded that observed decrease in enslaving of elderly individuals indicates a change in the central command to the motoneuronal pool.
Shinohara et al. (2003b) showed that with age intrinsic hand muscles lose proportionally more strength than extrinsic hand muscles. The method of controlling the relative contribution of intrinsic and extrinsic finger muscles was described in section 2.4.1. The experiment generally supported previously reported age-related differences in peak force, enslaving and force deficit but the magnitude of results differed between the two sites. Peak force decreased more in tasks performed at the proximal phalanges (mainly intrinsic muscles), 30% vs. 19% at the distal phalanges (mainly extrinsic muscles). Enslaving and force deficit were both larger in tasks performed at the proximal phalanges in the elderly individuals. These results agree with studies that report more loss of muscle strength in distal muscles (Christ et al. 1992; Era et al. 1992; Rice and Cunningham, 2002).

These results also support the hypothesis of the central origin of indices of finger interaction. If force deficit and enslaving were mainly affected by local mechanical factors such as commonality of muscles and tendons, they would be expected to be of lesser degree when force is produced at the proximal phalanges (force mainly produced by digit specific intrinsic muscles) but the opposite was seen (Shinohara et al. 2003b).

**UCM**

Section 2.2 describes the methodology of the Uncontrolled Manifold hypothesis. Several age-related differences in performance have been revealed using UCM analysis of data from submaximal force tasks of elderly individuals (Shinohara et al. 2003b, 2004). When compared to the performance of young individuals, the elderly took longer time to generate force stabilizing synergies and showed decreased ability to stabilize total moment. This difference was particularly prominent during tasks where force was produced at the proximal phalanges. During that task, young individuals were able to stabilize both total moment and total force while elderly individuals stabilized total force to lesser degree and failed to stabilize total moment.
2.7.4 Age Related Differences in Prehension Tasks

The ability to effectively manipulate objects is one of great importance and a decreased ability to do so can greatly impair individuals’ ability to perform activities of daily living (Kinoshita and Francis, 1996). A decrease in dexterity during prehensile tasks has been reported for pinching (Ranganathan et al. 2001), lifting (Cole, 1991) and peg-board tasks (Ranganathan et al. 2001).

Previous studies on age related differences in prehension have reported that elderly individuals use excessive grip force when compared to young adults during stable holding of objects (Cole, 1991; Cole et al., 1998, 1999; Kinoshita and Francis, 1996) and elderly show larger variability in force fluctuations (Vaillancourt et al. 2002). Only one study has addressed differences in multi-finger prehension tasks between elderly and young individuals (Shim et al. 2004b). Participants held an instrumented handle with a prismatic grip and were required to produce maximal moment, maximal force and perform an accurate force and moment production tasks. In agreement to previous reports, it was seen that the elderly individuals produced less total force (15% difference) and less total moment (34% less). During the maximal force tasks the elderly subjects produced more of the force with their index and middle fingers and rolled the thumb upwards while young subjects rolled their thumb downwards. In the maximal moment task elderly produced larger antagonist moment, that is, force with the fingers that oppose the desired direction.

During the accurate force and moment production tasks, the elderly individuals were less accurate in their performance. Opposite to previous reports of finger co-variation in pressing tasks, both age groups showed a predominantly negative co-variation of finger forces from the beginning of the task for total force and total moment of the tangential and normal forces but in the elderly individuals these indices were significantly lower which can be interpreted as a decreased ability to produce force and moment stabilizing synergies in prehension (Shim et al. 2004b).
2.8 Aging and Strength Training

The steady decline in muscular strength with aging contributes to a decrease in ability of individuals to carry out daily activities. Strength training has been shown to be a powerful tool to increase muscle strength in the elderly and by that reverse some of the effects of aging. The training protocols reported in previous studies are as many as they are variable and results are for that reason not uniform. Training duration prescribed ranges for example from 2 to 25 weeks (Connelly and Vandervoort, 2000; Hakkinen et al. 1998a,b; Hunter et al. 2001; rev. in Barry and Carson, 2004 and Reeves et al. 2006) and the training has been shown to yield everything from no changes to approximately 60% improvements in isometric strength (rev. in Barry and Carson, 2004 and Reeves et al. 2006) but the general consensus is that with sufficient training volume (load, frequency and duration) the beneficial effects of strength training in elderly individuals is undisputed.

Most strength training studies in elderly individuals utilize commercially available machines that are designed to target one muscle or muscle group by moving in one plane. The training load is commonly determined relative to the maximum load that can be lifted and lowered under control at a given number of times (repetition maximum or RM). According to Evans (1999) and Kraemer et al. (2002), training load needs to range between 60-100% of 1RM to induce strength gains while other researchers have reported similar gains in strength following training at either 50% or 80% of 1RM (Vincent et al. 2002a) or 40% or 80% of 1RM (Hortobagyi et al. 2001; Pruitt et al. 1995). It has also been pointed out that in order to increase muscle strength the system has simply to be loaded to larger degree than it normally is during daily life (Reeves et al. 2005).

The positive effects of strength training have also been shown in studies where elderly master athletes were compared to age matched sedentary individuals (Ojanen et al. 2007; Pearson et al. 2002). Muscular power, isometric strength and thickness declined with age at a similar rate in the master athletes and the sedentary subjects but the differences between the groups were such that
master athletes performed equally or better than sedentary subjects 20 to 35 years their junior (Ojanen et al. 2007; Pearson et al. 2002).

The neuromuscular system of elderly just as young individuals has been shown to possess great abilities to adapt to strength training. These adaptive changes include localized changes in the muscles themselves (Reeves et al. 2004b; Vincent et al. 2002b; Williamson et al. 2000), changes in properties of tendons (Reeves et al. 2003) and neural adaptations (Akima et al. 1999; Carolan and Cafarelli, 1992; Connelly and Vandervoort, 2000; Hakkinen et al. 1998a, b).

On the muscular level, strength training of elderly individuals has been shown to reduce the coexpression of multiple MHC isoforms (hybrid fibers) of muscle fibers (Williamson et al. 2000), decrease oxidative stress in muscles which in turn may provide protective work against cellular ageing and sarcopenia (Vincent et al. 2002b) and increase both the fascicle length and pennation angle (Reeves et al. 2004b). It may be speculated that the changes in fascicle length and pennation indicate that the number of sarcomeres in series within the muscle has increased, causing each sarcomere to shorten more during contraction and thus generate more force (Reeves et al. 2004a, b).

During muscle contraction, tendons transmit the force generated to the skeleton and their properties have large effect on the speed by which the force is transmitted. A recent study showed that by strength training knee extensors in elderly individuals, the stiffness of the patella tendon is increased by 66% (Reeves et al. 2003). A consequence of stiffer tendons is a decrease in their elongation and strain which may reduce the likelihood of tendon strain injury (Reeves et al. 2003).

Following strength training, strength gains have been observed that exceed the amount of increase that can be attributed to muscular hypertrophy, particularly in the early phase of training (Keen et al. 1994; Moritani et al. 1980). It has been suggested that these changes occur due to adaptations in the neural input. Some experimenters have reported a decrease in the agonist-antagonist co-activation (Carolan and Cafarelli, 1992; Hakkinen et al. 1998), others an increased neural drive to agonist muscles, yielding in additional motor units to be activated (Akima
et al. 1999; Connelly and Vandervoort, 2000; Enoka, 1997; Hakkinen et al. 1998; Moritani et al. 1980) while yet others have failed to show any changes in the activation pattern (Harridge et al. 1999; Knight et al. 2001).

During submaximal isometric and anisometric contractions, elderly individuals show greater fluctuations in force than their young counterparts (Galganski et al. 1993; Laidlaw et al. 1996, 2000). Training has been seen as an effective way to attenuate these changes (Keen et al. 1994; Kornatz et al. 2005; Laidlaw et al. 1999; Tracy et al. 2004) while the intensity and duration of the training program needed to obtain these effects is unclear. Keen et al. (1994) saw a decrease in force fluctuations during isometric contractions following a 12 week strength training program, Laidlaw et al. (1999) observed reduction in force fluctuations of both isometric and anisometric contractions in finger abductors after 4 weeks of training while Tracy et al. (2004) saw reduction only in anisometric contractions of the quadriceps muscle following 16 weeks of training. Kornatz et al. (2005) reported that 2 weeks of light training improved the steadiness of force production while Ranganathan et al. (2001) saw increased steadiness after 8 weeks of skilled finger movement exercises, indicating that the decrease in force fluctuation are possibly due to neural factors rather than peripheral changes in the motor units.
CHAPTER 3 General Methods

3.1 Subjects

All subjects were healthy and right-handed, according to their preferential hand use during writing and eating. In all studies we attempted to recruit an equal number of males and females. The young subjects, aged 20-35 years were recruited among students of Penn State University, colleagues and friends. The elderly subjects, aged 70-88 years were recruited from three locations: 1. Flyer hung up at a local YMCA recreation facility 2. Distribution of flyers through a contact person at the “Foxdale Village” retirement community located in State College 3. Distribution of flyers through a contact person at “The Village at Penn State” retirement community in State College. It should be noted that the recruitment strategy used may limit the generalizability of the results to elderly individuals of similar to those recruited, i.e. of average or high educational and socioeconomical status. In order to be eligible for participation in the studies, the elderly subjects had to pass a two stage screening process (see later). We purposefully selected for participation elderly subjects who exercised regularly and were generally in a good physical condition (self reported). The experiments aimed to include in both the elderly and the young subject groups proportional representation of minorities that reflected their representation in their overall population. Each subject received a compensation for their time, $20 per hour.

All subjects gave informed consent (appendix A) according to the procedures approved by the Office for Research Protection of The Pennsylvania State University.

3.2 Screening Process

Prospective elderly subjects went through a two stage screening process. First, individuals that had shown interest in participation by contacting the investigators were sent a package with questionnaires (see later) via mail. They were instructed to fill out the questionnaires and mail back to principal
investigator who handed them to the physician assistant (Mr. Lembeck-Edens, R.N.) at the General Clinical Research Center (GCRC) at Penn State University. The physician assistant determined if any of the information in the questionnaires indicated exclusion from the study. For those individuals that did meet the inclusion criteria of the first stage, a visit to the GCRC was scheduled to complete the second stage of the screening (neurological examination, quantitative sensory testing, and mental status exam). After the completion of the second stage, the physician assistant determined whether individuals were eligible for the study or not. The purpose of the studies was to describe normal aging in an otherwise healthy population, therefore the aim of the inclusion/exclusion process was to recruit such a population.

3.2.1 Inclusion criteria.

Normally aging individuals between 70 and 95 years old and normally functioning individuals between 20 and 35 years old as controls.

3.2.2 Exclusion criteria.

1). Persons with specialized finger training history such as professional musicians where finger use is central (piano, string instruments, saxophone, etc), typists, stenographers, etc. Potential subjects were asked about their occupation, current or past. They were excluded if they make/made most of their income in one of these occupations. Secretaries, as distinct from typists, were not excluded. In addition, subjects were asked how many hours per week, now and five years ago, they spent with a finger intensive activity (such as one of the above).

2). Persons with pathologically abnormal neurological function in the hands. We excluded true pathology while included normal aging. It could be argued that some neurological dysfunction is a part of normal aging. Thus the approach of this screening process was to exclude gross pathology while not necessarily searching out subtle "abnormal" changes. To do this we employed a questionnaire, a standard clinical examination and a simple test of sensory function.
2a). The questionnaire did seek out history of diagnosed disease. All of the items below lead to exclusion: Stroke or "ministroke" (even perceived as fully resolved); Peripheral neuropathy (as manifested by perceived numbness, tingling, burning or any other abnormal sensation in the hand or hands; these screening questions also picked up undiagnosed carpal tunnel syndrome); Diagnosis of carpal tunnel syndrome in either hand, whether corrected surgically or not; Parkinson's disease; Cervical spine disc disease or arthritis causing radiculopathy, or history of cervical spine surgery; Cervical spinal stenosis; Multiple Sclerosis; Myasthenia Gravis; Polio; Osteoarthritis; Other nerve or muscle disease; Skeletal pain causing diminished use ("Do you have pain in the shoulders, elbows, wrists or fingers severe enough that it limits what you can do with your arms / hands at least once each day?"). The questionnaire answers were reviewed by the study physician assistant who made the final determination whether the answers meet the stated inclusion/exclusion criteria.

2b). A routine neurological examination was performed by the study physician assistant. The following clinically apparent findings lead to exclusion: Pill rolling tremor; Cogwheel rigidity; Clearly abnormal Babinsky reflex; Obviously abnormal strength at the shoulders, elbows, wrists; abnormal hand grip strength; inability to rise up from a chair without assistance; abnormal finger-to-nose test, heel-to-shin test; asymmetry in strength, reflexes or sensation (pinwheel, "Does this feel the same in all places on both sides?") in upper extremities.

2c). Quantitative sensory testing was performed. The study physician assistant used the 0.385 g monofilament to test sensation at the tip of the 3d finger of both hands (Schulz et al., 1998). This monofilament was chosen as representing the upper limit of normal sensation in this population. A standard forced choice protocol – “am I touching you now or now” - was used with the eyes closed, normal being defined as correct identification of the touch 4 of 5 times in both hands.
3). Persons using medications that can alter mental alertness. Daily use of the following medications lead to exclusion: Narcotics; Benzodiazepines; Antidepressants other than SSRIs; Phenothiazines and related medications.

4). Mental status changes that would compromised the understanding or motivation/effort level of the volunteer such as dementia or depression. Specifically a score of less than 24 points in the MiniMental State Exam (appendix E) or greater than 20 points in the Beck Depression Inventory (appendix D) lead to exclusion.

3.2.3 Subject screening statistics

For the five studies included in the thesis, 64 elderly individuals volunteered for participation. Out of these thirty individuals did not pass through one or the other stages of the screening, the most common reason being usage of medications.

3.2.4 Questionnaires

As a part of the screening process the following questionnaires were used to identify individuals that were eligible for the study. All elderly individuals that participated in the studies were asked to fill out these questionnaires.

Questionnaire on finger activity and medical history (appendix B). The purpose of this questionnaire was to identify individuals that had participated in activities that might enhance their coordination regularly and individuals with major neurological diseases.

Screening physical examination-GCRC (appendix C). This questionnaire asks for general medical history that focuses on obtaining information on the health issues that might lead to exclusion from the study.

Beck Depression inventory (appendix D). A score of greater than 20 points on this inventory lead to exclusion.

Mini Mental State Exam (appendix E). This questionnaire tests for several aspects related to mental acuity. A score of less than 24 lead to exclusion.
3.2.5 Clinical functional hand tests.

To link together indices of finger synergies and subjects hand function we use the following clinical hand function tests. All elderly individuals that participate in the studies were asked to do these tests.

**ABILHAND** (appendix F). This is a self-assessment questionnaire where subjects rate 23 items on a 3 point scale, impossible (1), difficult (2) and easy (3). Penta et al. (1998) reported that application of this instrument to 33 patients with rheumatoid arthritis allowed for 6 to 7 statistically significant levels of ability to be distinguished.

**The Grooved Pegboard test** (Lafayette Instr., Model 32025) (appendix G). This test consists of a peg tray and 25 key-shaped holes with randomly positioned slots arranged in 5 rows of 5 holes each. The pegs have a key along one side. They are to be picked one by one and inserted into the slots starting with the top left hole and going along rows. Each row has to be filled before moving to the next row. The time it takes to complete the test and the number of dropped pegs are the main outcome measures.

**Jebsen-Taylor hand function test** (Jebsen et al. 1969) (appendix G). This test has been used for elderly subjects and is age-normalized (Agnew and Maas 1982; Hackel et al. 1992). The test involves seven subtests, writing, card turning, moving small objects, simulated feeding, checkers, moving large light objects, and moving heavy large objects. The time to complete each subtest is the main outcome measure.

3.3 Equipment

3.3.1 Experimental Setup 1 – The Pressing Setup

The pressing setup is used in the studies described in chapters 4, 5, 6 and 7 and is displayed in figure 3.1. Four unidirectional piezoelectric force sensor (Model 208A03, PBC Piezotronics Inc, Depew, NY, USA) amplified by AC/DC conditioners (M482M66, PCB Piezotronics Inc, Depew, NY, USA) were used to measure the vertical force produced by the four fingers (I, M, R, L). The sensors
were placed in a metal frame, sitting in a grove on a wooden board. Cotton pads were attached to the surface of the sensors to increase friction and prevent possible effects of skin temperature. The sensors were medio-laterally spaced 3.0 cm apart. Their position in forward-backward direction was adjustable within 6.0 cm to fit each subject’s hand anatomy. Once the appropriate position of the sensors was determined, double sided tape was placed under the bases of the sensors to prevent them from moving from that position. During the experiments, the subjects were seated in a chair that faced the testing table with the right shoulder at approximately 45° of abduction and flexion, and the elbow flexed about 135°. Metacarpophalangeal joints were flexed about 20° and all interphalangeal joints slightly flexed such that the hand formed a dome. A wooden piece, shaped to fit comfortably under the subjects palm, helped to maintain a constant configuration of the hand and fingers. Velcro straps were used to attach the subjects forearm to the board.

Figure 3.1 Experimental setup for pressing studies.

A 17” computer screen, located approximately 65 cm away from the subject, displayed the task and the actual total force or total moment the subject produced with all four fingers. In reaction trials of the study described in chapter 5, auditory signals were delivered to the subject via headphones.
3.3.2 Experimental Setup 2 – The Suspension Setup

The suspension setup is used in the study described in chapter 8 and is displayed in figure 3.2. Four unidirectional piezoelectric force sensor (Model 208A03, PBC Piezotronics Inc, Depew, NY, USA) amplified by AC/DC conditioners (M482M66, PCB Piezotronics Inc, Depew, NY, USA) are used to measure the vertical force produced by the four fingers (I, M, R, L). Each sensor is connected in series with a wire that is suspended through a slot from the top plate of an inverted U-shaped metal frame (see figure 3.2). A butterfly nut secures the attachment of the wires to the top plate. The slots are spaced 3.0 cm in the medio-lateral direction and allow for forward-backward adjustments of the wires to fit individual subjects anatomy. At the bottom of each wire is a rubber coated loop that can be placed either at the fingertip/distal phalanx (DP) or the base/proximal phalanx (PP) of individual fingers. Changing the location of the loops changes the relative contribution of intrinsic and extrinsic hand muscles to the force production, that is, when the loops are located at the fingertip force is mainly produced by extrinsic muscles but when placed at the proximal phalanx force intrinsic muscles produce majority of the force. During the experiment, the subjects sit in a chair facing the testing table with the shoulder at approximately 45° of abduction and flexion, and the elbow flexed about 135°. The forearm rests on a padded armrest and secured with Velcro straps. The position of the hand is maintained stable by a padded metal “clasp” made up of a cylindrical bar (lower part) and a concave bar (upper part). The palm rests on the lower bar with the thumb below it and is secured by the upper concave bar just below the MCP joints on the back of the hand. During the experiments all precautions are made to maintain stable configuration of the forearm and hand. A 17” computer monitor, located about 65 cm away in front of the subject, displays the total force of all four fingers or the force of individual fingers, depending on the task.

During the experiment described in chapter 8, the suspension system is used to test both right and left hands.
3.4 Data Acquisition

3.4.1 Unidirectional Force Transducers

In all experiments using the unidirectional force transducers, data were collected using LabView based software (National Instruments, Austin, Tx). Sampling frequency was either 1000 Hz or 200 Hz, depending on if EMG data was also being collected simultaneously from the subjects.

3.5 Data Analysis and Statistics

Here, the general approach to data analysis is described. More detailed discussion can be found in individual chapters.

All data were processed using Matlab 7.0 (MathWorks Inc, Natick, MA, USA) and Excel (Microsoft Inc, Redmond, WA, USA). Statistics were calculated using Matlab, Minitab (Minitab Inc., State College, PA, USA) and SPSS (SPSS
In all studies, statistical significance was set at $p = 0.05$, using Bonferroni correction for repeated tests. Most of the experiments involved repeated measures design, repeated measures ANOVA was used for most of the data. Other statistical measured used included basic statistics, linear regression, etc.
CHAPTER 4 Age Related Changes in Moment of Force Production Patterns in Multi-Finger Pressing Tasks
Age-related changes in multifinger synergies in accurate moment of force production tasks

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Olafsdottir H, Zhang W, Zatsiorsky VM, Latash ML. Age-related changes in multifinger synergies in accurate moment of force production tasks. J Appl Physiol 102: 1490–1501, 2007. First published January 4, 2007; doi:10.1152/japplphysiol.00966.2006.—The purpose of this investigation was to document and quantify age-related differences in the coordination of fingers during a task that required production of an accurate time profile of the total moment of force by the four fingers of a hand. We hypothesized that elderly subjects would show a decreased ability to stabilize a time profile of the total moment of force, leading to larger indexes of moment variability compared with young subjects. The subjects followed a trapezoidal template on a computer screen by producing a time profile of the total moment of force while pressing down on force sensors with the four fingers of the right (dominant) hand. To quantify synergies, we used the framework of the uncontrolled manifold hypothesis. The elderly subjects produced larger total force, larger variance of both total force and total moment of force, and larger involvement of fingers that produced moment of force against the required moment direction (antenomist moment). This was particularly prominent during supination efforts. Young subjects showed covariation of commands to fingers across trials that stabilized the moment of total force (moment-stabilizing synergy), while elderly subjects failed to do so. Both subject groups showed similar indexes of covariation of commands to the fingers that stabilized the time profile of the total force. The lack of moment-stabilizing synergies may be causally related to the documented impairment of hand function with age.

age; synergy; finger; moment of force; hand

AGING IS ACCOMPANIED BY well-documented changes in manual dexterity and strength that can have a negative effect on the activities of daily living (2, 13, 18, 21, 22, 35). This decline in hand function has been attributed to both peripheral changes, such as a drop in the number of motor units, an increase in their average size, and general slowing down of their contractile properties (5, 10, reviewed in Ref. 25) and changes at the level of central commands to the motoneuronal pool (8, 9, 42).

Earlier studies have revealed age-related differences in indexes of finger interaction during multifinger force production tasks. On average, elderly individuals produce lower maximal voluntary contraction (MVC) force and show changed indexes of finger interaction (42, 43). These findings have been interpreted as evidence for a neural origin of age-related changes in finger coordination (42, 43).

Most studies of finger coordination have focused on force production during pressing (43, 44) and grasping tasks (6–8). Much less attention has been paid to the ability to produce an accurate rotational hand action, which is essential for many daily activities, such as drinking from a glass, writing with an implement, or using a hand-held tool (reviewed in Refs. 28, 51). A number of studies investigated rotational actions but with the focus on grip force production by the thumb and index finger during a pinch grip (20, 23). The main purpose of the present study has been to document and quantify changes in indexes of finger interaction during tasks that required the production of an accurate time profile of the moment of force (rotational action) by the four fingers of the hand.

The pressing task used in the present study may be viewed as reflecting control processes at one of the two hypothetical levels involved in hand action (1, 32). The two levels are as follows: 1) distributing the task between the thumb and the “virtual finger” (VF; an imagined finger whose mechanical action is equivalent to the combined action of a set of actual fingers); and 2) distributing the action of the VF among the actual fingers. A series of earlier studies of prehensile tasks with a rotational component have addressed synergies at the thumb-VF level (39, 40, 49; reviewed in Ref. 51), including one study of elderly individuals (41). The latter study has demonstrated deficits in synergies involved in the rotational hand action at the thumb-VF level. Our present study addresses multifinger synergies involved in stabilizing the rotational action of the VF at the lower level of the hierarchy that does not involve the thumb.

To quantify multifinger synergies, we used the framework of the uncontrolled manifold (UCM) hypothesis (37). The UCM hypothesis assumes that the controller acts in the space of elemental variables and limits variability of these variables across trials to a subspace corresponding to a desired value of an important performance variable. The hypothesis allows multidigit synergies involved in both pressing and rotational finger action to be quantified (26, 27, 36).

Based on an earlier study (53), we hypothesized that young subjects would show high indexes of stabilization of the moment of force, while elderly subjects were expected to show a decreased ability to stabilize the rotational multifinger action. We also hypothesized that elderly subjects would produce relatively larger forces by fingers that generate moments of force directed against the required moment direction (cf. Ref. 41). Such a strategy may be viewed as adaptive, that is, less economical but assuring higher stability of performance by an increase in the peripheral resistance of the hand to possible rotational perturbations.

A couple of secondary issues were addressed in the study. These include stabilization of the total force produced by the fingers in such tasks. Earlier studies have documented lower
indexes of multifinger synergies stabilizing the total force in elderly (42–44), but only in tasks that involved the production of a time profile of the total force. Based on those studies, we expected elderly subjects to show lower indexes of force stabilization in tasks that required the production of a time profile of the moment of force. We also addressed the contribution of the fingers with the longer moment arm (index and little fingers) to the supination (SU) and pronation (PR) moments. The “mechanical advantage hypothesis” proposes that, when multiple effectors act together to produce moment of force, those with the longer moment arms contribute more to the total task (4, 15, 34, 41, 48). Based on this idea, we hypothesized that the moment produced by index and little fingers would exceed 50% of the PR and SU moments, respectively. In addition to that, we also explored possible differences in the ability of the elderly to produce stable rotational actions in PR and in SU.

METHODS

Subjects

Twelve young (26 ± 3 yr old) and twelve elderly (77 ± 4 yr old) subjects volunteered to participate in the study. Both groups consisted of six men and six women. The average height and weight were, respectively, 171.0 ± 9.5 cm and 69.5 ± 16.6 kg for the young subjects, and 167.9 ± 10.2 cm and 72.2 ± 15.5 kg for the elderly subjects. All subjects were healthy and right-handed, according to their preferential hand use during writing and eating. 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. We purposefully selected for the study elderly subjects who exercised regularly and were in generally good physical shape (self-reported). We also purposefully set the tasks to be easier for the elderly group to avoid possible effects related to fatigue (see later). All subjects gave informed consent according to the procedures approved by the Office for Research Protection of The Pennsylvania State University.

Apparatus

Figure 1 displays the experimental setup. Four piezoelectric sensors (model 208A03, PBC Piezotronics, Depew, NY) amplified by AC/DC conditioners (M482M66, PBC Piezotronics) were used to measure the vertical forces generated by the fingers. Cotton pads were attached to the surface of the sensors to increase friction and prevent possible effects of skin temperature. The sensors were placed in a metal frame sitting in a groove on a wooden board. The sensors were mediolaterally spaced 3.0 cm apart and could be adjusted in the forward-backward direction within 6.0 cm to fit each subject’s hand anatomy. Once the appropriate position of the sensors had been determined, double-sided tape was placed under the bases of the sensors to prevent possible force production by the noninstructed fingers of the hand and fingers. The forearm was attached to the board with Velcro straps. A 17-in. computer monitor, located ∼65 cm away from the screen (from now on referred to as “force task”), and an accurate Mtot production task (“accurate moment task”). The force task had two conditions: maximal force production with instructed finger(s) and single-finger force ramp production. The accurate moment task had only one condition: accurate production of a total moment profile. During all of the tests, the forces produced by all four fingers were collected. In the force task, MVC force of each finger pressing together (IMRL) was first measured. In these trials, subjects were asked to press “as hard as possible” with the instructed finger(s). Subjects were given 3 s to reach peak force. The intervals between the trials were at least 30 s. Two MVC trials were recorded for each of the tasks, and the trial with the highest magnitude of the task force was used to set up other tasks.

The second force task condition involved subjects to produce single-finger force ramps. The subjects were asked to produce a ramp pattern of force from 0 to 25% of each finger’s MVC over 5 s by pressing down with an instructed finger; different fingers were instructed in separate trials. An oblique blue line was shown on the screen, and the participant’s task was to trace this line in time with the cursor representing the force of the instructed finger. These data were used to generate linear estimates of the relations between changes in commands to individual fingers and change in the Ftot during multifinger tasks (the Jacobian; Ref. 36). These relations are nontrivial because of the phenomenon of enslaving (24a, 29, 30, 52). In both of the control sets, subjects were instructed not to pay attention to possible force production by the noninstructed fingers of the hand and not to lift any finger off its sensor at any time.

The accurate moment task required the subjects to follow a trapezoidal template on the screen by producing a time profile of the Mtot

Fig. 1. A: schematic illustration of the experimental setup. B: the experimental task shown on the computer screen. C: finger and force sensor configuration.
computed with respect to a horizontal axis passing between the M and R fingers while pressing with all four fingers (see Fig. 1). Pressing down with the I and M fingers produced a positive PR moment, while pressing down with the R and L fingers produced a negative SU moment. The initiation of each trial was indicated by two beeps generated by the computer, and a line appeared on the screen showing $M_{tot}$ computed online using the finger force signals:

$$ M_{tot} = d_{IF}F_I + d_{MF}F_M - d_{RF}F_R - d_{LF}F_L \tag{1} $$

where subscripts I, M, R, and L stand for the index, middle, ring, and little finger, respectively, and d stands for the lever arms ($d_I = d_R = 4.5$ cm, $d_M = d_L = 1.5$ cm). This approximation assumes that the points of force application on the sensor surfaces do not move in the mediolateral direction.

To follow the template, the subjects had first to produce a constant level of PR moment over 3 s, then to change from PR to SU moment over a 3-s interval, maintain the SU moment for 2 s, then change from SU to PR moment over 3-s interval, and maintain the PR moment for 3 s. Each trial lasted 14 s, but only the middle 10 s were used for the data analysis. Maximal levels of PR and SU moments were set at 5% of the maximal moment produced by the I finger for elderly subjects but at 10% of that value for young subjects (computed as 5 and 10% of $d_{IMVC}$). During pilot tests, we noticed that elderly subjects could have problems with producing SU moments of a large magnitude (see Results). This may be related to a relatively small decrease in the I finger force with age compared with the R and L finger forces (42).

We selected the two magnitudes for the main task to make the task comparably challenging for the two subject groups. Note that between-group comparisons were performed in units normalized to the magnitude of the task (see the next section). Young subjects performed 25 trials within a series, while elderly subjects performed only 20 trials. This was done to minimize chances of fatigue in elderly subjects. Five practice trials were given before the collection of the data, and trials were repeated during the series if the experimenter or the subject noticed an obvious mistake, for example producing a wrong constant-force level, taking a finger off its sensor, “giving up” in the middle of a trial, etc. On average, less than one trial per series was repeated.

Data Analysis

The data were processed offline using MatLab 7.0, Excel, and SPSS. In the MVC tasks, peak forces were measured when the instructed finger force reached its maximum.

During the experiment, the maximal moment a subject was required to reach was set for elderly subjects as 5% of that subject’s I finger MVC multiplied by its moment arm ($d_{IMVC} = 4.5$ cm $\times$ MVC$_I$), and at 10% of $d_{IMVC}$ for young subjects. This was done because, during a pilot study, it became apparent that the elderly subjects could have problems with the task set at 10% $d_{IMVC}$, particularly during SU efforts. For across-subjects comparisons, the force data were normalized by 5 or 10% of MVC$_I$ (for elderly and young subjects, respectively), while the moment data were normalized by 5 or 10% of $d_{IMVC}$ (for elderly and young subjects, respectively). In other words, across-subjects comparisons were done in “task units”.

To test the effects of age on the contribution of individual digits to the total PR and SU moments, $M_I/M_{PR}$ and $M_L/M_{SU}$, across two time intervals (PR and SU), two repeated-measures two-way ANOVAs were used. Multiple comparisons with Bonferroni corrections were used as post hoc to analyze significant effects. The level of significance was set at $P = 0.05$.

UCM Analysis

Further analysis was done using the framework of the UCM hypothesis (37; reviewed in Ref. 27). The description below applies to the analysis of forces, but a similar procedure was used when moments of force were analyzed; the only difference was in the linear

Statistics

The data in the text and Figs. 3–8 are presented as means and SE. After the data had been “trimmed” to 10 s, each trial was divided into five time intervals: “prepronation” (PR$_{pre}$; 1–1,000 ms); “pronation-supination” (PR-SU; 1,001–4,000 ms); “supination” (SU; 4,001–6,000 ms); “supination-pronation” (SU-PR; 6,001–9,000 ms); and “postpronation” (PR$_{post}$; 9,001–10,000 ms) (see Fig. 2). For the force task, the effect of age (young vs. elderly) on forces produced by individual fingers (I, M, R, L) and by the four fingers together (IMRL) was analyzed with a two-way ANOVA with repeated measures and one-way ANOVA, respectively.

For the accurate moment task, the effect of age across three steady-state time intervals (PR$_{pre}$, SU, PR$_{post}$) on the $F_{tot}$ and $M_{tot}$ were analyzed with repeated-measures two-way ANOVAs. In a similar fashion, the effects of age across all five time intervals (PR$_{pre}$, PR-SU, SU-PR, PR$_{post}$) on the $V_I$ and $V_M$ were analyzed with repeated-measures two-way ANOVAs.

To test the hypothesis of a larger $M_{Ant}$ production by the elderly subjects, we compared the effects of age and torque (PR vs. SU) across time intervals on the magnitude of $M_{Ant}$ produced. Due to the symmetry of the moment template (see Fig. 1), repeated-measures three-way ANOVAs on two indexes, $M_{Ant1}$ and $M_{Ant2}$, were used. Each trial was first divided into two 5,000-ms parts (1–5,000 ms and 5,001–10,000 ms), and then each of them was divided into 500-ms intervals. $M_{Ant1}$ represented the first half of the trials, with the moment changing from PR to SU, and $M_{Ant2}$ described the second half, with the moment changing from SU to PR.

To test the effects of age on the contribution of individual digits to the total PR and SU moments, $M_I/M_{PR}$ and $M_L/M_{SU}$, across two time intervals (PR and SU), two repeated-measures two-way ANOVAs were used. Multiple comparisons with Bonferroni corrections were used as post hoc to analyze significant effects. The level of significance was set at $P = 0.05$.

Fig. 2. The template and the five time intervals. PR, pronation; SU, supination; PR$_{pre}$, prepronation; PR$_{post}$, postpronation.
equations that link the performance variables to individual finger forces \( F_{tot} = F_L + F_R + F_{L2} + F_{R2} \); \( M_{tot} = dF_L + dF_R + dF_{L2} + dF_{R2} \). The UCM hypothesis assumes that the controller organizes covariation among elemental variables to stabilize a certain value of a performance variable (here \( F_{tot} \) or \( M_{tot} \)). Individual finger forces cannot be manipulated independently by the controller because of the phenomenon of enslaving, i.e., unintended force production by fingers when other fingers of the hand produce force (24a, 30). Hence, the first step was to convert the data sets from time series of finger forces to time series of elemental variables, force modes.

Force modes were defined similarly to previous studies (26, 36). Briefly, single-finger force ramp trials were used to compute the enslaving matrix \( E \) for each subject. The entries of the \( E \) matrix were computed as the ratios of the change in the force of each finger to the change in the \( F_{tot} \) over the ramp duration. The \( E \) matrix was used to compute changes in the vector of hypothetical commands to fingers (force modes, \( m \)) based on force changes.

Further analysis was done across repetitive trials performed by a subject within the main series at different time slices over the duration of the task. According to the UCM hypothesis, more variance in the \( m \) space per dimension is expected within the manifold (UCM), corresponding to a constant value of \( F_{tot} (M_{tot}) \) than in an orthogonal complement to the UCM. For each subject and for each time slice, the average across trials mode vector \( m_{avg} \) was computed. Then, for each trial \( j \), deviations (\( \Delta m_{j} \)) between \( m_{avg} \) and \( m_{j} \) were computed. Variance of the \( \Delta m \), data set was then computed along a direction orthogonal to the UCM computed for the average value of \( F_{tot} (M_{tot}) \) observed across trials at that particular time slice. We will refer to this index as \( V_{tot} \). This was done using the Raleigh fraction:

\[
V_{tot} = \frac{J_{m} \text{cov}(m) J_{m}^{T}}{J_{m} J_{m}^{T}} = \frac{\mathbf{J}^{-1T} \mathbf{E}^{-1} \text{cov}(\mathbf{f}) \mathbf{E}^{-1T} \mathbf{E}^{-1T}}{\mathbf{J}^{-1T} \mathbf{E}^{-1} \mathbf{E}^{-1T} \mathbf{J}^{-1T}}
\]

where \( J \) is the Jacobian matrix relating small changes in modes (\( J_{m} \) or forces \( J \)) to changes in the \( F_{tot} \), \( \text{cov}(\mathbf{m}) \) is the covariance matrix in the mode space, \( \text{cov}(\mathbf{f}) \) is the covariance matrix in the force space, and \( T \) is the sign of transpose. For \( F_{tot} \), \( J = [1, 1, 1] \), while for \( M_{tot} \), \( J = [4.5, 1.5, -1.5, -4.5] \); \( \Delta m = J^{-1T} \).

The difference between the total amount of variance (\( V_{tot} \)) and \( V_{tot} \) corresponds to variance that does not affect the average value of the performance variable. We will address this variance as \( V_{UCM} \) (variance within the UCM; cf. Ref. 26): \( V_{UCM} = V_{tot} - V_{tot} \). Note that the force mode space is four-dimensional, \( V_{tot} \) lies along a one-dimensional subspace, while \( V_{UCM} \) is three-dimensional. To compare the amounts of variance per dimension the following index was used:

\[
\Delta V = \frac{(V_{UCM} - V_{tot})}{V_{tot}}
\]

where \( \Delta V \) is the difference in variance. Normalization by the \( V_{tot} \) per dimension \( (V_{tot}/4) \) was used to compare the data across subjects who could show different amounts of the total variance.

Note that positive values of \( \Delta V \) correspond to proportionally more \( V_{UCM} \), i.e., they are compatible with a constant value of \( F_{tot} (M_{tot}) \). Therefore, \( \Delta V > 0 \) may be interpreted as a multimode synergy stabilizing \( F_{tot} (M_{tot}) \). If \( \Delta V = 0 \), this means that the amount of variance per dimension is the same in directions that correspond to a change in \( F_{tot} (M_{tot}) \) and along directions that keep the variable unchanged. \( \Delta V < 0 \) may be interpreted as covariation among changes in finger modes contributing to a change in \( F_{tot} (M_{tot}) \) or destabilizing it. For statistical purposes, the \( \Delta V \) time profiles computed for \( F_{tot} (\Delta V_F) \) and for \( M_{tot} (\Delta V_M) \) were averaged over the duration of the test for each subject, and a one-group Student’s \( t \)-test was used to define if the \( \Delta V \) value within each age group was, on average, different from zero. Furthermore, a two-way ANOVA was used to explore possible differences in the time profiles of \( \Delta V \) indexes with the factor time (5 levels as described earlier).

RESULTS

Force Task

Individual and four-finger forces. In the single-finger force tasks, young subjects produced on average 18% larger forces with individual fingers than the elderly subjects, but this difference was under the level of significance, according to a two-way ANOVA with factors age and finger (factor age: \( F_{1,22} = 1.11, P = 0.3 \)). Statistical differences were, however, found in the performance of individual fingers (factor finger: \( F_{3,66} = 49.41, P < 0.001 \)). The I finger produced on average the largest force, then the M finger, followed by the R and L fingers. The forces produced by the R and L fingers were not different from each other \( (P = 0.28) \). In the four-finger task, no differences were found between the two age groups in a one-way ANOVA with factor age \( (F_{1,22} = 1.19, P = 0.29) \). The results of the single-finger and four-finger force tasks are displayed in Table 1 as averages and SEs.

Accurate Moment Production Task

\( F_{tot} \) and total \( M_{tot} \). The task of following the template with the signal corresponding to the \( M_{tot} \) produced with respect to the midpoint between the M and R fingers proved to be quite challenging for the subjects. All subjects were, however, able to produce the required time profile \( M_{tot} \) after the practice trials. Figure 3 shows the patterns of the \( F_{tot} \) and \( M_{tot} \), averaged across trials for two representative subjects. Subjects of both age groups showed an increase in \( F_{tot} \) during the task, such that they produced more force to maintain the same level of PR moment at the end of the trials than at its start. Young subjects produced overall larger forces during the task than elderly subjects, increasing on average from 8.17 ± 1.07 to 15.80 ± 2.36 N over the trial duration compared with the 3.96 ± 0.76 and 6.96 ± 0.92 N forces in elderly subjects. The average peak target \( M_{tot} \) magnitude for the young subjects was significantly larger than for the elderly subjects \( (21.15 ± 2.48 \text{ vs. } 10.36 ± 2.08 \text{ Ncm}; P < 0.05) \). These differences were largely due to the differences in setting the magnitude of the peak target \( M_{tot} \) for the two groups. Therefore, the moment of force data were normalized by the magnitude of \( M_{tot} \), and the force data were normalized by the percentage of the I finger MVC force that was used to set \( M_{tot} \) (see METHODS). From this point onward, we present and analyze normalized data.

Normalized \( F_{tot} \) and \( M_{tot} \). Figure 4 shows the patterns of \( F_{tot} \) and \( M_{tot} \) averaged across subjects. The average \( M_{tot} \) profile matched the template (dotted lines) closely in both age groups. The similarity in the performance of \( M_{tot} \) of the two groups was confirmed by a two-way ANOVA with factors age and time (the data were averaged over time within the three intervals: PRpre, SU, PRpost; see Fig. 2) that showed no effects of age \( (P = 0.57) \) or age \( \times \) time interaction

Table 1. Single- and four-finger force task results

<table>
<thead>
<tr>
<th>Index</th>
<th>Middle</th>
<th>Ring</th>
<th>Little</th>
<th>IMRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elderly</td>
<td>41.46±4.60</td>
<td>30.95±2.89</td>
<td>19.93±1.76</td>
<td>19.09±2.08</td>
</tr>
<tr>
<td>Young</td>
<td>45.95±5.24</td>
<td>34.59±3.66</td>
<td>26.68±3.62</td>
<td>22.07±2.78</td>
</tr>
</tbody>
</table>

Values are means ± SE in newtons. IMRL, index, middle, ring, and little fingers together.
Similar to the nonnormalized data (Fig. 3), normalized F\textsubscript{tot} nearly doubled over the duration of the task in both subject groups. In elderly subjects, F\textsubscript{tot} increased from an average of 1.75 ± 0.25 in the PR\text{pre} phase to 3.55 ± 1.00 in the SU phase, but dropped slightly to 3.34 ± 1.24 in the PR\text{post} phase, while young subjects increased their F\textsubscript{tot} gradually throughout the task (1.71 ± 0.23 in PR\text{pre}; 2.65 ± 0.70 in SU; and 3.26 ± 0.84 in PR\text{post}). A two-way ANOVA on F\textsubscript{tot} with repeated measures, with factors age and time (three levels: PR\text{pre}, SU, PR\text{post}; see Fig. 2) showed a significant effect of time (F\textsubscript{2,44} = 39.22, P < 0.001) and a significant age × time interaction (F\textsubscript{2,44} = 3.16, P < 0.05). Multiple comparisons with Bonferroni correction revealed that, while the average values of F\textsubscript{tot} during the PR\text{pre} and PR\text{post} phases were not different when the two groups were compared (P = 0.098 for PR\text{pre} and P = 0.433 for PR\text{post}), elderly subjects produced significantly larger force in the SU phase than did the younger ones (P < 0.05). In both groups, PR\text{pre} phase differed from both SU and PR\text{post} phases (P < 0.05), but SU and PR\text{post} phases were not different from each other (P = 1.0 for elderly subjects and P = 0.127 for young subjects).

\(V_F\) and \(V_M\): Time profiles of the variance of normalized \(F_{\text{tot}}\) (\(V_F\)) and \(M_{\text{tot}}\) (\(V_M\)) were computed across all trials for each of the subjects. \(V_F\) and \(V_M\) were then averaged over each of the five time intervals (PR\text{pre}, PR-SU, SU, SU-PR, PR\text{post}; see Fig. 2). Figure 5A shows \(V_F\) for the two age groups averaged across subjects with SE bars. The elderly subjects showed larger \(V_F\) than the young subjects within all time intervals, except in the PR-SU phase. In both age groups, \(V_F\) increased dramatically in the beginning of the task but then leveled off. In elderly subjects, \(V_F\) grew from PR\text{pre} (0.07 ± 0.01) to PR-SU (0.19 ± 0.02) and to SU (0.611 ± 0.14) phases, leveled off in SU-PR phase (0.60 ± 0.15), and decreased significantly in the PR\text{post} phase (0.47 ± 0.12). Young subjects showed a similar pattern of changes in \(V_F\), but a significant difference was only found between the PR\text{pre} phase (0.04 ± 0.01) and the other time phases (PR-SU, 0.16 ± 0.04; SU, 0.26 ± 0.05; SU-PR, 0.19 ± 0.03; and PR\text{post}, 0.19 ± 0.03). This was confirmed by the significant effects of age (\(F_{1,22} = 39.90, P < 0.05\)) and time (\(F_{4,88} = 15.49, P < 0.01\)) and age × time interaction (\(F_{4,88} = 4.878, P < 0.05\)) in a two-way ANOVA with repeated measures on \(V_F\) and multiple comparisons with Bonferroni corrections (P < 0.05).

Similar analyses of \(V_M\) showed substantially higher indexes of \(M_{\text{tot}}\) variability in the elderly subjects than in the young subjects. Figure 5B shows \(V_M\) for the two age groups averaged across subjects with SE bars. \(V_M\) was substantially larger for the elderly subjects than for the young subjects in all time intervals. In particular, the elderly subjects showed larger values of \(V_M\) during the two intervals where switching of the moment direction occurred (PR-SU and SU-PR). \(V_M\) was
~30% larger in the SU-PR phase compared with the PR-SU phase. Young subjects also showed larger VM during the PR-SU phase, while VM during the SU-PR phase was relatively modest. A two-way repeated-measures ANOVA on VM with factors age and time (five levels: PR pre, PR-SU, SU, SU-PR, PR post) showed significant effects of age ($F_{1,22} = 13.99, P < 0.001$), time (five levels: PR pre, PR-SU, SU, SU-PR, PR post; see Fig. 2) ($F_{4,88} = 14.77, P < 0.001$), and age × time interaction ($F_{4,88} = 5.82, P < 0.001$) in support of the mentioned differences.

$M_{Ag}$ and $M_{Ant}$. As described in METHODS, we define $M_{Ag}$ as a moment produced in the direction that meets the current task requirements. $M_{Ag}$ was produced by the I and M fingers when the task was required to produce PR moment, and it was produced by the R and L fingers when the task required production of a SU moment. $M_{Ant}$ acted against $M_{Ag}$ such that, during the PR portion of the task, it was produced by the R and L fingers, and during the SU portion of the task, it was produced by the I and M fingers. $M_{Ag}$ and $M_{Ant}$ were averaged over twenty 500-ms time intervals for each subject separately and further averaged across subjects. The time profiles of $M_{Ag}$ (open bars) and $M_{Ant}$ (solid bars) averaged across subjects with SE bars are shown for the elderly subjects in Fig. 6, top and for the young subjects in Fig. 6, bottom. Note the higher solid bars for the elderly subjects, particularly in the middle portion of the trial.

To compare the magnitudes of $M_{Ant}$ during PR and SU efforts, when the task involved either a PR-SU change (1–5,000 ms) or a SU-PR change (50,001–10,000 ms), the $M_{Ant}$ data were divided into two 5,000-ms parts ($M_{Ant1}$ and $M_{Ant2}$) that were analyzed separately using two three-way ANOVAs with factors age, torque, and time, where torque had two levels, PR ($M_{Ant}$ is negative) and SU ($M_{Ant}$), and time had 10 levels, corresponding to the 500-ms intervals. For the first half of the task duration ($M_{Ant1}$), the ANOVA showed significant effects of age ($F_{1,22} = 4.90, P < 0.05$), torque ($F_{1,22} = 45.55, P < 0.001$), and time ($F_{4,88} = 44.69, P < 0.001$), and all of their interactions except age × time ($P = 0.15$). Multiple comparisons with Bonferroni correction showed that the elderly subjects produced significantly larger $M_{Ant1}$ than the young subjects during SU (0.63 ± 0.06 vs. 0.42 ± 0.06; $P < 0.05$) but not during PR. In addition, in both age groups, $M_{Ant1}$ was significantly larger in SU than in PR ($P < 0.01$).

For the second half of the task ($M_{Ant2}$), the ANOVA showed only significant effects of time ($F_{4,88} = 75.65, P < 0.001$), age × torque ($F_{1,22} = 15.96, P < 0.01$), and

![Fig. 5](https://example.com/fig5.png)

Fig. 5. A: average variance of the total force ($V_F$) during the five time intervals with SE bars. The data were averaged over each of the five time intervals and further across subjects. Elderly subjects are represented by solid bars, and young subjects by open bars. B: average variance of the total moment ($V_M$) during the five time intervals with SE bars. The data were averaged over each of the five time intervals and further across subjects. Elderly subjects are represented by solid bars, and young subjects by open bars.

![Fig. 6](https://example.com/fig6.png)

Fig. 6. Average agonist ($M_{Ag}$, open bars) and antagonist moment ($M_{Ant}$, solid bars) of elderly (top) and young (bottom) subjects with SE bars. $M_{Ag}$ and $M_{Ant}$ were averaged over half-second intervals and further across subjects of each age group.
torque \times time (F_{4,86} = 4.34, P < 0.05). Multiple comparisons with Bonferroni correction revealed that the elderly subjects produced larger M_{Ant2} than the young subjects during SU (0.81 ± 0.07 vs. 0.51 ± 0.07; P < 0.01) but not PR (P = 0.783). Only in young subjects did M_{Ant2} differ between SU and PR (P < 0.01).

Moments of force produced by individual fingers. The accurate moment task was set such that the moment arms of the I and L finger forces were three times longer than those of the M and R finger forces (4.5 vs. 1.5 cm). The mechanical advantage hypothesis states that, when multiple effectors (muscles or fingers) act together to produce a moment of force, those with longer moment arms contribute more to the total task compared with the ones with shorter moment arms (4, 15, 34, 41, 48). According to this hypothesis, the I and L fingers were expected to contribute significantly more than 50% to the respective PR and SU moments. We tested this hypothesis.

Figure 7 displays the shares of the I and L fingers in the PR and SU moments, respectively: M_I/M_{PR} (A) and M_L/M_{SU} (B) averaged over 1-s intervals and across subjects with SE bars. Figure 7, C and D, depicts further analysis where M_I/M_{PR} (C) and M_L/M_{SU} (D) have been averaged over the two steady-state PR intervals (bars 1 and 10 in A and B) and the two steady-state SU intervals (bars 5 and 6 in A and B). To test whether I and L fingers contributed proportionally more to the PR and SU moments than M and R fingers, a two-way ANOVA with repeated measures with factors age and time was run separately for M_I/M_{PR} and M_L/M_{SU}. Here, the time factor had two levels: PR and SU. Both indexes (M_I/M_{PR} and M_L/M_{SU}) for PR were calculated by first averaging them over time for each of the two 1,000-ms PR intervals (bars 1 and 10, A and B in Fig. 7) and then taking the average across them. For SU, the indexes were calculated in a similar way for each of the two 1,000-ms SU intervals (bars 5 and 6, A and B in Fig. 7) and then averaging across them. The I finger contributed between 72 and 80% of the total PR moment during both PR and SU efforts in elderly subjects. In young subjects, its contribution was ~80% during PR efforts (when it acted as an agonist), but dropped significantly to ~58% in SU (when it acted as an antagonist, P < 0.001). The two-way ANOVA on M_I/M_{PR} showed a significant effect of time (F_{1,22} = 29.46, P < 0.001) and age \times time interaction (F_{1,22} = 8.41, P < 0.01).

The L finger’s contribution to the total SU moment was in both age groups significantly larger during SU efforts (elderly, 66 ± 5%; young, 69 ± 5%) than during PR efforts (elderly, 56 ± 3%; young, 57 ± 3%) (P < 0.05), while no differences were found between the age groups. The two-way ANOVA on M_L/M_{SU} showed only a significant effect of time (F_{1,22} = 16.68, P < 0.001), corresponding to an increase in the proportion M_L/M_{SU} over the trial duration (see Fig. 7B).

UCM analysis. The UCM analysis offers a method to quantify two components of the total variance in the space of commands to the fingers (modes) that correspond to keeping a
potentially important performance variable (F$_{tot}$ and M$_{tot}$ in our study) unchanged (“good variability” or V$_{UCM}$) and contributing to its changes (“bad variability” or V$_{ort}$). We computed V$_{UCM}$ and V$_{ort}$ for F$_{tot}$ and M$_{tot}$ separately, at each time sample across trials for each subject. An index, $\Delta V$, reflecting the difference in the magnitude of “good” and “bad” variability, was computed as described in METHODS. Positive $\Delta V$ values can be interpreted as multifinger synergies stabilizing that particular performance variable.

Figure 8 depicts the average $\Delta V_F$ and $\Delta V_M$ computed across subjects within each age group with SE bars. The data for the elderly subjects are shown in A ($\Delta V_M$) and C ($\Delta V_F$), while B ($\Delta V_M$) and D ($\Delta V_F$) show the data for the young subjects. Young subjects were able to stabilize the time profile of M$_{tot}$, reflected by positive $\Delta V_M$ values across the task duration (panel B, average 0.65 ± 0.2, $P < 0.01$), while elderly subjects failed to do so, as reflected by $\Delta V_M$ values that are not significantly different from zero (panel A, average 0.15 ± 0.47, $P = 0.759$). On the other hand, all subjects were able to stabilize the time profile of the F$_{tot}$ as reflected by positive $\Delta V_F$ values across the task (panels C and D, on average 0.41 ± 0.13 for elderly and 0.53 ± 0.13 for young); $\Delta V_F$ showed a tendency to drop to less positive values over the duration of the task. A one-sample $t$-test on the average $\Delta V_F$ showed that, in both age groups, average $\Delta V_F$ was significantly above zero ($P < 0.05$).

A two-way ANOVA with repeated-measures run separately for $\Delta V_F$ and $\Delta V_M$ with factors age and time (five intervals: PR$_{pre}$, PR-SU, SU, SU-PR, PR$_{post}$; see Fig. 2) showed significant effects of time for both $\Delta V_F$ ($F_{4,88} = 9.05, P < 0.001$) and $\Delta V_M$ ($F_{4,88} = 6.59, P < 0.001$). $\Delta V_F$ generally decreased along the time intervals, but a statistical difference was only found between PR$_{pre}$ and the other four intervals ($P < 0.05$).

DISCUSSION

The goal of this study was to investigate age-related changes in finger coordination during tasks that require the production of accurate time profiles of moment of force. We hypothesized that elderly individuals would show lower indexes of synergies stabilizing both M$_{tot}$ and F$_{tot}$. The former hypothesis received support in the experiment: the young subjects showed covariation of commands to fingers that stabilized the time profile of the moment of force, while the elderly subjects failed to do so. In contrast, there were no age-related changes in the ability of the subjects to stabilize the time profile of the F$_{tot}$: both subject groups showed covariation of commands to fingers that stabilized the F$_{tot}$, even though they were not specifically instructed to do so and got no visual feedback on the F$_{tot}$. These observations
suggest that age may be associated with an impairment of rotational hand actions that goes beyond the documented impairment in the control of finger force (43, 44). It may contribute to failure at a variety of everyday tasks relying on rotational hand action, including spilling the contents of a mug, failing to turn the key to open the door lock, producing poorly legible handwriting, etc. In the remainder of the discussion, we address these and other issues, in particular those related to possible adaptive motor strategies seen in elderly persons leading to less economical but safer performance.

Age Effects on Force Production

With advancing age, the human muscle undergoes many physiological changes. The number of α-motoneurons declines (5, 16), larger motor units lose their resistance to fatigue (reviewed in Ref. 31), motor units decrease in number (5, 11) but increase in size (24), peak tension and length of the muscle twitch increases (10), and overall the muscles lose both mass and strength (12). For this study, we purposefully selected elderly individuals who were in an excellent physical condition. As a result, there were only marginal changes between the subject groups in their ability to produce finger force. The elderly subjects produced, on average, 18% lower peak forces during both one-finger and four-finger MVC trials, but these differences were not statistically significant. Elderly subjects showed significantly higher indexes of variability, despite the fact that their task was set to be easier than that of the younger subjects. The VF was significantly larger for the elderly subjects in all time intervals, and particularly during the SU, SU-PR, and PRpost intervals. The finding of higher force variability in the elderly is in agreement with previous studies (14, 46). It is unlikely to reflect a difference in setting the tasks, since the tasks for the elderly required lower finger forces, and VF has been shown to increase with force magnitude (33). Since the subjects did not receive any explicit feedback on the Ftot and had no visual feedback on its value.

Age Effects on Rotational Action by the Fingers

Only a handful of earlier studies used tasks that explicitly required accurate hand torque exertion. Several studies that have addressed hand rotational action have focused on grip force production by the thumb and I finger during a pinch grip (20, 23). Other studies had steady-state torque production as an implicit component required to keep a hand-held object vertical (50, 40, 15). A couple of recent studies have explored finger coordination during accurate isometric moment of force production by young adults (54). An earlier study explored effects of age on digit interaction during gripping tasks, with an implicit requirement to keep the orientation of the hand-held object unchanged (41).

The average performance in the main task was defined by the template, and all subjects could perform the task well. However, the time profiles of the variance (VM) of the Mtot revealed significant differences between the two age groups: the elderly subjects produced larger VM during all time intervals, but especially during the phases when the direction of the moment of force changed: PR-SU and SU-PR. Note that the time profile of VM across the five time intervals is different from the time profile of VF; in particular, in both groups, the highest values of VM were seen during the steady-state production of SU moment of force, while the highest values of VM were seen during the PR-SU and SU-PR time intervals. These results suggest that the differences in VM characteristics were not simply by-products of differences in force characteristics between the subject groups, but likely reflected different coordination of commands to fingers with respect to force and moment of force production.

Both groups showed higher VM values during the PR-SU and SU-PR intervals when the magnitude of the total moment was, on average, smaller compared with the other three intervals: PRpre, SU, and PRpost. This observation contrasts the well-established force-force variability relations, which suggest an increase in force variability with an increase in the force magnitude (reviewed in Refs. 33, 45). Note that the Ftot on average, showed a transient drop at the times when the moment of force changed its direction (Fig. 4). As such, force changes could not account for the increase in VM over those time intervals. These results provide more support for the idea that the variability of the moment of force was not simply a reflection of variability of individual finger forces but was to a large degree defined by covariation of commands to fingers, that is, a moment-stabilizing synergy.

The transient increase in VM during the switch of direction of the moment of force (53) may be due to the relatively high rate of change of the moment of force combined with an error in the timing of control signals (19). Since VM was computed in relative units, the higher VM values in elderly subjects during the PR-SU and SU-PR intervals suggest an increase in the timing error, which can include timing offset errors or errors in the timing parameter that define the rate of change of the moment of force. Errors in timing of motor acts have been shown to increase with age (47) in support of this hypothesis.

The higher variability in the moment of force produced by a set of fingers by elderly persons is a novel finding. It extends the early report on increased variability of the rotational action of the thumb and the VF with age (41). As mentioned, this phenomenon may have profound effects on a variety of activities of daily living.

An earlier study reported larger magnitudes of the moment produced by fingers acting against the required moment direction (Mxam) by elderly persons in a static prehension task (41).
Our results are partially in agreement with that observation: elderly subjects produced significantly larger $M_{\text{Ant}}$ than the young subjects when the total moment was in SU. The higher $M_{\text{Ant}}$ may be viewed as an adaptive strategy, increasing the resistance of the hand and fingers to possible rotational perturbations (cf. Ref. 41). It may represent a consequence of the weaker moment-stabilizing synergies in elderly persons.

The experimental task involved tracking a visual template, and, as such, it could be affected by age-related differences in visual tracking tasks. On the one hand, visual and manual tracking performance has been shown to suffer with age (3, 32a). These differences, however, are particularly pronounced during tracking unpredictable signals (3), while the template used in our study was always the same and perfectly predictable. On the other hand, elderly are known to rely more on visual information during accurate motor tasks (38). Given that all of our participants had vision corrected to normal and the task involved only predictable, not very quick actions, the nature of the task could be expected to favor elderly subjects.

**Aging and the Principle of Mechanical Advantage**

When several effectors contribute to a common mechanical effect while acting in the same direction, sharing patterns among the elements may be defined by optimization rules. The mechanical advantage hypothesis has been suggested as a principle that defines sharing patterns for multimuscle and muscle-digit actions (4, 34). The general idea is that effectors with larger lever arms should produce larger shares of the total moment because they have to produce relatively smaller forces per unit of $M_{\text{tot}}$. In our study, the I and L fingers had moment arms three times as large as those for the M and R fingers. According to the mechanical advantage principle, the I finger should contribute more than one-half of the total PR moment, and the L finger should contribute more than one-half to the SU moment. The young subjects showed modulation of the percentage of the total moment produced by the I and L fingers, such that the mechanical advantage hypothesis was true, but only when the fingers acted as agonists (produced $M_{\text{Ag}}$); the hypothesis failed when the fingers produced $M_{\text{Ant}}$. In contrast, the elderly subjects did not show a comparable modulation of the percentage of the total moment produced by the I finger: they produced close to 80% of the total PR moment of force with that finger over the whole trial duration. This result may reflect the reduced flexibility in the control of the moment of force in the elderly, which may be a consequence of their weaker synergies. Note that one advantage of having strong synergies stabilizing a performance variable is in the possibility to use multiple, flexible solutions (17). The difference in the tasks was not expected to lead to such results, because the tasks were set at rather low values. For young persons, $4 \text{ N}$ of force by the I finger are typically under 10% of its maximal force (see Table 1). Hence, the requirement to produce such a low force is not expected to be a limiting factor in using the I finger to produce required moment of force.

**Changes in Multifinger Synergies With Age**

The principle of abundance views synergies as neural organizations that provide for flexible families of solutions for motor tasks, based on apparently redundant sets of effectors (17). The UCM hypothesis (37) has formalized this principle and suggested that the purpose of synergies is to minimize variability along particular directions in the space of elemental variables (that change a desired value of an important performance variable, “bad variability”), while allowing variability in other directions. For example, if the controller tries to ensure accurate production of a particular value of the total moment produced by a set of fingers, it is expected to keep the variability of commands to fingers across trials mostly confined to a subspace (a UCM) in the finger mode space that does not lead to changes in that value. The index of synergy we used in this study ($\Delta V$, see also Refs. 39, 44) was computed in such a way that its positive values corresponded to proportionally more variability within the corresponding UCM, which can be interpreted as a multifinger synergy stabilizing either $F_{\text{tot}}$ or $M_{\text{tot}}$ ($\Delta V_F$ and $\Delta V_M$, respectively).

Consider the task of supporting a heavy object with two fingers (Fig. 9). If the forces of the two fingers vary independently, the object may be expected to move up and down and/or to tilt. If, however, the forces covary negatively, the $F_{\text{tot}}$ may be expected to stay relatively unchanged (more variability confined to the UCM computed for the $F_{\text{tot}}$, $\Delta V_F > 0$), but the $M_{\text{tot}}$ will show large variations (more variability orthogonal to the UCM for the total moment, $\Delta V_M < 0$). If the two forces covary positively, the total moment will be relatively stabilized ($\Delta V_M > 0$), but the $F_{\text{tot}}$ will not ($\Delta V_F < 0$). The system of only two effectors illustrated in Fig. 9 is only marginally redundant (26) and cannot stabilize these two variables at the same time. The availability of four fingers in our tasks allowed simultaneous stabilization of both $F_{\text{tot}}$ and $M_{\text{tot}}$.

The main results of the study summarized in Fig. 8 show that both subject groups were able to covary commands to fingers to stabilize $F_{\text{tot}}$ ($\Delta V_F > 0$), while only young subjects stabilized $M_{\text{tot}}$ ($\Delta V_M > 0$). The former result is counterintuitive, since the subjects got no feedback on $F_{\text{tot}}$ and were given no instruction about it. The latter result supports our main hypothesis and suggests that age is associated with a decrease in the
ability to coordinate commands to digits to produce rotational actions. 

Note that our task was designed to minimize possible involvement of the forearm, i.e., its radio-ulnar proximal and distal joints, into the moment production: the palm was supported by a wooden block and the forearm was attached to the board with Velcro strap. This was done purposefully to avoid possible changes in the moment due to forearm PR/SU. The task used in the study may be viewed as artificial and even odd, but it has allowed us to address the issue of synergies among commands to fingers that stabilize their combined rotational action. This action can be formally expressed as that by the VF (Refs. 1, 32, also see the Introduction). An earlier study (41) analyzed synergies at the higher level of the hypothetical control hierarchy, that is, at the level of coordinated action of the thumb and the VF. For example, during drinking from a glass, the thumb and combined finger (VF) actions have to be coordinated to stabilize the Mtot applied to the glass. Com-

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CHAPTER 5 Elderly Show Decreased Adjustments of Motor Synergies in Preparation to Action
Elderly show decreased adjustments of motor synergies in preparation to action

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Abstract

Background. Aging is associated with decreased manual dexterity. Recent findings have identified changes in multi-finger synergies in elderly individuals. The purpose of current work was to study age-related changes in adjustments of multi-finger synergies in preparation to a quick targeted force pulse production task.

Methods. Right-handed elderly and young subjects produced quick force pulses by pressing on individual force sensors with the four fingers of the right hand. Prior to the force pulse, the subjects produced a constant low level of the total force. An index of multi-finger synergies was computed across trials for each time sample for each subject and each condition.

Findings. During steady-state force production, subjects showed co-variation of commands to fingers that stabilized the total force. An index of this co-variation started to decrease prior to the initiation of the force pulse (anticipatory synergy adjustment). Anticipatory synergy adjustments in young subjects started earlier and were larger than in elderly subjects. In particular, young and elderly subjects showed significant anticipatory synergy adjustments starting about 150 ms and about 50 ms prior to the force pulse initiation, respectively. There were no significant differences between the two groups in other indices of performance such as reaction time, time to peak force, and magnitude of the peak force.

Interpretation. We conclude that healthy aging is associated with decreased feed-forward adjustments of multi-finger synergies in preparation to action. This may contribute to the age-related decline in the hand function. Based on similarities in age-related changes in anticipatory postural adjustments and anticipatory synergy adjustments we suggest a hypothesis that the two phenomena may share common mechanisms.

1. Introduction

Aging is associated with a general decline in the hand function, which interferes with activities of daily living (Francis and Spirduso, 2000; Giampaoli et al., 1999; Hughes et al., 1997; Rantanen et al., 1999). These changes may receive contributions from the changes in the number of motor units, muscle composition, and muscle strength (Bemben, 1998; Campbell et al., 1973; Kirkendall and Garrett, 1998; Owings and Grabiner, 1998; Winegard et al., 1997). In recent studies, changes in multi-digit synergies have been documented in elderly that can also potentially contribute to decreased performance in everyday prehensile tasks (Shim et al., 2004; Shinohara et al., 2003, 2004). Those studies used a definition of a synergy as a neural organization of elemental variables that stabilizes an important performance variable over repetitive trials at a task (reviewed in Latash et al., 2002). In different studies, elemental variables were associated either with forces and moments of forces produced by individual digits on a hand-held object (Shim et al., 2003; Zatsiorsky and Latash, 2004) or with hypothetical commands to fingers (finger modes, Danion et al., 2003; Latash et al., 2001). Multi-digit
synergies stabilizing such performance variables as the total force and the total moment of force produced on an external object have been shown to be weaker in elderly as compared to young persons (Shim et al., 2004; Shinohara et al., 2003).

In this study, we use the idea of multi-digit synergies to address the following question: Is aging associated with a decreased modulation of multi-finger synergies in a feed-forward manner in preparation to a quick action? This question is based on a recent series of studies that have demonstrated a novel phenomenon termed anticipatory covariation (ACV) or anticipatory synergy adjustment (ASA) (Olafsdottir et al., 2005; Shim et al., 2005). Those studies have shown that an index of a multi-finger synergy stabilizing the total force produced by a set of fingers shows a decline 100–150 ms prior to the initiation of a quick force pulse. Such changes were not seen when the subjects were required to produce similar force pulses under a simple reaction time instruction (Olafsdottir et al., 2005). The functional importance of ASAs has been assumed to turn off synergies that would otherwise counteract a planned quick action.

There is another phenomenon that resembles ASAs, anticipatory postural adjustments (APAs, reviewed in Massion, 1992). APAs are seen, in particular, in standing subjects as changes in the activity of postural muscles about 100 ms prior to an action by the subject that is associated with a postural perturbation. APAs have been interpreted as reflections of a feed-forward control mechanism with the purpose to generate forces and moments of force that act against expected perturbing forces and torques (Bouisset and Zattara, 1990; Cordo and Nashner, 1982). APAs have been reported to be delayed and reduced in magnitude in elderly persons (Inglis and Woollacott, 1988; Rogers et al., 1982; Woollacott et al., 1988).

In an earlier paper (Olafsdottir et al., 2005), we have speculated that ASAs and APAs could be phenomena of a common nature: Both reflect feed-forward changes in multi-muscle synergies related to a planned adjustment of a steady-state (postural) task. Based on this idea, we hypothesized that elderly persons would show a reduced ability to produce ASAs, similar to their documented reduction in APA generating abilities. Testing this hypothesis is important for two reasons. First, if supported, this hypothesis would provide additional evidence for the commonality of the phenomena of ASAs and APAs – a result that would mean reconsideration of the nature and role of APAs in postural control.

2. Methods

2.1. Subjects

Ten young (on average, 27 years old with the standard deviation, SD = 4) and ten elderly (77 years old, SD = 4) subjects volunteered to participate in the study. Both groups consisted of five males and five females. The average height and mass were 172 (SD = 12.1) cm and 66.1 (SD = 13.0) kg for the young subjects, and 165.4 (SD = 10.5) cm and 72.9 (SD = 14) kg for the elderly subjects. All subjects were healthy and right-handed, according to their preferential hand use during writing and eating. 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. We purposefully selected for the study elderly subjects who exercised regularly and were in a generally good physically shape (self-reported). All subjects gave informed consent according to the procedures approved by the Office for Research Protection of The Pennsylvania State University.

2.2. Apparatus

Four piezoelectric sensors (Model 208A03, PBC Pieztronics Inc., Depew, NY, USA) amplified by AC/DC conditioners (M482M66, PBC Piezotronics, Inc., Depew, NY, USA) were used to measure the forces generated by the fingers. Cotton pads were attached to the surface of the sensors to increase friction and prevent possible effects of skin temperature. The sensors were placed in a metal frame sitting in a grove on a wooden board. The sensors were medio-laterally spaced 30 mm apart and could be adjusted in the forward–backward direction within 60 mm to fit each subject’s hand anatomy. Once the appropriate position of the sensors had been determined, double-sided tape was placed under the bases of the sensors to prevent them from moving from that position.

During the experiment, the subjects sat in a chair facing the testing table with the right shoulder at approximately 45° of abduction and flexion, and the elbow flexed about 135°. Metacarpophalangeal joints were flexed about 20° and all interphalangeal joints were slightly flexed such that the hand formed a dome. A wooden piece, shaped to fit comfortably under the subject’s palm, helped maintain a constant configuration of the hand and fingers. The forearm was attached to the board with Velcro straps. A 17” computer monitor, located about 0.8 m away from the subject, displayed the task (see later) and the actual total force produced by all four fingers. In reaction time trials, imperative auditory signals were delivered through the headphones. Fig. 1 displays the experimental setup. A LabVIEW-based program (National Instruments, Austin, TX, USA) was used for data acquisition. The data were collected at 1000 Hz with a 12-bit resolution.

2.3. Procedure

Prior to each trial the subject sat relaxed with the fingers of the right hand resting on the sensors. The computer gen-
erated two beeps (get ready) and a cursor showing the total force generated by all four fingers started to move across the screen. There were six control trials and two main series. First, maximal voluntary contraction (MVC) force was measured. In these trials, the subjects were required to press “as hard as possible”, with all four fingers. Subjects were given an interval of 3 s to reach peak force. Two attempts at the MVC task were recorded, and the attempt with the higher peak force was used to set up other tasks. Following the MVC task, subjects were asked to produce ramp patterns of force from 0% to 10% of MVC over 5 s by pressing down with one finger at a time in separate trials. They were instructed not to pay attention to possible force production by other fingers of the hand and not to lift any finger off its sensor at any time. An oblique blue line was shown on the screen, and the participant’s task was to trace this line in time with the cursor representing the force of the task finger. These data were used to generate linear estimates of the relations between changes in individual finger forces and change in the total force during multi-finger tasks (the Jacobian; Scholz et al., 2002). These relations are non-trivial because of the phenomenon of enslaving, i.e., unintended force production by fingers when other fingers of the hand produce force (Kilbreath and Gandevia, 1994; Zatsiorsky et al., 2000).

There were two main series of trials, reaction time (RT) and self-paced (SP). In these series, horizontal lines representing a background force ($F_{BG}$, 5% MVC) and a target force ($F_T$, 25% MVC with 5% error margins) were displayed on the screen. A vertical line indicated the time of 3 s after the initiation of each trial. Each trial lasted 7 s. At the trial initiation, the subject sat relaxed with the right hand fingers positioned on the sensors. After a get ready signal, a cursor showing the total force started moving over the screen at a constant speed. The subject was asked to press on the sensors such that the total force trace followed the $F_{BG}$ line, wait until the cursor crossed the vertical line, and then produce a very quick force pulse to $F_T$. All the subjects were able to stabilize total force by the time 3 s; this was confirmed by visual observation. We also performed linear regression analysis on the force data from four randomly selected subjects within the time window from 3 to 3.3 s. The largest slope of the regression line was 0.0005 N/s suggesting that the subjects did indeed achieve steady-state force production by that time. Hence, the interval from crossing the vertical line to the force pulse initiation is referred to as “steady-state”.

In SP trials, the subject was free to initiate the force pulse at any time after the vertical line but was specifically instructed not to produce the pulse immediately after the cursor crossed the vertical line. In RT trials, the subjects produced the force pulse as quickly as possible in response to a brief (100 ms) “chirp” sound, delivered via head-phones unpredictably within a 300 ms time interval starting 300 ms after the force trace crossed the vertical line on the screen. Young subjects performed 15 trials within each series with 8 s intervals between the trials and 3 min intervals between the series. Elderly subjects performed 20 trials.
within each series. More trials were collected for elderly subjects because we expected more rejected trials for this group (see later). The trials within each series were presented in blocks. The order of series was balanced across subjects. Three practice trials were given prior to each series.

2.4. Data analysis

The data were processed off-line using MatLab-based software. The force data were low-pass filtered at 80 Hz using a 2nd-order, zero-lag Butterworth filter prior to computation of the derivative of the force with respect to time \( (dF/dt) \). Unfiltered data were used for the analysis of force variance components. The following time indices were calculated for the SP and RT series. Time of the initiation of change in the total force \( (t_i) \) during the force pulse was defined as the time when \( dF/dt \) reached 5% of its peak value in that particular trial. Reaction time \( (t_{RT}) \) was defined as the time from the beginning of the auditory signal to \( t_F \). Trials in the RT series with reaction times shorter than 100 ms and longer than 300 ms as well as trials within both RT and SP series that showed multiple force peaks were rejected from further analysis. On average, for the young subjects, 0.7 trials were rejected in the RT series and 2.1 trials in the SP series while respectively 4.9 and 3.4 trials were rejected for the elderly subjects. Trials with the peak landing outside the error margins were rejected and repeated during the experiment. For both groups, on average, four trials were repeated per subject. Time to peak force \( (t_{PF}) \) was defined as the time from \( t_F \) to the time when peak force \( (F_{PEAK}) \) occurred. Prior to further analysis, all the trials within each series were aligned by \( t_F \).

For further analyses, we used the framework of the uncontrolled manifold (UCM) hypothesis (reviewed in Latash et al., 2002; Scholz and Schöner, 1999). The hypothesis assumes that the controller organizes covariation among elemental variables to stabilize a certain value of a performance variable (total force in our study). Individual finger forces cannot be considered independent elemental variables because of the phenomenon of enslaving (Kilbreath and Gandevia, 1994; Zatsiorsky et al., 2000). Hence, the first step was to convert the data sets from time series of finger forces to time series of elemental variables, force modes.

Force modes were defined similarly to previous studies (Latash et al., 2001; Scholz et al., 2002). Briefly, single-finger force ramp trials were used to compute the enslaving matrix \( \mathbf{E} \) for each subject. The entries of the \( \mathbf{E} \) matrix were computed as the ratios of the change in the force of each finger to the change in the total force over the ramp duration. The \( \mathbf{E} \) matrix was used to compute changes in the vector of hypothetical independent commands to fingers (force modes, \( \mathbf{m} \)) based on force changes.

Further analysis was done across repetitive trials performed by a subject at different time slices over the duration of the task. According to the UCM hypothesis, more variance in the \( \mathbf{m} \) space per dimension is expected within a manifold (UCM) corresponding to a constant value of the total force than in an orthogonal complement to that manifold. For each time, \( t_j \), the average vector \( \mathbf{m}_{AV} \) was computed. Then, for each trial \( j \), deviations \( (\Delta \mathbf{m}_j) \) between \( \mathbf{m}_j \) and \( \mathbf{m}_{AV} \) were computed. Variance of the \( \Delta \mathbf{m}_j \) data set was then computed along a direction orthogonal to the UCM computed for an average value of the total force observed across trials at that particular time slice. We will refer to this index as \( V_{ORT} \). This was done using the Raleigh fraction (Goodman et al., 2005):

\[
V_{ORT} = \frac{\mathbf{J}_m \mathbf{COV}(\mathbf{m}) \mathbf{J}_m^T}{\mathbf{J}_m \mathbf{J}_m^T} = \frac{\mathbf{J} \mathbf{E}^{-1} \mathbf{E}^{-1} \mathbf{COV}(\mathbf{f}) \mathbf{E}^{-1} \mathbf{E}^{-1} \mathbf{J}^T}{\mathbf{J} \mathbf{E}^{-1} \mathbf{E}^{-1} \mathbf{J}^T},
\]

where \( \mathbf{J} \) is the Jacobian matrix relating small changes in modes \( (\mathbf{J}_m) \) or forces \( (\mathbf{J}) \) to changes in the total force, \( \mathbf{COV}(\mathbf{m}) \) is the covariance matrix in the mode space, \( \mathbf{COV}(\mathbf{f}) \) is the covariance matrix in the finger force space, and \( \mathbf{T} \) is the sign of transpose. For total force stabilization analysis, \( \mathbf{J} = [1,1,1,1] \), \( \mathbf{J}_m \) can be computed as: \( \mathbf{J}_m = \mathbf{JE}^{-1} \).

\( V_{ORT} \) reflects the amount of mode variance in the data set that corresponds to a change in the total force. The difference between the total amount of variance \( (V_{TOT}) \) and \( V_{ORT} \) corresponds to variance that does not affect the average value of the performance variable, the total force. We will address this variance as \( V_{UCM} \) (variance within the UCM, cf. Latash et al., 2002): \( V_{UCM} = V_{TOT} - V_{ORT} \).

Note that the finger mode space is four-dimensional, \( V_{ORT} \) lies along a one-dimensional sub-space corresponding to a change in the total force, while \( V_{UCM} \) lies in a three-dimensional null-space, where the total force is constant. Therefore, to compare the amounts of variance per dimension, the following index was used:

\[
\Delta V = \frac{(V_{UCM}/3 - V_{ORT})}{V_{TOT}/4}
\]

Normalization by the total amount of variance per dimension \( (V_{TOT}/4) \) was used to compare the data across subjects who could show different amounts of the total variance. Note that positive values of \( \Delta V \) correspond to proportionally more variance within the UCM, i.e., they correspond to a predominantly negative co-variation among changes in finger modes and may be interpreted as a synergy stabilizing a constant value of the total force. If \( \Delta V = 0 \), this means that the amount of variance per dimension is the same in directions that correspond to a change in the total force and along directions that keep the force unchanged. \( \Delta V < 0 \) may be interpreted as a reflection of a predominantly positive co-variation among changes in finger modes contributing to a change in the total force or destabilizing it.

2.5. Statistics

The data in the text are presented as group means and standard deviations. Since the experiment was focused on
effects of aging, the data were pooled across the genders. For statistical analysis, we used non-parametric tools because of the small number of subjects. Non-parametric Mann–Whitney test was used to compare maximal total force in the four-finger MVC task, peak force ($F_{\text{peak}}$), time to peak force ($t_{\text{PF}}$) and reaction time ($t_{\text{RT}}$) within and between the age groups.

To compare $\Delta V$ time profiles between the two tasks (RT and SP), a time interval from 300 ms before $t_F$ to the onset of force pulse ($t_F$) was selected. Average $\Delta V$ indices were computed for each subject and each task over six 50 ms time windows within that time interval. Non-parametric Friedman's test with factors Condition (RT and SP) and Time was used to test for main effects on $\Delta V$. The level of significance was set at $P = 0.05$. For post hoc comparisons, Mann–Whitney tests were used with the $P$-value adjusted for multiple comparisons ($P = 0.0083$).

3. Results

The two subject groups did not differ in most of their performance indices. In particular, the elderly subjects were not significantly weaker and not significantly slower than the young subjects. The only significant difference between the two groups was in the pattern of the $\Delta V$ index of force stabilization by multi-finger synergies.

The elderly subject group produced, on average, 86.2 (SD = 32.0) N in the four-finger MVC task, which was not significantly different from the 96.5 (SD = 29.2) N produced, on average, by the younger subjects. Fig. 2 shows a typical performance by a young (solid line) and elderly (dashed line) subject in a reaction-time (RT) trial. Elderly subjects produced force pulses that, on average, reached a peak of 21.0 (SD = 7.9) N in RT trials and 21.5 (SD = 7.5) N in SP trials. These indices were not significantly different from 24.0 (SD = 7.3) N and 24.3 (SD = 7.5) N peak forces produced by the younger subjects in respective tasks ($P > 0.05$; Mann–Whitney test).

The time from the onset of the force pulse ($t_F$, defined as the time when the rate of force change reached 5% of its peak value in that trial) to the force peak ($t_{PF}$) was approximately 15 ms shorter in the RT trials (young subjects: 115.4 ms, SD = 36.0; elderly subjects: 115.4 ms, SD = 21.0) than in the SP trials (young subjects: 130.7 ms, SD = 29.6 ms; elderly subjects: 131.0 ms, SD = 23.8) in both age groups. This difference was statistically significant ($P < 0.05$) but no difference was found between the age groups within the RT and SP conditions ($P > 0.05$). The reaction time ($t_{RT}$) was, on average, 194.3 (SD = 25.3) ms for the elderly and 206.6 (SD = 27.0) ms for the young subjects, this difference was not statistically significant ($P > 0.05$).

To analyze changes in covariation patterns of hypothetical independent commands to fingers (finger modes), we used an index $\Delta V$ computed within the framework of the UCM hypothesis (see Section 2). During steady-state force production, $\Delta V$ was consistently positive in all subjects corresponding to covariation of finger modes that stabilized the total force value across trials. During the steady-state phase, the average value of $\Delta V$ was 1.03 (SD = 0.03) in RT trials and 0.99 (SD = 0.03) in SP trials for the young subjects while $\Delta V$ was, respectively, 0.67 (SD = 0.04) and 0.84 (SD = 0.03) for the elderly subjects. The difference between the young and elderly subjects in $\Delta V$ value was significant for RT trials ($P < 0.05$, Mann–Whitney test) but did not reach significance level for SP trials. Not that the index $\Delta V$ reflects the relative amount of “good variability” (variance within the UCM) in the total variability of commands to fingers (modes); hence higher $\Delta V$ in one subject group does not by itself imply that that group was more or less accurate than the other subject group.

Prior to the initiation of a force pulse, $\Delta V$ in SP trials started to drift down, whereas in RT trials no such drift was observed. This was true for both elderly and young subjects, but in young subjects this early drift was larger and started earlier. Since subjects could show significantly different baseline $\Delta V$ values during steady-state force production, to compare changes in $\Delta V$ across subjects, an index ($\Delta \Delta V$) was computed reflecting changes in $\Delta V$ as compared to its value 300 ms prior to $t_F$. Fig. 3 illustrates $\Delta \Delta V$ time profiles averaged across subjects within each group, for the SP (solid lines) and RT (dashed lines) conditions separately. For statistical comparisons, $\Delta \Delta V$ values were averaged over 50 ms time windows starting 300 ms prior to $t_F$ to $t_F$. A Friedman test showed for both age groups significant effects of both factors, condition (two levels, RT and SP) and time (six levels) ($P < 0.05$) on the $\Delta \Delta V$. Mann–Whitney test has confirmed that, in young subjects, $\Delta \Delta V$ for the SP trials became smaller than for the RT trials 150 ms prior to $t_F$. ($P < 0.008$). In contrast, elderly subjects showed a significant difference between the two conditions only 50 ms prior to $t_F$ ($P < 0.008$). The early drop in $\Delta \Delta V$, estimated from 300 ms prior to $t_F$ to $t_F$, was more than twice as large in the young subjects compared to the elderly subjects (0.24 vs. 0.09) but this difference did not reach significance ($P > 0.05$, Mann–Whitney test).
During the force pulse, all subjects showed a drop in $\Delta V$, commonly into negative values (Fig. 3). This was quantified by calculating the difference between the baseline value 300 ms before $t_F$ and the minimum value of $\Delta V$ after $t_F$. On average, young subjects had a maximal drop of about 2.2 (SD = 1.0) in RT trials and 2.0 (SD = 1.0) in SP trials whereas elderly subjects showed on average a maximal drop of about 1.4 (SD = 0.8) in RT trials and 1.7 (SD = 1.0) in SP trials. This difference was not significant in any of the comparisons ($P > 0.05$; Mann–Whitney).

4. Discussion

The main result of the current experiment is the demonstration of significant differences between young and elderly persons in the processes of preparation to a quick action. Both groups were able to modify multi-digit force-stabilizing synergies in preparation to a quick force pulse. However, such preparation started later in elderly persons and led to smaller changes in the synergy index. This finding supports our hypothesis on an age-related decrease in the anticipatory modifications of multi-element synergies during preparation to an action. Taken together with earlier reports on delayed and decreased anticipatory postural adjustments (APAs) in elderly (Inglis and Woolacott, 1988; Rogers et al., 1982; Woolacott et al., 1988), the findings suggest that advanced age leads to a generally decreased use of feed-forward control in preparation to self-initiated actions.

We would like to emphasize that our elderly subjects were purposefully selected to match the young controls in their level of performance. They did not show significantly longer reaction times (cf. Stelmach et al., 1987; Welford, 1984), slower force development (cf. Owings and Grabiner, 1998), or lower force producing abilities (cf. Narici et al., 1991; Shinohara et al., 2003; Winegard et al., 1997) as compared to the younger subjects. Therefore, the observed age-related differences in the synergy index changes were not related to the difference in characteristics of the prepared actions. The contrast between the basically unchanged performance and significantly changed processes of preparation is the strongest reason to claim that the changed indices of preparation of multi-finger synergies is a sign of aging that may be unrelated to the mentioned, well-documented changes such as weakening and slowing down.

4.1. Force-stabilizing synergies in multi-digit action

A number of studies have documented multi-digit force-stabilizing synergies during steady-state force production tasks and slow changes in the total force (Latash et al., 2001; Scholz et al., 2002; Shim et al., 2004). However, several studies showed that fast changes in the total force could be associated with co-variation of signals to fingers that could potentially destabilize the total force (Latash et al., 2001, 2002; Scholz et al., 2002). In particular, it was shown that the amount of finger variance within the UCM ($V_{UCM}$) changed in parallel with the force level while the amount of variance orthogonal to the UCM ($V_{ORT}$) changed in parallel with the first derivative of force. A recent modeling study based on experiments with fast multi-finger force production has confirmed these observations by showing that $V_{ORT}$ could exceed $V_{UCM}$ during fast force changes (Goodman et al., 2005).

Our task involved both steady-state and quick force pulse components. During the steady-state force production, both young and elderly persons showed multi-finger synergies stabilizing the total force (positive $\Delta V$ values). These results are similar to those reported in earlier studies (Shinohara et al., 2003, 2004). In one of the earlier studies, it has been shown that the index of synergy stabilization is smaller in elderly persons than in younger persons (Shinohara et al., 2004). Our subjects showed a similar trend with smaller $\Delta V$ values observed in the elderly subjects. This difference was significant for the steady-state values observed in the RT trials and was under the level of significance in the SP trials.

During the quick force pulse production, both subject groups showed a rapid drop in the synergy index leading sometimes to its negative values that correspond to destabilization of the total force. These results are in line with the mentioned experimental and modeling studies (Goodman et al., 2005; Latash et al., 2001; Scholz et al., 2002).

4.2. Aging effects on feed-forward control

A number of studies reported age-related deficits in the production of adequate adjustments in preparation to
action. In particular, elderly subjects use excessive grip forces and smaller grip force modulation prior to lifting an object (Cole, 1991; Cole et al., 1999; Kinoshita and Francis, 1996; Gilles and Wing, 2003). They also show smaller and delayed APAs (Inglin and Woollacott, 1988; Rogers et al., 1982; Woollacott et al., 1988).

All the mentioned studies analyzed outputs of particular motor elements (muscles and digits), not patterns of their coordination with respect to important task-specific performance variables. In contrast, our study focused on an index of covariation of commands to fingers related to the production of a particular time profile of the total force. The demonstration of delayed and decreased anticipatory synergy adjustments (ASAs) allows to speculate on the relations between ASAs and APAs as well as on general effects of aging on feed-forward control.

ASAs and APAs show the following similarities (De Wolf et al., 1998; Lee et al., 1987; Massion, 1992; Olafsdottir et al., 2005; Shim et al., 2005). First, they are both observed 100–150 ms prior to an action. Second, they are both delayed, i.e., emerge closer to the time of action initiation under the simple reaction time instruction. Third, they are both decreased and delayed in elderly (the current study). This seems to us too much to consider these similarities as coincidental. In contrast, we would like to suggest that APAs, or at least some of the typical changes in muscle activity described as APAs, may represent a particular example of ASAs. In turn, ASAs represent a particular example of feed-forward changes in control signals, an example of changes that are not necessarily reflected in the explicit performance.

Taken together, our results and previously published data suggest that aging is associated with decreased feed-forward control of both explicit performance variables (such as grip force adjustments in Cole et al., 1999; Kinoshita and Francis, 1996) and multi-element synergies (such as those quantified in the current study).

5. Concluding comments

Our study did not show any differences in the performance of the task by the young and elderly subjects. A natural question emerges: What is the functional role of ASAs if they are not reflected in the task performance? We can only offer tentative suggestions that are beyond the scope of the present study and require further investigation.

First, not all young subjects demonstrate equally clear ASAs (Olafsdottir et al., 2005). Some young subjects show minimal $\Delta V$ changes in preparation to action; the mentioned earlier study has suggested that using larger $\Delta V$ changes might help subjects avoid excessive destabilization of the total force during the force pulse production. This was supported by more negative values of $\Delta V$ during the force pulse in those subjects who showed smaller ASAs. However, in our study, no significant differences were found in the minimal $\Delta V$ values during the pulse production.

Another recent study (Kim et al., 2006) investigated ASAs during multi-finger constant force production tasks in preparation to self-triggered and unexpected perturbations applied to one of the fingers. In self-triggered conditions, ASAs were seen starting about 150 ms prior to the perturbation. When similar perturbations were applied unexpectedly, no ASAs were observed. After the perturbation, the subjects restored the force-stabilizing synergy significantly quicker in trials with ASAs. So, one can tentatively conclude that ASAs are not an obligatory mechanism for quick actions or reactions but they may help stabilize the performance variable after the action. In the current study, the subjects were instructed to relax after the force pulse; therefore, we cannot compare the rate of synergy restoration after the force pulse across the subject groups.

All these hypothesis create room for new experimental studies that will hopefully shed more light on the nature and function of ASAs and their changes with age.

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References

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CHAPTER 6 Anticipatory Synergy Adjustments in Preparation to Self-Triggered Perturbations in Elderly Individuals

6.1 Introduction

Several recent papers described anticipatory synergy adjustments (ASAs) during multi-finger force production tasks (Kim et al. 2006, Olafsdottir et al. 2005b, Shim et al. 2005). In those studies, synergies were defined as patterns of co-variation among finger forces or finger modes (hypothetical independent control signals to individual fingers that are manipulated by the controller (Danion et al. 2003)) across repetitive trials that stabilized the total force (Latash et al. 2002, Scholz et al. 2002, Shim et al. 2005c). In tasks where the level of force had to be changed quickly in a predictable manner, a change in the index of finger force co-variation has been observed prior to the change in total force (Kim et al. 2006, Olafsdottir et al. 2005b, Shim et al. 2005c). This phenomenon, ASA started approximately 100-150 ms prior to the earliest change in the total force. ASAs have been assumed to reflect a feed-forward control mechanism similar to anticipatory postural adjustments (APAs) (Kim et al. 2006, Massion, 1992). APAs are seen as changes in the activity of postural muscles in preparation to an action that is associated with a perturbation to balance (Bouisset and Zattara, 1987).

Aging is associated with a variety of changes in the muscles, their motor unit composition, and neural control mechanisms (rev. in Reeves et al. 2006). In particular, APAs have been reported to be reduced in magnitude and delayed in elderly (Woollacott and Manchester, 1993). A recent study documented similar age-related changes in ASAs prior to a fast action (chapter 5). However, that study did not involve any perturbation. The main purpose of the current study has been to investigate possible anticipatory changes of indices of finger coordination prior to a predictable perturbation in elderly individuals. We hypothesized that ASAs would be observed in elderly, but that they will be smaller and delayed as compared to ASAs reported in a recent study of young persons (Kim et al. 2006).
6.2 Methods

6.2.1 Subjects

Thirteen elderly individuals volunteered to participate in the study (seven males and six females). Their average age, height and mass was 77 ± 4 years, 175.5 ± 6.6 cm and 84.8 ± 12.1 kg for the males and 77 ± 4 years, 160.4 ± 10.1 cm and 60.5 ± 7.8 kg respectively for the females. The 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. We purposefully selected for the study elderly subjects who exercised regularly and were in a generally good physically shape (self-reported). All subjects gave informed consent according to the procedures approved by the Office for Research Protection of The Pennsylvania State University.

6.2.2 Apparatus

Four electromagnetic locks were suspended with plastic strings over an inverted U-shaped metal frame via a pulley system (Figure 6.1). The other end of each plastic string had a loop through which a finger could be inserted. Each electromagnetic lock had a load attached to it (200 g for males, 100 g for females); a load could be released by pressing a button on the trigger box. Four piezoelectric force sensors (Model 208A03, Piezotronic, Inc. Depew, NY, USA) were placed inside a metal frame and under the fingertips of the fingers of the right hand.
Figure 6.1 A schematic illustration of the experimental setup. A. The metal frame with the pulley system that the loads were suspended over. The force sensor positions were adjusted to fit the individual subject’s anatomy. The electromagnetic locks could be turned off by pressing a button, which released the load. The trigger box was located to the left of the subject in self-triggered trials and behind a screen during experimenter-triggered trials. B. The position of the subject and C. an example of its performance.

The four sensors were medio-laterally distributed 3 cm apart and could be adjusted in the forward-backward direction within 6 cm to fit individual subject’s hand anatomy. Once a comfortable position of the sensors had been found, double sided tape was used to keep them in place. The sensors measured the pressing force produced by the fingers. The plastic loops were positioned under the distal interphalangeal joints of the fingers so that the loads caused vertical forces acting on each finger. As a result, the subjects had to produce a flexion force by each finger to touch the force sensors.
6.2.3 Procedure

During the experiment, subjects sat on a chair facing the testing table with their right shoulder at about 45° of abduction and 45° of flexion, the elbow flexed approximately 45° and the wrist in neutral position. A dome shaped wooden piece was placed under the subject’s palm to help maintain a constant hand configuration. A 17” computer monitor, located about 80 cm away from the subject, displayed the task (see later) and the actual total force produced by all four fingers. Black cardboard divider was used to block both the loads and the trigger box from the subject’s view. During trials with self-triggered perturbations, the trigger box was placed to the left of the subjects and their left index finger was placed on the load releasing button. A LabVIEW-based program was used for data acquisition. The data were collected at 1000 Hz with a 12-bit resolution.

The experiment consisted of two series of trials, with self-triggered (SELF) and experimenter-triggered (EXP) perturbations of the middle finger. Before each trial, the subject was instructed to place the fingers on the force sensors but refrain from pressing down. The computer generated two “beeps” (get ready) and a cursor showing the total force produced by all four fingers started to move across the screen. The screen also showed a horizontal template line at the 8 N force level. The subjects were asked to press on the force sensors with all four fingers and match the total force output to the horizontal line. Each trial lasted 10 s. During a 3-second interval, starting 3 s after the beginning of the trial, the middle finger (the task finger) was unloaded by pushing the corresponding load-release button, either unexpectedly by the experimenter or by the subject at a self-selected time. Unloading the finger caused its recorded level of force to increase. Subjects were asked to try to maintain the total force level at 8 N at all times and return to it as quickly as possible following a perturbation. Each subject performed 15 trials within each condition with 10 s intervals between trials and 3 min interval between the conditions. The order of conditions was balanced across the subjects and 4-7 practice trials were given prior to each condition.
6.2.4 Data Analysis

The data were analyzed off-line using a MatLab-based software (MathWorks Inc. Natick, MA). The force data were filtered at 100 Hz using a 2-order, zero-lag low-pass Butterworth filter. When the trigger button was pushed, a rectangular electrical pulse was recorded. The data were aligned in time by the time of the ascending edge of the pulse, t0.

The average time profiles of the individual finger forces, \( F_i(t) \) (i = I, M, R, L) and of the total force, \( F_{TOT}(t) \) were computed across trials within each condition for each subject. The average time profiles of the force of the middle finger (\( F_{M}(t) \)) and the total force of other fingers (\( F_{IRL}(t) \)) were computed. To compare the sharing of the total force between the M and IRL fingers before and after the perturbation, \( F_{M}(t) \) and \( F_{IRL}(t) \) and the total force, \( F_{TOT}(t) \) were averaged across two 200 ms time intervals, from 700 ms to 500 ms prior to \( t_0 \) and from 1500 to 1700 ms after \( t_0 \).

The variance of individual finger forces, Var\( F_i(t) \), and the variance of the total force, Var\( F_{TOT}(t) \), were computed across trials for each point in time. Further the sum of the variances of individual finger forces, \( \sum \text{Var}\( F_i(t) \) \), was computed. Co-variation among finger forces was estimated using an index \( \Delta V(t) = \sum \text{Var}\( F_i(t) \) - Var\( F_{TOT}(t) \)/\( \sum \text{Var}\( F_i(t) \). Note that \( \Delta V(t) > 0 \) corresponds to negative co-variation among finger forces, and the variance of the total force is lower than if the individual finger force deviations were independent (Bienaymé theorem). Therefore, \( \Delta V(t) > 0 \), can be interpreted as reflecting a synergy stabilizing the total force. To study deviations of \( \Delta V \) from its steady-state level across subjects, we computed an index \( \Delta \Delta V(t) \) that reflected changes in \( \Delta V \) as compared to its value 200 ms prior to the time of perturbation (\( t_0 \)).

The data are presented in the text as means and standard errors of the mean. Mixed-effects two-way ANOVA with factors Task (two levels: SELF and EXP) and Time (two levels: before and after the perturbation) was used to quantify differences in the steady-state level of \( F_{M}(t) \), \( F_{IRL}(t) \) and \( F_{TOT}(t) \) before and after \( t_0 \). For statistical analysis of the time evolution of \( \Delta \Delta V \), the time interval from 200 ms before \( t_0 \) until \( t_0 \) was divided into eight 25 ms time intervals. ANOVA
with repeated measures with factors *Task* (two levels: SELF and EXP) and *Time* (eight levels corresponding to time intervals from 200 ms before \( t_0 \) until \( t_0 \)) was used. Multiple comparisons with Bonferroni corrections were used to further analyze the effects of the ANOVAs. Level of significance was set at \( p = 0.05 \).

6.3 Results

The unloading of the middle finger caused its pressing force to increase sharply. Following the force increase, an adjustment of all finger forces was observed until the prescribed force level was reached again. Figure 6.2 shows the time profiles of \( F_M \) and \( F_{\text{IRL}} \) in both SELF and EXP conditions, averaged across subjects.

![Figure 6.2](image_url)

**Figure 6.2** Averaged across subjects time profiles of the forces produced by the middle finger (\( F_M \), solid traces) and other fingers (\( F_{\text{IRL}} \), dashed traces) in both self- (thick traces) and experimenter-triggered (thin traces) trials. All trials were aligned by the time of unloading, \( t_0 \).

Prior to the unloading, the middle finger produced, on average, one-third of the total force in both conditions (SELF: 34.15 ± 0.02 %; EXP: 33.79 ± 0.02 %). Following the perturbation, the adjustment of finger forces caused a new sharing pattern at the new steady-state. M finger increased its contribution to about 40% (SELF: 42.31 ± 0.02 %; EXP: 40.11± 0.02 %) while the other fingers (IRL)
decreased their force output. This effect was confirmed by a two-way ANOVA that showed significant effects of *Time* on both $F_M$ and $F_{IRL}$ ($F_M$: $F_{1,48} = 16.43$, $p < 0.001$; $F_{IRL}$: $F_{1,48} = 5.94$, $p < 0.05$) but no effect of *Task* ($F_M$: $p = 0.78$; $F_{IRL}$: $p = 0.58$). The total force, $F_{TOT}(t)$ was slightly larger after the perturbation than before in both conditions (SELF: $7.83 \pm 0.03$ N vs. $8.09 \pm 0.12$ N; EXP: $7.80 \pm 0.03$ N vs. $8.21 \pm 0.13$ N) but only in the experimenter-triggered condition did this difference reached significance ($p < 0.01$).

During the steady-state before the perturbation, the subjects showed predominantly negative covariation among finger forces. This was reflected in positive values of $\Delta V$, $0.89 \pm 0.02$ in SELF and $0.95 \pm 0.01$ in EXP. In the EXP condition, $\Delta V$ maintained its level until the time of perturbation ($t_0$), whereas in the SELF condition, an early decrease in $\Delta V$ could be seen, starting approximately 50 to 100 ms prior to $t_0$. Figure 6.3 shows the average change in $\Delta V$ ($\Delta\Delta V$) over all subjects in both SELF and EXP conditions with standard errors. A repeated-measures ANOVA confirmed significant effects of *Task* ($F_{1,12} = 6.182$, $p < 0.05$), *Time* ($F_{7,84} = 8.754$, $p < 0.001$) and *Task x Time* ($F_{7,84} = 6.250$, $p < 0.05$). Multiple comparisons with Bonferroni correction confirmed that $\Delta\Delta V$ in the SELF condition was significantly smaller than in the EXP condition over three time intervals, starting 75 ms before $t_0$ until $t_0$ ($p < 0.05$). In SELF condition $\Delta V$ dropped, on average, by $0.06 \pm 0.01$ by $t_0$, while in EXP condition no change in $\Delta V$ was seen (on average, under 0.01).
Figure 6.3 Time profile of changes ($\Delta V$) in the index of finger force co-variation ($\Delta V$) averaged across all subjects with standard errors. Thick solid and dashed lines show the average and standard error for the experimenter-triggered condition and thin solid and dashed lines show the corresponding data for the self-triggered condition. Time zero ($t_0$) is the time of the middle finger unloading.

6.4 Discussion

The main finding of the experiment is that, when a finger force was perturbed by the subjects themselves (SELF), they were able to modify the pattern of finger force co-variation in advance, that is, show ASAs, while no ASAs were seen when a similar perturbation was triggered unexpectedly (EXP). Hence, elderly subjects are able to use feed-forward adjustments in multi-finger synergies in anticipation of a self-triggered perturbation. The pattern of change in the index of co-variation ($\Delta V$) was similar to a pattern reported in a similar study of young subjects (Kim et al. 2006). However, in the study of young persons, the magnitude of $\Delta V$ drop was significant 125 ms prior to the time of perturbation and its magnitude was about 0.2. In the current study, $\Delta V$ changes in the elderly emerged significantly later (75 ms prior to $t_0$), and their magnitude (0.06) was about one-third of that in younger persons.
The findings of smaller and delayed ASAs resemble closely the observations of the smaller and delayed anticipatory postural adjustments (APAs) in the elderly (Woollacott and Manchester, 1993). In both studies, feed-forward adjustments to a self-triggered perturbation could be generated by the elderly subjects, but these adjustments were smaller and closer in time to the action initiation. This age-related change may contribute to the well-documented impairment of the manual dexterity and quality of life with age (Francis and Spirduso, 2000).

Another potentially important finding is the change in the sharing pattern of the total force between the perturbed finger (M) and other fingers (IRL) after the perturbation. Such a change in sharing was observed in the previous study of young subjects (Kim et al. 2006). This result reflects the preserved ability of elderly persons to explore the flexibility of the mechanically redundant multi-finger system and find different solutions for the task of force production.
CHAPTER 7 The Effects of Repetitive Testing on Indices of Finger Interaction in Elderly Individuals

7.1 Introduction

The purpose of this study was to provide control data for the training experiment, described in chapter 8. The training study examines the effects of training of specific hand muscles on their performance, i.e. strength and indices of finger interaction. Subjects train their hand muscles daily and are tested four times during a period of 6 weeks. In spite of the testing task being relatively easy, one apparent issue is the testing-retesting effects. Testing-retesting effects refer to the possibility that when a group of individuals is tested using the same procedure on multiple occasions, their performance improves in later testing sessions regardless of whether they received any treatment or training aiming to enhance it. This may occur due to several factors such as subject’s familiarity with testing procedures, comfort, practice, etc.

During this experiment subjects performed the same set of tasks 3 times over a period of 5 weeks but did otherwise not receive any treatment or training. We hypothesized that testing the same subject group in multiple sessions would not cause statistically significant improvements in their performance.

7.2 Methods

7.2.1 Subjects

Fourteen elderly (seven males and seven females) individuals volunteered to participate in the study. Their average age, height and weight was 77 ± 4 years, 175.7 ± 6.6 cm and 84.8 ± 12.1 kg for the males and 77 ± 4 years, 160.4 ± 10.1 cm and 60.5 ± 7.8 kg respectively for the females. Due to illness one female subject dropped out of the study after the first testing session, and thus her data is not included in the results.
7.2.2 Apparatus

The experimental setup, displayed in figure 7.1 was previously described in section 3.2.1.

A LabVIEW-based program was used for data acquisition. Sampling frequency was set at 1000 Hz with a 12-bit resolution.

![Figure 7.1 The experimental setup. The position of the hand and wrist was maintained as stable as possible by placing a dome shaped wooden piece in subjects palm (not seen in illustration) and attaching the forearm to the table with Velcro straps.](image)

7.2.3 Experimental Procedure

The experiment lasted 5 weeks and during that time each subject was tested three times, in week 1, 3 and 5.

During the experiment the subject sat relaxed with the fingertips of the right hand resting on the sensors. The computer generated two beeps “get ready” and “trial starting” and a cursor showing the total force produced by the task fingers started to move across the screen. Subjects produced maximal voluntary force (MVC) with each of the fingers individually (I, M, R, L) or with all four fingers together (IMRL). In these trials, subjects were instructed to press “as hard as possible” with the task finger/s, not to lift the other fingers and not to pay attention to the force they might produce. Each trial lasted 10 s and subjects were asked to produce peak force within a 3 s time interval marked with two vertical
lines on the screen. Two trials were collected for each task finger/s and the one with better performance used. All subjects received 2 practice trials to get familiar with the task and 30 s rests between all trials to avoid fatigue.

### 7.2.4 Data Analysis

The data were processed off-line using Matlab 7.0 and Excel. In each trial, the force produced by individual fingers was measured at the time when the force produced by the task finger/s reached peak value. These values were used to calculate the enslaving forces for single finger trials; force deficit and force sharing for four finger trials. Enslaving, force deficit and sharing were defined in section 2.4.1 but are described here as a reminder. Enslaving forces are forces produced by “enslaved” fingers, that is, fingers that produce force when they are not instructed to do so. Enslaving of each finger is expressed as percentage of its own MVC when acting as a task finger. By calculating enslaving for each individual finger, an enslaving matrix is generated. For further comparison, the indices of enslaving are averaged across the slave fingers. Force deficit of a finger is defined as the difference between the MVC force in its single-finger trial and its performance during the four-finger trial. Force deficit is expressed as percentage of each finger’s MVC and is then averaged across all fingers for further comparisons. The share of each finger is calculated as the ratio between the force it produces during the four finger task and the total force of that task.

### 7.2.5 Statistics

Standard descriptive statistics were used. Data is presented in text and figures as mean and standard error. In figures black bars represent the first testing session (week 1), white bars the second testing session (week 3) and striped bars the third session (week 5). Repeated measures ANOVA’s were used to test the effects of multiple testing on peak force, sharing, enslaving and force deficit. Factors were Test (three levels, Test 1, 2 and 3) and Finger (four levels, I, M, R, L). Multiple comparisons with Bonferroni correction were used as a post hoc to
analyze significant effects. Level of significance was set at $p = 0.05$. Statistics were calculated using SPSS (SPSS Inc, Chicago, IL, USA) and MiniTab (Minitab Inc., State College, PA, USA).

7.3 Results

Overall, the performance of subjects neither improved nor worsened during the course of the experiment.

7.3.1 MVC

During both the single- and four-finger trials, index and middle fingers produced the largest peak forces, followed by ring and little finger. Generally the peak forces reached during the four finger trials were smaller than those produced during individual finger trials. Total force during single-finger trials was approximately 110 N in all testing sessions and approximately 83 N in all testing sessions during four-finger trials. Figure 7.2 displays the maximal forces produced by the fingers individually as well as their sum during: A. single-finger trials and B. four-finger trials for the three testing sessions.
The lack of effects of the repetitive testing on the total peak force during single- and four finger trials was shown by repeated measures ANOVA’s with within subject factor Test (Single finger trials: p = 0.481; Four-finger trials: p = 0.244). Similarly two-way repeated measures ANOVA’s with within subject factors Finger and Test showed no effects of the repetitive testing on the force produced by individual fingers during the single-finger (p = 0.481) and four-finger (p = 0.244) trials; showed significant difference between the force of individual fingers which was expected (single-finger: $F_{1.5,15.5} = 35.4$, p = 0.000; four-finger $F_{3,30} = 37.5$, p = 0.000) but none of the Finger x Test interaction (single-finger: p = 0.15; four-finger: p = 0.078).

### 7.3.2 Force Deficit

During the four-finger trials each finger produced less force than it did during the single-finger trials. Figure 7.3 A. shows the average force deficit of individual fingers and averaged across all fingers (All). Little finger produced overall the largest force deficit then index finger but middle and ring fingers the smallest. Force deficit, averaged across all fingers (total force deficit), was on average $21.8 \pm 3.6 \%$ during the first test, $21.7 \pm 4.1 \%$ during the second test and $29.1 \pm 3.2 \%$ during the third test. A repeated measures ANOVA with within subject factor Test showed no difference between the three testing sessions (p =
0.251) in total force deficit and a repeated measures ANOVA with within subject factors *Finger* and *Test* showed no effect of *Test* (*p = 0.296*) or the *Finger x Test* interaction (*p = 0.145*). As expected significant effect of *Finger* on force deficit were found (*F*₃,₃₀ = 33.271, *p = 0.000*).

![Graph A: Force Deficit (%)](image1)

![Graph B: Enslaving (%)](image2)

**Figure 7.3 A.** Average force deficit of I, M, R and L fingers and an average across all fingers (All) for the three testing sessions. **B.** Average enslaving of I, M, R and L fingers and an average across all of them (All) for the three testing sessions. All numbers are shown with standard error bars.

### 7.3.3 Enslaving

In the single-finger trials, ring and little finger were the most enslaved while index finger was the most independent finger. Figure 7.3 B. shows average enslaving, of individual fingers and average enslaving across all fingers (All) for the three testing sessions. Total enslaving was around 16-17% during all three testing sessions and the lack of effect of their repetitions was shown with an ANOVA of repeated measures with within factor *Test* (*p = 0.617*). A two-way repeated measures ANOVA with within subject factors *Test* and *Finger* showed no effect of *Test* (*p = 0.617*) or *Finger x Test* interaction (*p = 0.406*) but did show the expected main effects of *Finger* (*F*₃,₃₀ = 9.643, *p = 0.000*).

### 7.3.4 Sharing

Generally, index and middle fingers produced the largest share of the total force, approximately 30-35%, ring finger approximately 20% and little finger
about 15%. The multiple testing did not alter the share of individual fingers except for ring finger who produced significantly larger share in testing session 2 (22.9 ± 1.2%) than in testing session 3 (18.8 ± 0.9%) (p = 0.006). This was seen by repeated measures ANOVA’s with within subject factor Test that showed no effects of Test on the share of index finger (p = 0.063); middle finger (p = 0.646) and little finger (p = 0.747) but before mentioned effects on the ring finger (F2,20 = 8.0, p = 0.003). Figure 7.4 shows the force sharing of individual fingers for the three testing sessions.

![Figure 7.4 Average Sharing of I, M, R and L for the three testing sessions with standard error bars. An asterisk (*) refers to significant effects of test.](image)

### 7.4 Discussion

The results of the study were in agreement with our suggestions that testing subjects on multiple occasions would not improve their performance in the MVC tasks. All indices, peak force, force deficit, enslaving and sharing showed some fluctuations in their magnitude but none of them were significantly dependent on the multiple testing except for the share of ring finger who was smaller during the third testing session than the second one. The reason for that difference is unclear.

When compared to other studies of maximal force production tasks in elderly individuals (Shinohara et al. 2003b), it can be seen that the group of
elderly that participated in this study were on average stronger than those in previous studies. Here the average total force of task fingers during single-finger trials was approximately 110 N and 83 N in the four-finger trials compared to ~84 N and 50 N in the previous study (Shinohara et al. 2003b). The sharing pattern observed was however similar to what was seen in the previous study, with index and middle fingers producing about a third of the total force each. In this study, the overall force deficit when averaged across all fingers in the elderly individuals was between 22 and 29% which is considerably smaller than the average of 43% observed by Shinohara et al. (2003b) and is more similar to the force deficit seen in the young control group of that study. The fingers of the subjects that participated in this study were more enslaved during the single-finger trials when compared to previous study. Average enslaving of the elderly subjects in this study was approximately 16-17%, which is considerably larger than the 10% reported by Shinohara et al. (2003b) and is closer to typical values observed for young subjects (Shinohara et al. 2003b). The reasons for the differences seen between the two studies are possibly the results of differences in physical condition between the two subject groups. The subjects that participated in this study were people that live a very active lifestyle and are in exceptionally good physical condition as can be seen in their much larger peak forces while this was not noticed for the group of subjects of the previous study.

We conclude that multiple testing of the same subject group in MVC tasks does not improve their performance and suggest that since indices of finger interaction may have great between-subject variability due to physical condition, testing the same group of individuals on multiple occasions to estimate the effects of training can be supported.
CHAPTER 8 The Effects of Resistance Training on Manual Strength and Dexterity in Elderly Individuals.

8.1 Introduction

The muscles that control the fingers of the hand can be divided into two groups, intrinsic and extrinsic. The intrinsic muscles are relatively small muscles that are located inside the hand and attach mostly to the proximal phalanges while the larger extrinsic muscles are located in the forearm and attach to the intermediate or distal phalanges. In most manipulative tasks, both muscle groups are activated but their relative involvement may differ (Darling et al. 1994; Maier and Hepp-Reymond 1995a, b). Due to differences in the attachment sites of the extrinsic and intrinsic muscles, their relative involvement in a task can be influenced by changing the point of force application (Danion et al. 2000; Li et al. 2000). Pressing down with the fingertips activates mostly the extrinsic muscles while when pressing down with the proximal phalanges majority of the force is produced by the intrinsic muscles (An et al. 1985; Chao et al. 1976). Previous studies of peak force production have shown that elderly individuals not only produce less force but also show a disproportional loss of strength in the intrinsic hand muscles (Shinohara et al. 2003a). It has been suggested that this imbalance in strength between the two muscle groups may contribute to the impaired ability of elderly individuals to produce synergies that stabilize the total force and total moment of force in multi-finger tasks that require accurate force production (Shinohara et al. 2003a, 2004, Shim et al. 2003) as well as to the observed decrease in dexterity with ageing.

Strength training has been shown to be an effective way to improve the force producing capacity of muscles in the elderly and reverse the changes observed in the muscles architecture with increased age (Narici et al. 2004; Reeves et al. 2004, 2006). However, the effect of site specific strength training on indices of finger interaction has not been investigated.

We hypothesize that the training will improve strength, specifically when produced by the trained proximal sites due to larger loss in strength of the muscles
involved. Previous studies of fatigue showed that the effects of the fatiguing exercises transferred to un-fatigued sites (Danion et al., 2000, 2001) and we do expect to see some transfer of the effects of training between sites. Enslaving has been seen to be to be positively correlated to the maximal force produced by the fingers (Danion et al. 2000, 2001; Latash et al. 2002; Shinohara et al, 2003a, b). Consequently, we expect to see the magnitude of enslaving to increase in parallel to the improvements in strength. The enslaving index indicates to what degree individual fingers can be moved without inducing movement in other fingers. Therefore an increase in enslaving can be interpreted as a decrease in finger individuation and promotes positive co-variation among finger forces (that is, with larger enslaving the involuntary force production of fingers that are not explicitly involved in the task). During accurate force production tasks where the goal is to control the total force output of the fingers, good performance requires the fingers to show error compensation, that is, negative co-variation among finger forces so that when one finger introduces an error the other change their output and their common output remains unchanged. Positive co-variation of finger forces during such a task would endorse error amplification and impair performance. We suggest that due to increased enslaving, we will see the performance on the accurate ramp task and in the clinical functional tests to worsen following the training.

8.2 Methods

8.2.1 Subjects

Twelve elderly (six males and six females) individuals volunteered to participate in the study. Their average age, height and weight was 79 ± 6 years, 173.4 ± 6.1 cm and 80.1 ± 7.5 kg for the males and 72 ± 1 years, 160.7 ± 6.8 cm and 69.7 ± 12.7 kg respectively for the females. The elderly subjects were recruited from local retirement communities. In order to be eligible for participation in the studies, the elderly subjects had to pass 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.

We purposefully selected for participation elderly subjects who exercised regularly and were generally in a good physical condition (self reported). All subjects gave informed consent according to the procedures approved by the Office for Research Protection of The Pennsylvania State University.

8.2.2 Apparatus

Experimental Setup

The experimental setup, displayed in figure 8.1 was previously described in section 3.2.2.

A LabVIEW-based program was used for data acquisition. Sampling frequency was set at 200 Hz with a 12-bit resolution.
Hand training device

The hand training device, Digi-Flex (IMC Products Corp, Hicksville, NY) is shown in figure 8.2. The devices come in 5 levels of resistances that are color coded. A yellow device has the resistance of 22.5 N for the four fingers; red 44.1 N; green 71.5 N; blue 101.9 N and black 138.2 N. The training devices were used in two different ways corresponding to the two positions of the fingers illustrated in Figure 8.2. Panel A shows how the fingertips were used to press down (training targeting mostly extrinsic finger muscles, distal training, DS training) and panel B shows the position when the proximal phalanges of the fingers were used (training targeting mostly intrinsic finger muscles, proximal training, PS training).
8.2.3 Experimental Procedure

General

The experiment lasted 6 weeks, and during that time each subject was tested four times, in the beginning of week 1, 2, 4 and 7. Clinical tests of the hand function were admitted only in the first and the last testing sessions. During each testing session, both the proximal and distal sites of both hands were tested.

Clinical functional tests

To quantify functional manual ability, all subjects performed two clinical tests, the Jebsen-Taylor Hand function test (Jebsen et al. 1969) and the Grooved Pegboard test (Ruff and Parker, 1993), and filled out the ABILHAND questionnaire (Penta et al. 1998). The Jebsen-Taylor Hand function test has 7 tasks involving manipulation of objects of various sizes under the instructions of performing the tasks as fast as possible. For each task the total time required to complete the task is recorded. The Grooved Pegboard test requires subjects to put key-shaped pegs into keyholes on a small board as fast as they can and the time needed to complete the task is recorded. The ABILHAND questionnaire requires the participants to rate their perception of the difficulty of 23 everyday tasks, ranging from “Impossible” to “Difficult” or “Easy”.

Figure 8.2 The Digi-Flex hand training device and the two finger positions used: A. Pressing with fingertips (training targeting mostly extrinsic hand muscles) and B. Pressing with bases of fingers (training targeting mostly intrinsic hand muscles).
MVC and Ramp tasks

Every testing session included a maximal force production (MVC) task and an accurate force production (Ramp) task performed by each hand and each site of force production, DS and PS, using the system with suspended sensors (see Figure 8.1). Prior to each trial the subject sat with the fingers of one of the hands resting in the loops, which were positioned either at the fingertips (distal site, DS) or the base of the fingers (proximal site, PS). The computer generated two beeps that indicated “get ready” and “trial starting”, and a cursor representing the total force of the task fingers started to move across the screen.

During the MVC tasks, the maximal force produced by each of the fingers individually (I-index, M-middle, R-ring, L-little) or by all four fingers acting together (IMRL) was measured. During these trials, subjects were instructed to “press as hard as possible” with the instructed finger(s) in a self-paced manner after the cursor reached a vertical line at the 2.5 s mark. Subjects were given 4.5 seconds to reach peak force and could relax once they had done so. Each trial lasted 10 s and two trials were recorded for each of the task finger(s) and the trial with the larger magnitude used.

The ramp task required the subjects to produce a ramp pattern of force from 0-25% of MVC over 4 s, by pressing down either with one finger at a time (I, M, R, L) or all four fingers together (IMRL). An oblique blue line was shown on the screen, starting 3 s after the initiation of the trial and the subject’s task was to trace this line in time with the cursor. Each trial lasted 10 s and two trials were collected for the single-finger ramps and 12 for the four-finger ramps. The interval between trials in both the MVC and the ramp task was at least 30 s for series of trials within a testing site and at least 5 minutes between the two sites. During each trial at both tasks, all fingers were in the loops, their forces were recorded, and the subjects were instructed not to lift other, “non-task” fingers and not to pay attention to possible force produced by those fingers.
Training

Subjects were divided randomly into two equal groups, a) “Right-DS training & Left-PS” training and b) “Left-DS training & Right PS-training”. After the first testing session, the subjects were assigned training devices; this was done by calculating 50% of their four-finger MVC (MVC\textsubscript{IMRL}) of the corresponding hand-site combination, and the device with the resistance closest to that value was used. This process was repeated after each testing session to adjust to strength increments over the time of the experiment. Subjects were instructed to train twice daily, every day except on testing days, with two sets of 10 repetitions within a training session. The explicit instruction on the method of training was: “The strengthening exercise should consist of a slow and controlled squeeze of the DIGI-FLEX device until the springs from all fingers are fully compressed, holding the squeeze for 2 seconds and then releasing it”. During the first testing session, the subjects received training on the usage of the devices (see figure 8.2) and an instructional sheet with photographs (appendix H) to take home and use as a reminder of the correct positioning of the hand on the device and method of training, as well as a training calendar where they marked off each time they trained. To further ensure correct training, the experimenter reminded the subjects by phone or visited them at home as needed. During each subsequent visit, subjects were also asked to demonstrate their training technique.

8.3 Data Analysis

All the data were analyzed using Matlab 7.0 (MathWorks Inc, Natick, MA, USA) and Excel (Micorsoft Inc, Redmond, WA, USA). Here only the data obtained test-1 (prior to training) and test-4 (post training) are presented.

8.3.1 Clinical functional tests

For the grooved pegboard test, Jebsen-Taylor test and the ABILHAND questionnaire, performance pre- and post- training was compared.

This was done by calculating for each of the tests the total score of dominant and non-dominant hands for test 1 and test 4.
8.3.2 MVC Task

For each trial at the MVC task, the instantaneous force produced by individual fingers was measured at the time when the task finger(s) (I,M,R,L or IMRL) reached maximum value. These data were used to calculate the sum of maximal individual finger forces ($\sum\text{MVC}_1 = \text{MVC}_I + \text{MVC}_M + \text{MVC}_R + \text{MVC}_L$), the maximal total force in the four-finger task ($\text{MVC}_4$), and the enslaving forces during single-finger trials for each hand and each sites of force application separately. Note that for purposes of simplification, hereafter $\sum\text{MVC}_1$ will be referred to as “total force of single-finger MVC tasks”. Enslaving forces are forces produced by non-task fingers, that is, fingers that produce force when the subject is not explicitly asked to press with those fingers. The enslaving force of each finger was expressed as percentage of its own MVC force when it acted as the task finger in its single-finger task. By doing that for each single-finger trial (I, M, R, L) an enslaving matrix was generated for both sites (DS and PS) and both hands. For further comparisons, the enslaving indices were averaged across all slave fingers to yield a grand mean for each site and hand.

8.3.3 Ramp Task

Performance

For each site and testing session, subject’s performance during the four-finger task was quantified by calculating the root mean square (RMS) of the difference between the target (template) ramp and actual ramps over the whole ramp interval.

$$\Delta\text{Ramp}(t) = \text{Ramp}_{\text{Actual}}(t) - \text{Ramp}_{\text{template}}(t)$$

$$\text{RMS} = \sqrt{\frac{x_1^2+x_2^2+x_3^2+...+x_n^2}{n}}$$

where $x(t) = \Delta\text{Ramp}(t)$.

Since force variability is known to depend on force magnitude (reviewed in Newell and Carlton 1993), for between-tests comparisons, we computed RMS during the pre- and posttraining sessions using time intervals that corresponded to identical force ranges. For this purpose, a 1-s time interval (starting 1.5 s before
the end of the ramp) was selected for each subject for the pre-training (test 1) trials. The absolute force range (in newtons) was defined for that interval and, for the post-training (test 4) trials, a 1-s interval was selected that spanned the same force range.

For further analysis, the average RMS scores over the whole ramp duration were further averaged across both hands and sites and the difference between the RMS indexes in test-1 and test-4 was calculated:

\[ \Delta \text{RMS} = \text{RMS}_4 - \text{RMS}_1 \]

**Uncontrolled Manifold Hypothesis analysis**

The data from the ramp task was analyzed within the framework of the Uncontrolled Manifold Hypothesis (UCM). According to the UCM hypothesis the controller is assumed to organize co-variation among elemental variables in order to stabilize a certain performance variable. Due to the mentioned phenomenon of enslaving (Kilbreath and Gandevia 1992; Li et al. 1998; Zatsiorsky et al. 2000) individual finger forces cannot be considered independent elemental variables (Kilbreath and Gandevia 1992; Li et al. 1998; Zatsiorsky et al. 2000) and have to be converted into elemental variables, finger modes, that can at least hypothetically be changed by the controller one at a time. This was done using the corresponding enslaving matrix.

Single-finger trials were used to generate the enslaving matrix. For each single-finger trial a linear regression of the forces produced by individual fingers against the total force produced by all four fingers over a 3 s time interval in the middle of the ramps was performed. The ratios between the changes in individual finger forces and the change in the total force were used to construct an enslaving matrix for each subject as follows:
$E = \begin{bmatrix}
\Delta f_{i,l} & \Delta f_{i,m} & \Delta f_{i,r} & \Delta f_{i,l} \\
\Delta F_i & \Delta F_m & \Delta F_r & \Delta F_l \\
\Delta f_{m,l} & \Delta f_{m,m} & \Delta f_{m,r} & \Delta f_{m,l} \\
\Delta F_i & \Delta F_m & \Delta F_r & \Delta F_l \\
\Delta f_{r,l} & \Delta f_{r,m} & \Delta f_{r,r} & \Delta f_{r,l} \\
\Delta F_i & \Delta F_m & \Delta F_r & \Delta F_l \\
\Delta f_{l,l} & \Delta f_{l,m} & \Delta f_{l,r} & \Delta f_{l,l} \\
\Delta F_i & \Delta F_m & \Delta F_r & \Delta F_l 
\end{bmatrix}$

where $\Delta f_{j,k}$ are the changes of individual finger forces $j$ ($j =$ index (i), middle (m), ring (r), and little (l)) and $\Delta F_k$ are the changes of the respective total forces, produced during the ramp when finger $k$ ($k =$ i, m, r, l) is the instructed task or master finger. This matrix is a linear approximation of a matrix containing partial derivatives $\frac{\partial f_{j,k}}{\partial \Phi}$, where $\frac{\partial f_{j,k}}{\partial \Phi}$ and $\frac{\partial F_k}{\partial \Phi}$ are the infinitesimal changes of individual and total finger forces.

The force data from the four finger ramp trials were converted to modes by using the enslaving matrix ([E]): $m_j = [E]^{-1} \cdot F_j$, where $j =$ I, M, R, L fingers.

According to the UCM hypothesis, more variance is expected within the manifold (UCM) that corresponds to a constant value of total force than in an orthogonal complement to the UCM. For each subject and for each time, $t_j$ the average across trials mode vector $m_{av}$ was computed. Then, for each trial, $k$, deviations ($\Delta m_k$) between $m_k$ and $m_{av}$ were computed. Variance of the $\Delta m_k$ data set was then computed along a direction orthogonal to the UCM computed for an average value of the total force observed across trials at that particular time slice. This index is referred to as $V_{ORT}$. This is done using Raleigh fraction (Goodman et al. 2005):

$$V_{ORT} = \frac{J_m \text{cov}(m) J_m^T}{J_m J_m^T} = \frac{JE^{1T}E^{-1}\text{cov}(f)E^{1T}E^{-1}J^T}{JE^{1T}E^{-1}J^T}$$
Where $J$ is the Jacobian matrix relating small changes in modes ($J_m$) or forces ($J$) to changes in the total force, $\text{cov}(m)$ is the covariance matrix in the mode space, $\text{cov}(f)$ is the covariance matrix in the finger force space, and $T$ is the sign of transpose. For total force $J=[1,1,1,1]$. $J_m=JE^{-iT}$. The difference between the total amount of variance ($V_{\text{TOT}}$) and $V_{\text{ORT}}$ corresponds to variance that does not affect the average value of the performance variable. This variance is addressed as $V_{\text{UCM}}$ (variance within the UCM; cf. Latash et al. 2001) and $V_{\text{UCM}}=V_{\text{TOTAL}}-V_{\text{ORT}}$. Finger mode space is four dimensional, $V_{\text{ORT}}$ lies along a one dimensional subspace; hence, $V_{\text{UCM}}$ is three dimensional. In order to compare the amounts of variance per dimension, an index $\Delta V$ was used:

$$\Delta V = \frac{(V_{\text{UCM}}/3)-V_{\text{ORT}}/1}{V_{\text{TOT}}/4}$$

where $\Delta V$ is the change in variance. Normalization of the $\Delta V$ index by the total variance per dimension was done to be able to compare the data across subjects that might show different amounts of the total variance.

It should be noted that positive values of $\Delta V$ correspond to proportionally more $V_{\text{UCM}}$, that is, to proportionally more variance compatible with a constant value of the total force. Therefore positive $\Delta V$ can be interpreted as a multi-mode synergy stabilizing total force. A $\Delta V = 0$, means that the amount of variance per dimension is the same in directions that correspond to a change in total force and along directions that keep it unchanged. A negative $\Delta V$ may be interpreted as co-variation among changes in finger modes that contribute to a change in the total force or destabilizes it.

The $\Delta V$ index has fixed limits. On the one hand, if all variance falls within the UCM space, $\Delta V$ reaches its maximum of 1.33; on the other hand, if all the variance falls within the orthogonal space $\Delta V$ reaches its minimum value of -4.

Due to these limits, the $\Delta V$ data were not normally distributed and, therefore, a z-transformation was used to normalize the data and make parametric statistics applicable:
\[
\Delta V_z = 0.5 \times \ln \left( \frac{1 + \Delta \tilde{V}}{1 - \Delta \tilde{V}} \right)
\]

where \( \Delta \tilde{V} = a \times \Delta V + b \); \( a = \frac{2}{5.33} \) and \( b = 1 - \left( \frac{2.33}{5.33} \times 1.33 \right) \).

For further analysis, \( \Delta V_z \) was:

1. averaged over both sites and hands for 4 1 s intervals of the ramp
2. averaged over both sites and hands for the whole ramp interval, and then the difference between the test 1 and test 4 calculated,
\[
\Delta \Delta V_z = \Delta V_{z4} - \Delta V_{z1}.
\]

### 8.3.4 Statistical analysis

The analysis was performed using SPSS (SPSS Inc, Chicago, IL, USA). Standard methods of parametric statistics were used. The level of significance was set at \( p = 0.05 \).

Results of the clinical functional tests were analyzed using 2-way repeated measures ANOVA with factors: \textit{Test} (two levels, test 1 and test 4) and \textit{Hand} (two levels, dominant and non-dominant). To estimate the effects of training, on \( \sum \text{MVC}_1 \), \( \text{MVC}_4 \), enslaving and RMS, two types of 3-way repeated measures ANOVAs were run with factors: a) \textit{Test} (two levels, test 1 and test 4), \textit{Hand} (two levels, right (R) and left (L) hands) and \textit{Site} (two levels, proximal site (PS) and distal site (DS)); and b) \textit{Test} (two levels, test 1 and test 4), \textit{Site-of-Training} (two levels, Trained and Untrained sites) and \textit{Site} (two levels, PS and DS).

Note that in the first comparison, the data were collapsed across different training types and in the second one the data were collapsed across the two hands.

In the first comparison the different combinations of hands and sites will be abbreviated as RD (right hand, distal site), RP (right hand, proximal site), LD (left hand, distal site) and LP (left hand, proximal site) while in the second comparison the different combinations of training and sites will be abbreviated by DS-Trained (trained distal sites), PS-Trained (trained proximal sites), DS-Untrained (untrained distal sites) and PS-Untrained (untrained proximal sites).
For $\Delta V_z$ a 2-way repeated measures ANOVA with factors Test (two levels, test 1 and test 4) and Time Interval (four levels, corresponding to the four consecutive one-second intervals of the ramp) was used (collapsed across sites and hands) to estimate the effects of training.

Significant effects were further analyzed using multiple comparisons with Bonferroni corrections.

To study possible links between the change in $\Delta \Delta V_z$ (the difference between $\Delta V_z$ of test 1 and test 4) and change in $\Delta \text{RMS}$, (the difference between RMS of test 1 and test 4) a linear regression analysis was used.

### 8.4 Results

#### 8.4.1 Functional Clinical Tests

**Grooved pegboard test**

Subjects were generally faster at completing the task with their dominant hand than their non-dominant hand. After the training period (test 4) their average time decreased in both hands, from $83.3 \pm 3.0$ s to $79.4 \pm 3.3$ s in the dominant hand and from $94.0 \pm 3.6$ s to $88.0 \pm 3.5$ s in the non-dominant hand, see figure 8.3. A 2-way repeated measures ANOVA with factors Test and Hand showed a significant effects of both Test ($F_{1,11} = 14.46$, $p < 0.05$) and Hand ($F_{1,11} = 15.49$, $p < 0.05$) but not their interaction. Pair-wise comparison revealed that only in the non-dominant hand was the decrease in time statistically significant ($p < 0.05$) and that the non-dominant hand was in both tests significantly slower than the dominant one ($p < 0.05$).
Figure 8.3 The results of the Grooved Pegboard test. Both hands improved their performance after the training (test 4) but the difference was only significant in the non-dominant hand (*). Both pre and post-training was the dominant hand faster than the non-dominant hand.

**Jebsen-Taylor Hand function test**

The total time subjects needed to complete all 7 tasks of the Jebsen-Taylor test was approximately 20 s less for the dominant hand. After the training the total time showed a modest decrease for both hands (from $53.1 \pm 3.1$ s to $50.4 \pm 2.9$ s in the dominant hand and from $72.0 \pm 4.6$ s to $70.6 \pm 4.8$ s in non-dominant hand). The difference between the hands was significant, while the difference between test-4 and test-1 was not as shown by a 2-way repeated measures ANOVA with factors Test ($F_{1,11} = 1.56$, $p = 0.238$) and Hand ($F_{1,11} = 39.33$, $p < 0.01$).

**ABILHAND questionnaire**

No difference was found in the score of this questionnaire pre and post training. In both instances subjects ranked at 22-23 out of 23 tasks on the list as “Easy”. The task subjects most commonly reported as “Difficult” was “threading a needle” and in many cases subjects commented that decreased eyesight rather than manipulation skills was to blame.
8.4.2 MVC task

$\Sigma$MVC$_1$ and MVC$_4$

Prior to the training period, the average total forces produced at the distal (DS) and proximal (PS) sites of both hands did not differ from one another in both single-finger ($\Sigma$MVC$_1$) and four-finger (MVC$_4$) tasks. The sum of the peak forces produced in the single-finger tasks was, on average, larger than the four-finger force both pre- (test 1) and post-training (test 4). After the training, the total force produced at both the proximal and distal sites of left and right hand increased for both $\Sigma$MVC$_1$ and MVC$_4$, on average about 14.5%. The average total force values produced at the proximal and distal sites, left and right hands and both tests are displayed in table 8.1 and figure 8.4. Panel A of figure 8.4 shows the results for $\Sigma$MVC$_1$ and panel B shows the MVC$_4$ data.

For $\Sigma$MVC$_1$ a 3-way repeated measures ANOVA with factors Test, Site and Hand showed significant effects of Test (F$_{1,11} = 17.17$, p < 0.05) and Site (F$_{1,11} = 13.94$, p < 0.05) but not of Hand (F$_{1,11} = 0.446$, p > 0.5) and no interactions. Pair-wise comparisons with Bonferroni corrections further revealed that the increase in $\Sigma$MVC$_1$ was statistically significant in three out of four sites (p < 0.05), only at the distal site of the left hand (DL) did the increase not reach significance (p = 0.187). After the training period (test 4), $\Sigma$MVC$_1$ produced at the proximal sites of both hands was significantly larger than the force produced at the distal sites (p < 0.05) while before the training (test 1) the difference between the DS and PS was not significant for either hand.

For MVC$_4$ a 3-way repeated measures ANOVA with factors Test, Site and Hand showed significant effects of Test (F$_{1,11} = 10.35$, p < 0.05) but not of Site (F$_{1,11} = 1.285$, p = 0.261) and Hand (F$_{1,11} = 1.334$, p = 0.272) and no interactions. Pair-wise comparisons with Bonferroni corrections showed that the increase in MVC$_4$ after the training reached significance at the proximal site of the right hand (p<0.05). No difference was found in MVC$_4$ between PS and DS in test-1 or test-4 for either of the hands.
Table 8.1 Total force of single-finger MVC’s ($\sum\text{MVC}_1$) and total force of the four-finger (MVC$_4$) task for individual sites in test 1 and test 4, averaged across subjects.

<table>
<thead>
<tr>
<th></th>
<th>$\sum\text{MVC}_1$ (N)</th>
<th>MVC$_4$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD$_{\text{Pre}}$</td>
<td>113.98±11.14</td>
<td>112.76±12.52</td>
</tr>
<tr>
<td>RP$_{\text{Pre}}$</td>
<td>123.30±12.88</td>
<td>108.86±13.42</td>
</tr>
<tr>
<td>LD$_{\text{Pre}}$</td>
<td>112.39±10.87</td>
<td>105.75±10.90</td>
</tr>
<tr>
<td>LP$_{\text{Pre}}$</td>
<td>123.88±12.8</td>
<td>108.28±12.71</td>
</tr>
<tr>
<td>RD$_{\text{Post}}$</td>
<td>129.52±11.30</td>
<td>122.53±11.70</td>
</tr>
<tr>
<td>RP$_{\text{Post}}$</td>
<td>139.83±12.88</td>
<td>127.78±14.09</td>
</tr>
<tr>
<td>LD$_{\text{Post}}$</td>
<td>120.33±12.09</td>
<td>113.03±11.68</td>
</tr>
<tr>
<td>LP$_{\text{Post}}$</td>
<td>137.79±14.97</td>
<td>123.71±14.32</td>
</tr>
</tbody>
</table>

Values are means and standard errors. MVC, maximal voluntary contraction. RD, distal site on right hand; RP, proximal site on right hand; LD, distal site on left hand and LP, proximal site on left hand. The subscripts Pre and Post refer to testing sessions before (test 1) and after (test 4) the training period.

Figure 8.4 Total force produced before (test 1) and after (test 4) training at the distal (D) and proximal (P) sites of the left (L) and right (R) hands, averaged across subjects with standard error bars for $\sum\text{MVC}_1$ (panel A) and MVC$_4$ (panel B). The black bars represent the pre-training testing session and white bars the post-training session. An asterisk (*) denotes a significant difference between the total force produced before and after the training.

When comparing the effects of training on the force produced at the trained and untrained sites, the data were collapsed across the hands. The average total forces of $\sum\text{MVC}_1$ and MVC$_4$ at the distal and proximal sites that either received training (DS-trained and PS-trained) or not (DS-untrained and PS-untrained) for the pre- and post- training testing sessions are shown in table 8.2.
Table 8.2 Total force of single-finger ($\sum$MVC\textsubscript{1}) and four-finger (MVC\textsubscript{4}) tasks averaged across subjects by site (distal and proximal) and training (trained or untrained) for the pre- (test 1) and post- training (test 4) tests.

<table>
<thead>
<tr>
<th></th>
<th>$\sum$MVC\textsubscript{1} (N)</th>
<th>MVC\textsubscript{4} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-Trained\textsubscript{Pre}</td>
<td>118.38±11.64</td>
<td>113.01±12.58</td>
</tr>
<tr>
<td>PS-Trained\textsubscript{Pre}</td>
<td>123.47±12.79</td>
<td>107.59±12.91</td>
</tr>
<tr>
<td>DS-Trained\textsubscript{Post}</td>
<td>125.74±11.30</td>
<td>120.30±10.41</td>
</tr>
<tr>
<td>PS-Trained\textsubscript{Post}</td>
<td>136.20±13.61</td>
<td>129.24±13.36</td>
</tr>
<tr>
<td>DS-Untrain\textsubscript{Pre}</td>
<td>107.99±10.10</td>
<td>105.50±10.81</td>
</tr>
<tr>
<td>PS-Untrain\textsubscript{Pre}</td>
<td>123.71±12.88</td>
<td>109.56±13.22</td>
</tr>
<tr>
<td>DS-Untrain\textsubscript{Post}</td>
<td>124.11±12.22</td>
<td>115.26±12.96</td>
</tr>
<tr>
<td>PS-Untrain\textsubscript{Post}</td>
<td>141.42±14.28</td>
<td>122.24±14.96</td>
</tr>
</tbody>
</table>

Values are means and standard errors. MVC, maximal voluntary contraction. DTDS, trained distal sites; PTPS, trained proximal sites; NTDS, untrained distal sites; NTPS, untrained proximal sites. The subscripts Pre and Post refer to testing sessions before (test 1) and after (test 4) the training period.

The total force summed over the single-finger tasks ($\sum$MVC\textsubscript{1}) increased with training at all the sites, regardless of whether they had received any training or not, see figure 8.5, panels A and B. A three-way repeated measures ANOVA with factors Test, Site-of-Training and Site showed significant effects of Test ($F_{1,11} = 17.17$, $p < 0.05$) and Site ($F_{1,11} = 13.94$, $p < 0.05$) but not of Site-of-Training ($F_{1,11} = 0.57$, $p = 0.47$) and no interactions. Pair-wise comparison with Bonferroni correction further revealed that the increase in $\sum$MVC\textsubscript{1} was significant for the PS-trained, PS-untrained and DS-untrained sites ($p < 0.05$) but not for the DS-trained site ($p = 0.15$). No difference was found in the total force produced by the DS-trained and PS-trained sites either before (test-1, $p = 0.49$) or after the training, although the difference by test-4 approached significance ($p = 0.08$).
Figure 8.5 The average total force ($\sum\text{MVC}_1$) produced before (test 1) and after (test 4) training at the trained and untrained sites in the single-finger tests with standard errors. Panel A: DS-Trained; PS-Trained sites. Panel B: DS-Untrained sites; PS-Untrained sites. Black bars represent pre-training tests and white bars post-training tests. Significant difference is indicated by an asterisk (*)..

After the training the total force produced in the four-finger tasks (MVC$_4$) increased for both sites and both training conditions. This increase, which ranged from 7 to 21 N, was shown to be statistically significant by a 3-way repeated measures ANOVA with factors Test, Site-of-Training and Site that showed main effect of Test ($F_{1,11} = 10.35$, $p < 0.05$) but not of Site-of-Training ($F_{1,11} = 2.20$, $p = 0.17$) or Site ($F_{1,11} = 1.29$, $p = 0.28$) and no interactions. Pairwise comparisons confirmed a significant effect of training only at the PS-trained ($p < 0.05$). Figure 8.6 displays the average total force of the four-finger task before (test 1) and after (test 4) the training period at the trained (panel A) and untrained (panel B) sites.
Enslaving

The enslaved forces were produced in single-finger MVC tasks by fingers that were not instructed to produce force. These forces were expressed as percentage of their respective maximal force when acting as instructed fingers; the enslaving indices were further averaged across fingers.

After the training (by test-4), subjects produced larger enslaving forces than before training (test-1). For the right hand, the average enslaving, increased from 13.71± 2.20 % to 19.96 ± 2.99 % at DS and from 20.79 ± 3.11 % to 28.35 ± 3.51 % at PS while the increase in the left hand was from 15.97 ± 2.30 % to 20.27 ± 3.06 % at DS and 19.46 ± 2.53 % to 26.55 ± 3.50 % at PS. The average enslaving of the distal and proximal sites of the two hands, pre- (test 1) and post-training (test 4) are shown in figure 8.7.

A three-way repeated measures ANOVA with factors Test, Site and Hand showed significant main effects of Test (F₁,₁₁ = 9.72, p < 0.05) and Site (F₁,₁₁ = 12.04, p < 0.05) but no effect of Hand (F₁,₁₁ = 0.006, p = 0.94) and no significant interactions. Further pair-wise comparisons with Bonferroni corrections showed that the increase between tests-1 and -4 was statistically significant for the PS of both hands and for the DS of the right hand (p < 0.05). Moreover, both prior to
and after the training the PS of the right hand showed, on average, higher enslaving than the DS of the right hand (p < 0.05) while for the left hand the differences between the sites were under the significance level in either of the tests (test-1, p = 0.17; test-4, p = 0.08).

![Bar chart showing the average enslaving at the distal and proximal sites of both hands produced during the pre- (test 1) and post-training (test 4) testing sessions with standard errors. RD, distal site of right hand; RP, proximal site of right hand; LD, distal site of left hand; LP, proximal site of left hand. Black bars represent pre-training tests and white bars post-training tests. Significant difference is indicated by an asterisk (*).](image)

Figure 8.7 The average enslaving at the distal and proximal sites of both hands produced during the pre- (test 1) and post-training (test 4) testing sessions with standard errors. RD, distal site of right hand; RP, proximal site of right hand; LD, distal site of left hand; LP, proximal site of left hand. Black bars represent pre-training tests and white bars post-training tests. Significant difference is indicated by an asterisk (*).

Figure 8.8 shows the average enslaving, pre- (test 1) and post-training (test 4) relative to whether the sites received training or not (DS-trained, from 14.69 ± 2.27% to 18.84 ± 2.34%; PS-trained, from 21.27 ± 2.70% to 30.52 ± 3.48%; DS-untrained, from 14.79 ± 2.27% to 21.39 ± 3.54% and PS-untrained, from 18.98 ± 2.95% to 24.38 ± 3.29%). Enslaving increased after the training at all sites and for all training conditions. A three-way repeated measures ANOVA with factors Test, Site-of-Training and Site showed significant effect of Test (F1,11 = 9.72, p < 0.05) and Site (F1,11 = 12.04, p < 0.05) but not Site-of-Training (F1,11 = 1.38, p = 0.27) or any of the interactions. Pair-wise comparisons with Bonferroni corrections confirmed the significant difference between the pre- (test-1) and post-tests (test-4) for the PS-trained (p < 0.05) and also showed a significantly larger enslaving
post training in PS-trained as compared to PS-untrained (p <0.05), and larger enslaving at PS-trained than at DS-trained, both in test-1 and -4 (p < 0.05).

Figure 8.8 The average enslaving at the trained and untrained sites during the pre-(test 1) and post-training (test 4) testing sessions with standard errors. Panel A: DS-Trained sites; PS-Trained sites. Panel B: DS-Untrained sites; PS-Untrained sites. Black bars represent pre-training tests and white bars post-training tests. Significant difference is indicated by an asterisk (*).

8.4.3 Ramp task
Performance
All subjects were able to perform the ramp task with relative ease, both before (test 1) and after (test 4) the training. Figure 8.9 shows the performance of a representative subject when force was generated at the PS of the right hand. The black lines show individual trials and the red line the target template subjects were asked to match up to. The results of test-1 and test-4 are shown in panels A and B respectively. Note how the quality of performance has apparently improved (the thin black line is better matched up with the template) in the post-training test in spite of the performance already being quite accurate prior to the training.
Figure 8.9 The performance of a representative subject in the ramp task when producing total force with the proximal site of the right hand during the pre-training testing session (Test 1 - panel A) and the post-training testing session (Test 4 - panel B). The black lines indicate individual trials and the red lines the task template.

To quantify the performance of subjects during the ramp task, the root mean square index (RMS) was calculated to reflect the difference between the actual force time profiles the subjects produced and the target ramp. RMS was then averaged over 1-s time intervals that corresponded to equal force ranges over the test-1 and test-4 trials. On average, RMS during performance at the right-proximal (RP), left-proximal (LP) and left-distal (LD) sites decreased after the training (see figure 8.10) but these differences did not reach statistical significance, as the effect of Test in a 3-way repeated measures ANOVA was under the level of significance ($F_{1,11} = 2.77$, $p = 0.12$), without effects of Site ($F_{1,11} = 0.27$, $p = 0.62$) and Hand ($F_{1,11} = 0.26$, $p = 0.62$), and no significant interactions.
Figure 8.10 The root mean square (RMS) of the difference between the actual ramps and the ideal (template) ramp for the proximal (P) and distal (D) testing sites of the right (R) and left (L) hands of the pre- (test 1) and post-training (test 4) testing sessions with standard errors. Black bars indicate results of the pre-training testing and white bars post-training testing.

When the two tests were compared relative to the trained and untrained sites, RMS decreased after the training across all conditions (PS-trained, DS-trained, PS-untrained and DS-untrained; Figure 8.11). A 3-way repeated measures ANOVA with factors Test, Site-of-Training and Site showed no significant effects of Test (F1,11 = 2.77, p = 0.12), Site-of-Training (F1,11 = 0.11, p = 0.75), Site (F1,11 = 0.27, p = 0.62). There was, however, a close to significant Test x Site interaction (p = 0.06). Multiple comparison with Bonferroni correction displayed significant differences between test-1 and test-4 for the PS-trained site (p< 0.05), but not for the other sites.
UCM analysis

To remind, variance in the space of four finger modes was quantified in two sub-spaces, the UCM (where an average total force value did not change) and orthogonally to the UCM (where the total force changed). Further, an index $\Delta V$ was computed such that its positive values reflected predominance of variance within the UCM; this index was transformed into $z$ scores, $\Delta V_z$.

After the training period (test 4), the transformed delta variance index ($\Delta V_z$) showed a general increase for all four time intervals of the ramp. Figure 8.12 shows $\Delta V_z$ of tests 1 and 4, averaged across all sites and hands for each of the four time intervals. This difference, which was very small, ranging from 0.013 to 0.104, was not statistically significant. A two-way ANOVA with repeated measures showed main effects of Time Interval ($F_{3,33} = 216.73$, $p < 0.000$) but not Test ($p = 0.576$) and no interaction.
Figure 8.12 $\Delta V_z$ (delta variance converted to z score) of the pre- (test 1) and post-training (test 4) testing sessions, averaged over 4, 1s time intervals with standard errors. Black bars represent the pre-training testing and white bars the post-training testing.

**Relations between $\Delta \Delta V_z$ and $\Delta RMS$**

Given the high variability of the effects of training on both the RMS index of performance in the ramp task and the $\Delta V$ index, we investigated the relation between the change in subjects’ performance (RMS, averaged across both hands and sites) with training and the change in the synergy index ($\Delta V$, also averaged across both sites and hands over the whole ramp interval).

For this purpose, the difference between the pre- (test 1) and post-training (test 4) tests was calculated for RMS ($\Delta RMS$) and $\Delta V_z$ ($\Delta \Delta V_z$) and a linear regression performed.

The results of the linear regression are shown in figure 8.13 with $\Delta RMS$ on the x-axis and $\Delta \Delta V_z$ on the y-axis. There was a significant linear correlation between $\Delta RMS$ and $\Delta \Delta V_z$ in such a way that subjects that displayed a decrease in $\Delta RMS$ were likely to also increased their $\Delta \Delta V_z$ score ($R = 0.69$, $p < 0.05$).
Figure 8.13 The relationship between $\Delta RMS$ (the difference in RMS pre- (test 1) and post-training (test 4), $\Delta RMS = RMS_{\text{post}} - RMS_{\text{pre}}$) and $\Delta \Delta V_z$ (difference in $\Delta V_z$ pre- and post- training, $\Delta \Delta V_z = \Delta V_{z,\text{post}} - \Delta V_{z,\text{pre}}$). $\Delta RMS$ is displayed on the x-axis and $\Delta \Delta V_z$ on the y-axis.

8.5 Discussion

The main goal of this study was to investigate the effects of resistance training on manual strength and coordination in elderly individuals. The elderly individuals that volunteered for participation in this study were all people in good health that exercised regularly and were generally in an excellent physical condition. This can be seen in the fact that the maximal values of force they produced before training were 25-40% larger than maximal values reported in previous studies (see chapter 7 and Shinohara et al. 2003a).

We hypothesized that training would cause strength to increase, and that the effects would be more prominent at the proximal site. We also hypothesized that, in parallel to the increase in strength, enslaving would increase. Larger enslaving, which translates to a decrease in finger individuation, in turn might be expected to cause performance in accurate force production tasks to suffer by promoting
positive co-variation of finger forces. This would be reflected in a decline in the performance of the ramp task, and performance on the clinical functional tests.

Following the training we saw a general increase in strength of both the proximal and distal sites of both hands. In a previous study (see chapter 7) we investigated the effects of repetitive testing on the maximal force produced by the fingers of elderly individuals. In that study the subjects performed maximal force production (MVC) tasks using individual fingers separately or all four fingers together on 3 separate occasions over the period of 4 weeks but did otherwise not receive any training. The multiple testing did not have any effect on the maximal force produced, that is, no difference was found in the magnitude of MVC produced during the 3 different testing sessions. These results support our argument that the changes in strength seen in the present study can be attributed to the training rather than to familiarity with the testing protocol.

In agreement with our predictions, enslaving showed a general increase after the training. We had hypothesized that larger enslaving might induce a decrease in the accuracy of performance by promoting positive co-variation among finger forces but the results did not support this hypothesis. The index quantifying performance, RMS, did not decrease but rather remained unchanged or improved slightly. Subjects did also perform better on the grooved pegboard test while the results of the Jebsen-Taylor test and the ABILHAND questionnaire were unchanged.

**Effectiveness of strength training**

The positive effects of resistance training on strength of elderly individuals have been reported on numerous occasions (Kornatz et al. 2005, Reeves et al. 2004, and Vincent et al. 2002a, b). The six weeks of training, applied in this study, increased the strength produced by both the distal and proximal sites of both hands, regardless if they had been trained or not. This increase which ranged from 6 – 20% was especially prominent at the trained proximal sites even though a considerable transfer of the effects of training to sites that had not been trained was observed. This phenomenon of transfer between distal and proximal sites was
previously seen in studies of fatigue where subjects induced fatigue by producing MVC force for one minute at one site or the other (Danion et al. 2000, 2001). Performing a fatiguing exercise at a site caused a drop in the maximal force (MVC) it could produce as well as in the force produced at the non-fatigued site. Inducing fatigue at a distal site caused an equal drop in MVC of the distal and proximal sites while fatigue of the proximal site caused its MVC to drop two-fold in comparison to the distal site. Interestingly, the overall largest effects of fatigue were seen in the proximal fatigued site, close to 40% drop in the four-finger MVC. The large effects of between-site transfer of the effects of strength training point at a neural site of changes responsible for the force increase.

Most everyday tasks involve manipulation of objects using the fingertips as point of contact. When a force is produced by the fingertips (i.e. at the distal site), a large external moment of force acts at the metacarpophalangeal (MCP) joint. The muscles activated to balance out this external moment are the main extrinsic finger flexors, flexor digitorum superficialis and profundus and the intrinsic muscles (Li et al. 2000). Thus, in order to prevent extension of the MCP joint to occur, the commands from the central nervous system to the extrinsic and intrinsic muscles need to be finely tuned. The intrinsic muscles have been shown to loose proportionally more strength with aging than the extrinsic muscles (Shinohara et al. 2003a). We suggest that, due to disproportional weakening of the intrinsic muscles, extrinsic muscles are not activated to their full potential. Training of the intrinsic muscles improves their force producing abilities and, in addition, allows the distal muscles to be activated to a larger degree. This might lead to an increase in the maximal force produced at the un-trained distal sites that was seen in the study.

**Changes in finger individuation**

The magnitude of enslaving has been shown to be strongly positively correlated to the magnitude of MVC (Danion et al. 2000, 2001; Latash et al. 2002; Shinohara et al, 2003a, b). Enslaving is larger in men than women (Shinohara et al. 2003b), larger in young than elderly (Shinohara et al. 2003a, b), it is decreased
with fatigue (Danion et al. 2000, 2001) and increased after practice in individuals with Down syndrome (Latash et al., 2002). Enslaving increased at both sites of both hands after the training and was, similarly to MVC, more notable at the trained proximal sites. Prior to the training, we saw values of enslaving that were larger than those observed for elderly subjects by Shinohara et al. (2003a), but the elderly people in this study were also overall much stronger than that group. After the training the observed values were closer to those seen for the young group in the previous study (Shinohara et al. 2003a). In a previous study of repetitive testing without training (chapter 7), no difference was seen in enslaving between the three testing sessions. A large increase in enslaving at the trained proximal sites is a non-trivial observation that provides further support to the notion of central origin of finger interactions. Force production by the proximal sites is generated mainly by the intrinsic hand muscles, which are separate for each finger (Li et al. 2000). If enslaving were caused mainly by peripheral factors, enslaving would first, not be expected to be larger at the proximal site, and second, not be expected to increase with training.

The enslaving index indicates to what degree the fingers can be controlled independently of one another and can be seen as a bad or a good phenomena depending on the task at hand. In tasks that require large amounts of prestidigitation, such as piano playing, enslaving seems to be disadvantageous while in many other tasks, such as holding a cup, a healthy amount of enslaving appears to be beneficial because it contributes to stabilization of the total moment of force applied to the hand-held object (Zatsiorsky et al. 2000; Zatsiorsky and Latash 2004). The idea of the existence of a strength-dexterity trade-off was introduced in a previous study (Shinohara et al. 2003b). Good dexterity is in general language associated with good individual control of the fingers and by that definition; the increased enslaving observed with increased strength due to training can be expected to lead to a decrease in dexterity. This led us to hypothesize that an increase in enslaving due to training might actually have negative effects on the performance of the subjects in the accurate force production tasks.
Change in dexterity

Our hypothesis of a decline in performance following the training was not supported. After the training period, subjects performed significantly better on the Grooved pegboard test and the score on the other functional tests did not change. It is though the opinion of the experimenter that the ABILHAND questionnaire is not an appropriate tool to estimate manipulating skills in this population. Prior to the training all the subjects reported the tasks on the questionnaire as “Easy” except for “treading a needle”, which was attributed to decreased eyesight.

Subjects’ performance in the accurate ramp task did not suffer and rather improved even though the change was not significant. Similarly, did the index of force stabilization, ΔV, remained unchanged or showed a slight improvement when averaged across sites and hands. However, when the changes in RMS (ΔRMS) and ΔV (ΔΔV) that occurred between the pre- and post-training sessions were observed on individual subject basis, non-consistency in their behavior was seen. The subjects that improved their performance, quantified by a decrease in RMS between the testing sessions also had a tendency to also improve their ΔV score, that is improve their production of a force stabilizing synergy. On the other hand, two of the subjects displayed completely opposite trends; they showed higher deviations from the required force profile and lower ΔV index after training. These results of a statistically significant negative correlation between changes in ΔV and RMS indicate that the ΔV index is a good predictor of performance in such tasks.

Shortcomings of the study

The study had several limitations that may influence the outcome. The training period lasted only 6 weeks and it is likely that training over longer period of time would have resulted in more dramatic changes. Previous studies have shown significant effects of training after as little as 2 weeks (Kornatz et al. 2005) but it was argued that the effects seen were most likely due to improved activation of the involved muscles. Moreover, only 12 subjects participated in the study and it is probable that the results were affected by the limited number of subjects.
CHAPTER 9   Conclusions

1) Elderly individuals show a reduced ability to produce force and moment-of-force stabilizing synergies.

   Synergy has been defined as a pattern of co-variation among finger forces or finger modes (hypothetical control signals to individual fingers that are manipulated by the controller) across repetitive trials that stabilize a performance variable such as the total force or total moment of force.

   During the accurate moment-of-force production task the young subjects were able to stabilize the moment of force while the elderly subjects failed to do so. Both elderly and young subjects were able to produce total force stabilizing synergies but the elderly subjects to a lesser degree. These results provide support for the hypothesis that aging is associated not only with a decrease in muscle force generating abilities but also with a diminished capability to coordinate commands to the fingers to stabilize rotational hand action. The weaker multi-digit synergies may contribute to the observed decrease in dexterity with aging.

2) Elderly individuals show a reduced ability to adjust multi-element synergies in a feed-forward manner in preparation to a predictable change in a performance variable.

   During multi-finger force production tasks, where a sudden change in the total force occurred in a predictable manner (due to a self-induced perturbation or a self-induced quick force pulse), both elderly and young subjects showed anticipatory changes in the index of force stabilizing synergies prior to the action or the reaction.

   In the elderly subjects these anticipatory changes, termed Anticipatory Synergy Adjustments (ASAs), were initiated later, (50-75 ms prior to the earliest change in force vs. 100-150 ms in younger persons) and were of smaller magnitude than in younger subjects. The functional role of ASAs has
been proposed to bring about a purposeful weakening of force stabilizing synergies that otherwise would counteract the planned change in total force. As such, ASAs reflect an important feed-forward mechanism of control of multi-element systems.

The results suggest that aging is associated with a decreased ability to control multi-element synergies in a feed-forward manner and provide further support for a feed-forward origin of ASAs.

3) **Six weeks of strength training of the fingers of elderly individuals brings about changes, likely both at the level of muscles and at the level of neural commands, that result in a general increase in maximal voluntary force produced at both proximal and distal finger sites of both hands. Strong transfer effects of the strength training were documented. Strength training also has positive effects on performance in multi-finger accurate force production tasks and functional tests.**

The control of the fingers of the hand is performed by two groups of muscles, intrinsic and extrinsic. These two muscle groups attach at different anatomical sites, which allows their relative contribution to force production tasks to be modified by changing the point of force application along the finger. The focal force generator during force production by the distal phalanges is the flexor digitorum profundus (an extrinsic, multi-digit muscle), while the intrinsic finger-specific muscles are mainly responsible for force generated by the proximal phalanges. The strength gain observed following the 6 weeks of training was particularly prominent at the trained proximal sites, even though considerable transfer effects to the untrained sites were observed. These observations support the hypothesis that the documented disproportionate loss of muscle force in the intrinsic muscles with age is a limiting factor across a variety of finger actions. In particular, strengthening the intrinsic muscles may enable the extrinsic muscles to produce larger forces.
Enslaving (the lack of individuation) is the force production by fingers of a hand that are not instructed to produce force, when other finger(s) produce force purposefully. An increase in the index of enslaving was observed with strength training bringing the magnitude of this index closer to values observed in younger subjects. The apparent loss of finger individuation may be viewed as facilitating positive co-variation among finger forces, which could be useful in multi-digit prehensile tasks. However, this phenomenon would be disadvantageous in tasks with accurate production of the total force. Contrary to the latter prediction, the training induced increase in the index of enslaving did not bring about a decline in the performance in the accurate force production task and in the functional hand tests. Actually, a trend towards better performance in those tasks has been observed suggesting that an increase in enslaving does not mean worse performance in accurate force production.

4) Our experiments have also shown that:
   a. As compared to younger persons, elderly subjects generated larger variance of the total moment of force in the accurate moment production tasks, particularly when they had to switch the direction of the produced moment (i.e. from supination moment to pronation moment or from pronation to supination). This points at a larger error in the timing of the control signals to individual fingers in the elderly.

   b. Elderly subjects produced larger antagonist moment of force (moment of force produced by fingers, which act against the required direction of the moment of force) in the accurate moment production task. This may be interpreted as an adaptive strategy that increases the resistance of the hand and fingers to possible rotational perturbations. This strategy may be a response to the decreased ability to produce moment-of-force stabilizing synergies.
c. The mechanical advantage hypothesis was supported in the accurate moment of force production task. Fingers with longer moment arms produced larger proportion of the total moment of force than fingers with shorter moment arms in both elderly and young subjects.

d. Repetitive testing of elderly subjects without strength training did not lead to changes in maximal finger force or indices or finger interaction.
CHAPTER 10  General Discussion

Aging is traditionally associated with a loss of function of many aspects of life, physiological, psychological, social etc. Numerous studies have reported a decrease in manual dexterity and general strength of hands with increasing age (Boatright et al. 1997; Francis and Spirduso, 2000; Giampaoli et al. 1999; Hackel et al. 1992; Hughes et al. 1997; Rantanen et al. 1999, 2002; Shinohara et al. 2003a).

In this series of studies we had two major goals. First, we attempted to identify if changes in finger interaction and coordination might contribute to the observed decrease in the hand performance in the older population. Second, based on earlier studies, we hypothesized that strength training of hand muscles, particularly of the intrinsic hand muscles, could reverse some of those changes and lead to better performance in functional hand tests.

Within the first goal, we used two quantitative approaches. First, we quantified finger interaction using such indices as enslaving and peak forces produced in single- and multi-finger tests (Li et al. 1998; Zatsiorsky et al. 2000). In addition, we used the framework of the uncontrolled manifold hypothesis (Scholz and Schöner 1999) to quantify finger coordination with respect to such performance variables as the total force and the total moment of force produced by a set of fingers. We focused mostly on multi-finger synergies related to the production of rotational hand actions (moment-of-force stabilizing synergies).

Within the second goal, we designed a strength-training protocol that required the subjects to perform strength-training exercises that focused predominantly on the extrinsic muscles (force production by the fingertips) and those that focused predominantly on the intrinsic muscles (force production at the proximal phalanges). This design allowed us to test effects of transfer between the two sites of force production and to explore the effectiveness of strength-training on a variety of tests that required either maximal force production or accurate submaximal force production.
The elderly individuals that participated in the studies were people in a very good physical condition and exemplify a group that displays successful aging. Within the field of gerontology, “normal”, non-diseased aging is divided into usual and successful aging (Rowe and Kahn, 1987, 1997). Three main components define successful aging: low probability of disease and disease-related disability, high cognitive and physical functional capacity, and active engagement with life (Rowe and Kahn, 1997). In our studies several factors that contributed to the participant selection, indicate that they fall within the category of successful aging. Prior to taking part in the studies, our participants had to undergo the screening process that, due to rather extensive exclusion criteria, yielded a group of high-functioning, fairly un-diseased and un-medicated individuals. Through interaction with the participants it also became clear that they were individuals that exercised regularly, actively participated in volunteer work, and were of higher education. All these factors may be partially related to the fact that they were recruited either from retirement communities or a recreational facility in a university town.

When applying force with a finger, the exerted force is not constant but fluctuates around an average value (Enoka et al. 2003; Tracy et al. 2002) and multiple studies have shown these fluctuations to increase with age (Galganski et al. 1993; Laidlaw et al. 1996, 2000; Vaillancourt and Newell, 2003). This increase in force variability potentially challenges the central nervous system in tasks that require accurate hand action. During the common task of holding an object, such as a cup full of liquid, the fingers have to coordinate their action in order to satisfy the task mechanics. In particular, the sum of the normal forces should equal the force of the thumb to prevent translation of the object sideways and be high enough to prevent slippage, the sum of the tangential forces of all the digits should be equal to the weight of the object to prevent translation in the vertical direction, and total moment of force produced by all the digits should be equal to the external torque to prevent object rotation. This example illustrates two main synergies, force stabilizing synergy, and moment-of-force stabilizing synergy at the level of individual digits that are important for many tasks of everyday living.
In our studies, the elderly subjects did not show moment-of-force stabilizing synergies during the accurate moment of force production task and showed a decreased ability to stabilize total force as compared to the young subjects. These results are in agreement with previous reports of a reduced ability of elderly individuals to produce both force and moment-of-force stabilizing synergies (Shinohara et al, 2004; Shim et al. 2004b) and support the hypothesis that aging is associated with a decrease ability to coordinate commands to fingers in order to stabilize rotational hand action.

Another important finding was the reduced ability of the elderly individuals to produce anticipatory synergy adjustments (ASAs), in preparation to either a self-induced quick change in force or a self-induced change in the external force (a perturbation) applied to one of the fingers.

Earlier, we have suggested that ASAs represent a feed-forward mechanism of similar origin as anticipatory postural adjustments (APAs). The proposed functional role of ASAs is to attenuate force stabilizing synergies that otherwise would counteract the intended change in total force (Kim et al. 2006; Olafsdottir et al. 2005b; Shim et al. 2005c). Our results of a reduced ability of elderly individuals to produce ASAs are in agreement with previous reports of delayed and diminished feed-forward postural adjustments (anticipatory postural adjustments, APAs) in the elderly (Inglin and Woollacott, 1988; Woollacott and Manchester, 1993). The similarity of the changes in APAs and ASAs with age suggests that these two phenomena of feed-forward control may have a common origin.

A number of studies have documented positive effects of strength training on motor performance in elderly. Most studies have focused on changes in muscle anatomy, biochemistry, and strength, the overall motor function, and psychological reactions (Sipila and Suominen 1995; Tsutsumi et al. 1997; Izquierdo et al. 2003). In particular, training has been shown to lead to higher forces and lower antagonist coactivation. Since muscle cross-sectional area shows minor changes in the process of relatively short-term training, neural adaptations are likely to play a major role (Hakkinen et al., 1996, 1998). A recent report has
suggested that the impaired ability of elderly to control pinch force accurately can be improved with specialized training (Ranganathan et al. 2001). In our study, we focused on potential effects of strength-training on indices of finger interaction and coordination. We view the demonstration of positive effects of strength training and large transfer effects on untrained sites and tasks as very promising for optimization of exercise to counteract negative effects of sarcopenia.

The elderly individuals that participated in our strength training study produced on average much larger voluntary maximal force than their counterparts in a previous study (Shinohara et al. 2003a), both before and after the training. Despite being very strong, prior to the training, the elderly participants produced approximately equal peak forces at the proximal and distal sites (in agreement to an earlier report, Shinohara et al. 2003a). After the training, relatively more force was produced at the proximal site, similar to what is seen in younger subjects (Danion et al. 2000, 2001; Latash et al. 2002c; Shinohara et al. 2003a). On the other hand, strength also improved at sites that had not received any training and we propose as a possible explanation that strengthening the intrinsic muscles enables the strong extrinsic muscles to be activated to a larger degree. In agreement with our expectations, indices of enslaving increased in parallel with the improvements in strength after the training period such that the magnitude of enslaving expressed in percent of the maximal force producing ability became similar to that reported for younger persons (Li et al. 1998; Zatsiorsky et al. 2000).

We expected the increased enslaving to hurt the performance of tasks that require accurate force production by a set of fingers, as it could be expected from the increased positive co-variation of individual finger forces. However, the increased enslaving did not induce a decrease in the performance of the accurate force production task and the clinical hand tests. This is a non-trivial finding: The central nervous system is apparently able to maintain or even improve its multi-finger performance in spite of having to cope with increased positive co-variation among the finger forces.
Overall, this series of studies has provided strong evidence for changes in finger interaction and coordination that happen with advanced age. The studies carry not only a negative message of impaired multi-finger synergies in the elderly but also a positive message that such changes may be counteracted or even reversed with appropriately designed exercise.
REFERENCES


APPENDIX A

Informed Consent
Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of Project: Finger Coordination in Elderly

Principal Investigator: Dr. Mark L. Latash, Rec.Hall-267, Department of Kinesiology
University Park, PA 16802; tel: (814) 863-5374; e-mail: mll11@psu.edu

Other Investigator(s): Dr. Vladimir Zatsiorsky, Halla Olafsdottir, Stacey Gorniak

1. Purpose of the study: This study is part of research intended to understand how finger coordination and hand function change with age. By performing this research, we hope to improve our present understanding of changes in motor coordination in elderly and make recommendation for rehabilitation approaches to improve hand function.

2. Procedures to be followed: If you agree to take part in this research, you will be asked to perform certain simple motor tasks such as pressing against a stop, gripping a handle, and holding an object with one or two hands. Prior to entering the study, you will also be asked to visit the General Clinical Research Center for a screening by a clinician or a nurse. The data will be pooled with the data of about 30 other participants to draw conclusions. You will be asked to fill a questionnaire during the first visit. The questionnaire contains questions about your ability to perform certain everyday activities involving the active usage of the hands. You may be asked to use a hand-held exerciser twice a day to strengthen your hand muscles. You will be shown how to use it by an Investigator who may visit you at home and will be reminded by phone to use it. You will have access to the outcome measures of any of the tests if you choose so.

3. Discomforts and risks: This study involves no discomfort and minimal risk; that is, no risk to your mental or physical health beyond those encountered in the normal course of everyday life.

4. Benefits: There is no direct personal benefit associated with participation in the study. The benefits to society include better understanding of changes in the hand function with age. This information may be used to improve current exercise and rehabilitation approaches to the hand function.

5. Duration/time of the procedures and study: Your participation in the research will take one to three visits to the Laboratory; each visit will last between 1 hour and 1 hour 30 minutes. The first visit/test may be scheduled now; other visits/tests may be scheduled at a later time.

6. Alternative procedures that could be utilized: There are no alternative procedures to this research.

7. Statement of confidentiality: Your participation in this research is confidential. Only the investigator and his/her assistants will have access to your identity and to information that can be associated with your identity. In the event of any publication or presentation resulting from the research, no personally identifiable information will be shared. To make sure your participation is confidential, only a code will be used to identify your data. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Dept. of Health and Human Services; The Penn State University Biomedical Institutional (IRB); The Office for Research Protections (ORP).

All records associated with your participation in the study will be subject to the usual confidentiality standards applicable to medical records (e.g., such as records maintained by physicians, hospitals, etc.), and in the event of any publication resulting from the research no personally identifiable information will be disclosed. Under the state law, an exception to confidentiality is required if a person indicates an intention to harm him or her self or another person.
8. **Right to ask questions:** The purpose of the research and your role will be explained in detail. You may ask any questions about the research procedures, and these questions will be answered. You may decline to answer specific questions. Further questions should be directed to Dr. Mark Latash at (814) 863-5374. If you have questions about your rights as a research participant, contact The Pennsylvania State University’s Office for Research Protections at (814) 865-1775.

9. **Compensation:** In return for your participation, you will be paid $20 for every hour of participation in the tests ($25 per visit). In case the total amount exceeds $25, total payments within one calendar year that exceed $600 will require the University to annually report these payments to the IRS. This may require you to claim the compensation that you receive for participation in this study as taxable income.

10. **Voluntary participation:** Participation is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer.

11. **Injury Clause:** In the unlikely event you become injured as a result of your participation in this study, medical care is available but neither financial compensation nor free medical treatment is provided. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

12. **Abnormal Test Results:** In the event that abnormal test results are obtained, you will be made aware of the results in two weeks and recommended to contact your private medical provider for follow-up.

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent for your records.

_____________________________________________  _____________________  
Participant Signature       Date

_____________________________________________  _____________________  
Person Obtaining Consent       Date
APPENDIX B

Questionnaire on Finger Activity and Medical History
Questionnaire on finger activity and medical history

Your Name: ____________________________ Age: ________ Sex: M / F Date: __/__/____

Apartment #: ____________ Phone: ________________

Q.1) Do (did) you make most of your income in one of the following occupations?
   Typists, stenographers or professional musicians where finger use is central (piano, string 
instruments, saxophone, etc)
   □ Yes
   □ No
   If “Yes”, specify occupation and term: ________________________________

Q.2) How many hours per week do (did) you spend with a finger intensive activity such as above?
   If nothing, fill out with “N/A”.
   Now: Activity _________________ _________ hours/week
   5 years ago: Activity _________________ _________ hours/week

Q.3) Do you have any history or symptoms of the followings?
   □ Stroke or “ministroke” (even perceived as fully resolved)
   □ Peripheral neuropathy (as manifested by perceived numbness, tingling, burning or any other 
   abnormal sensation in the hand or hands)
   □ Diagnosis of carpal tunnel syndrome in either hand, whether corrected surgically or not
   □ Parkinson’s disease
   □ Cervical spine disc disease or arthritis causing radiculopathy, or history of cervical spine surgery
   □ Cervical spinal stenosis
   □ Multiple Sclerosis
   □ Myasthenia Gravis
   □ Polio
   □ Other nerve or muscle disease: ________________________________
   □ Have pain in the shoulders, elbows, wrists or fingers severe enough that it limits what you can do 
   with your arms / hands at least once each day
   □ No, nothing above applies to me as far as I know.

Q.4) Do you use any of the following medications or similar one every day?
   □ Narcotics
   □ Benzodiazepines
   □ Sleep aids
   □ Antidepressants other than SSRIs (see enclosed list of SSRIs)
   □ Phenothiazines and related medications
   □ Other medications that can alter mental alertness: ________________________________
   □ No, I do not use any medications of the above kind every day.
APPENDIX C

Screening Physical Examination-GCRC
# SCREENING PHYSICAL EXAMINATION-General Clinical Research Center

Name: ___________________________________________ Date: _____________ GCRC ID #: ____________

Date of Birth _________________________________________

Local Address:       Phone #:  __________________________________
Street ______________________________________________
City/State/ZipCode____________________________________

Home Address:       Phone #: ___________________________________
Street ______________________________________________
City/State/ZipCode____________________________________

Parent/Guardian: _____________________________________ Phone #: ___________________________________

Emergency Contact: __________________________________ Phone #: ___________________________________
Family Doctor: ______________________________________ Phone #: ___________________________________

Address: (If Known)
Street ______________________________________________
City/State/ZipCode____________________________________

Date of last exam: ____________________________________

List any current medications and doses: (include vitamins, over the counter medications, herbals, birth control pills)

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List any allergies & **types of reactions**: (medications, latex, balloons, bananas, avocados, kiwi, chestnuts, animals, food, pollen, etc.)

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The following questions are to be answered “yes” or “no.” Please check the appropriate box.

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List ALL other Medical problems/concerns: ________________________________________________________________

___________________________________________________________________________________________________
Have you ever:

**GCRC ID# __________**

**YES** **NO**

() () Been hospitalized for a medical problem? What?

() () Had Infectious mononucleosis? If yes, + blood test? Yes No

() () Had Heat exhaustion or intolerance?

**YES** **NO**

() () Had recurring Headaches or migraines?

() () Had Loss of consciousness?

() () Had a Concussion?

() () Had a Convulsion (seizures) or epilepsy?

() () Had a Neck Injury?

() () Had a "Stinger", "burner", or "pinched nerve"?

**SURGICAL HISTORY**

Have you ever had any of the following surgeries:

**YES** **NO**

() () Hernia?

() () Hysterectomy?

() () Gall Bladder?

() () Appendectomy?

() () Any other surgeries?

Have you ever:

**YES** **NO**

() () Broken a bone?

() () Had a muscle injury?

() () Had a knee injury? R () L () Ligament () Meniscus () Other ()

() () If "yes," did you have surgery? Result:

() () Had a shoulder injury? R () L ()

() () If "yes," did you have surgery? Result:

() () Had a back injury?

() () If "yes," did you have surgery? Result:

() () Had a stress fracture? If so, location:

() () Had any other joint injuries?

If so please check appropriate box (es):
( ) Ankle ( ) Hip ( ) Elbow ( ) Wrist ( ) Foot ( ) Other

**FAMILY MEDICAL HISTORY**

Has anyone in your immediate family (please list relationship) ever had:

**COMMENTS:**

**YES** **NO**

() () Diabetes (high blood sugar)?

() () Sudden Death (age less than 50)?

() () High blood pressure?

() () High cholesterol?

() () Heart Attack (age less than 50)?

() () Heart Bypass/Angioplasty/Heart Stent? (Circle)

() () Asthma?

() () Cardiac Disease?

() () Convulsions (seizures) or epilepsy?

() () Hypertrophic cardiomyopathy (Enlarged Heart)?

() () Long “QT” syndrome, Marfans, irregular heartbeat? (Circle)

() () Stroke?

() () Osteoporosis?

() () Blood Clotting Problems?

List any other Family Medical problems ____________________________________________

________________________________________
OCCUPATION HISTORY

**GCRC ID # ____________**

**YES**  **NO**

1. Are you retired? If so, how many years? ________________________________________________

2. Current or past occupation? _________________________________________________________

3. In terms of physical demands, how would you rate your position listed above?

   Very active (walking & lifting)          active (standing & walking)          slightly active (sitting & standing)          sedentary (sitting)

SOCIAL HISTORY

**YES**  **NO**

Alcohol

( ) ( ) Do you drink alcohol? If yes: how many drinks at one time? ____________________________

how many days a week? __________________________________________

Tobacco

( ) ( ) 1. Do you use tobacco at present? Circle which type: cigarettes   cigars   pipe   chewing tobacco   snuff

   How many a day?____________________________________________________

   How long have you used tobacco _____________ (years)

( ) ( ) 2. Did you use tobacco in the past? Circle which type: cigarettes   cigars   pipe   chewing tobacco   snuff

   How many a day?____________________________________________________

   How long have you used tobacco _____________ (years)

   When did you quit? ________________________ (years ago)

LEISURE & EXERCISE

1. Do you take walks in good weather? Frequently          Sometimes          Infrequently

2. Do you routinely do manual labor at home? Frequently          Sometimes          Infrequently

   (Painting, mowing, shoveling, gardening, cleaning)

3. List the sports or exercise you engage in for **at least 30 minutes** at a time (Include the number of times per week)

   _____________________________________________________________________________

   _____________________________________________________________________________

   _____________________________________________________________________________

NUTRITIONAL HISTORY

1. How many meals do you eat a day?____________________________________________________

2. Are you dieting? ___________________________________________________________________

3. Are you happy with your weight? _________ If not, what is your desired weight? _______________

4. Are there any major food groups that you do not eat?____________________________________

**YES**  **NO**

( ) ( ) Have you ever had an eating disorder?

( ) ( ) Have you ever taken weight loss medicine?

( ) ( ) Have you ever taken laxatives to avoid weight gain?

( ) ( ) Have you ever self induced vomiting to avoid weight gain?

( ) ( ) Have you ever used excessive exercise to control your weight?

**FEMALE HISTORY**

**YES**  **NO**

1.a. Do you have regular menstrual bleeding each month?

   If no, explain: _________________________________________________________________

   ( ) ( ) b. Have you always had regular menstrual bleeding each month?

   If no, explain: _________________________________________________________________

2.a. Do you, or have you in the past take(n) oral contraceptive pills or other hormonal supplements?

   If yes, explain: _________________________________________________________________

   ( ) ( ) b. Have you ever taken oral contraceptive pills or other hormonal supplements?

   If yes, explain: _________________________________________________________________

3. Are you pregnant?

   (Signature) ___________________________ Date: _______________________

   (Signature of parent if < 18 yrs. old) Date:
**PHYSICAL EXAMINATION (To be completed by physician):**

<table>
<thead>
<tr>
<th>Normal</th>
<th>Abnormal</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Blood pressure _______ Pulse _____ Respiration _____ Temperature ______ GCRC ID # _________**

**Pain (0-10) _______ Height _______ Weight _______ BMI _______ Date of Birth _________**

- **HEENT**
- **Thyroid**
- **Lymphatics**
- **Cardiac**
- **Carotid Bruit: Yes No**
- **Lungs**
- **Skin**
- **Abdominal**
- **Genitalia**
- **Musculoskeletal:**
  - **Neck**
  - **Shoulder**
  - **Elbow**
  - **Wrist/hand**
  - **Back**
  - **Scoliosis: Yes No**
  - **Knee**
  - **Ankle, foot**
- **Neurological**

**Other:**

****************************************************************************************************************************

**Physician comments:**

**Clearance without restrictions or limitations:**

**Clearance pending further evaluation or testing:**

**Referral to ______________ prior to clearance.**

**Clearance with limitations:**

**Disqualification from study:**

**Signature of Examining Clinician ________________________ Date ________________**
APPENDIX D

Beck Depression Inventory
Beck Depression Inventory (II)

Name: ___________________________  ID: __________  Score: ________

This questionnaire consists of 21 groups of sentences. Please read each group of statements carefully, and then pick out the one statement in each group that best describes the way you have been feeling during the past two weeks, including today. Circle the number beside the statement you have picked. If several statements in the group seem to apply equally well, circle the highest number for that group. Be sure that you do not choose more than one statement for any group, including Item 16 or Item 18.

1. Sadness
   0  I do not feel sad.
   1  I feel sad much of the time.
   2  I am sad all the time.
   3  I am so sad or unhappy that I can't stand it.

2. Pessimism
   0  I am not discouraged about my future.
   1  I feel more discouraged about my future than I used to be.
   2  I do not expect things to work out for me.
   3  I feel my future is hopeless and will only get worse.

3. Past Failure
   0  I do not feel like a failure.
   1  I have failed more than I should have.
   2  As I look back, I see a lot of failures.
   3  I feel I am a total failure as a person.

4. Loss of Pleasure
   0  I get as much pleasure as I ever did from the things I enjoy.
   1  I don't enjoy things as much as I used to.
   2  I get very little pleasure from the things I used to enjoy.
   3  I can't get any pleasure from the things I used to enjoy.

5. Guilty Feelings
   0  I don't feel particularly guilty.
   1  I feel guilty over many things I have done or should have done.
   2  I feel quite guilty most of the time.
   3  I feel guilty all of the time.

6. Punishment Feelings
   0  I don't feel I am being punished.
   1  I feel I may be punished.
   2  I expect to be punished.
   3  I feel I am being punished.

7. Self-Dislike
   0  I feel the same about myself as ever.
   1  I have lost confidence in myself.
   2  I am disappointed in myself.
   3  I dislike myself.

8. Self-Criticalness
   0  I don't criticize or blame myself more than usual.
   1  I am more critical of myself than I used to be.
   2  I criticize myself for a lot of my faults.
   3  I blame myself for everything bad that happens.

9. Suicidal Thoughts or Wishes
   0  I don't have any thoughts of killing myself.
   1  I have thoughts of killing myself, but I wouldn't carry them out.
   2  I would like to kill myself.
   3  I would kill myself if I had the chance.

10. Crying
    0  I don't cry anymore than I used to.
    1  I cry more than I used to.
    2  I cry over very little thing.
    3  I feel like crying, but I can't.

Please go to the next page
11. Agitation
0  I am no more restless or wound up than usual.
1  I feel more restless or wound up than usual.
2  I am so restless or agitated that it's hard to stay still.
3  I am so restless or agitated that I have to keep moving or doing something.

12. Loss of Interest
0  I have not lost interest in other people or activities.
1  I am less interested in other people or things than before.
2  I have lost most of my interest in other people things.
3  It's hard to get interested in anything.

13. Indecisiveness
0  I make decisions about as well as ever.
1  I find it more difficult to make decisions than usual.
2  I have much greater difficulty in making decisions than I used to.
3  I have trouble making any decisions.

14. Worthlessness
0  I do not feel I am worthless.
1  I don't consider myself as worthwhile and useful as I used to.
2  I feel more worthless as compared to other people.
3  I feel utterly worthless.

15. Loss of Energy
0  I have as much energy as ever.
1  I have less energy than I used to have.
2  I don't have enough energy to do very much.
3  I don't have enough energy to do anything.

16. Changes in Sleeping Pattern
0  I have not experienced any change in my sleeping pattern.
1a  I sleep somewhat more than usual.
2a  I sleep a lot more than usual.
3a  I sleep most of the day.
1b  I sleep somewhat less than usual.
2b  I sleep a lot less than usual.
3b  I wake up 1-2 hours early and can't get back to sleep.

17. Irritability
0  I am no more irritable than usual.
1  I am more irritable than usual.
2  I am much more irritable than usual.
3  I am irritable all the time.

18. Changes in Appetite
0  I have not experienced any change in my appetite.
1a  My appetite is somewhat less than usual.
2a  My appetite is much less than before.
3a  I have no appetite at all.
1b  My appetite is somewhat greater than usual.
2b  My appetite is much greater than before.
3b  I crave food all the time.

19. Concentration Difficulty
0  I can concentrate as well as ever.
1  I can't concentrate as well as usual.
2  It's hard to keep my mind on anything for very long.
3  I find I can't concentrate on anything.

20. Tiredness of Fatigue
0  I am no more tired or fatigued than usual.
1  I get more tired or fatigued more easily than usual.
2  I am too tired or fatigued to do a lot of things I used to do.
3  I am too tired or fatigued to do most of the things I used to do.

21. Loss of interest in sex
0  I have not noticed any recent change in my interest in sex.
1  I am less interested in sex than I used to be.
2  I am much less interested in sex now.
3  I have lost interest in sex completely.

End of the questionnaire
APPENDIX E

Mini Mental State Examination
Mini-Mental State Examination (MMSE)

Instructions: Score one point for each correct response within each question or activity.

<table>
<thead>
<tr>
<th>Maximum Score</th>
<th>Patient’s Score</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>“What is the year? Season? Date? Day? Month?”</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>“Where are we now? State? County? Town/city? Hospital? Floor?”</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient’s response is used for scoring. The examiner repeats them until patient learns all of them, if possible.</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>“I would like you to count backward from 100 by sevens.” (93, 86, 79, 72, 65, …) Alternative: “Spell WORLD backwards.” (D-L-R-O-W)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>“Earlier I told you the names of three things. Can you tell me what those were?”</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>“Repeat the phrase: ‘No ifs, ands, or buts.’”</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>“Take the paper in your right hand, fold it in half, and put it on the floor.” (The examiner gives the patient a piece of blank paper.)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>“Please read this and do what it says.” (Written instruction is “Close your eyes.”)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>“Make up and write a sentence about anything.” (This sentence must contain a noun and a verb.)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>“Please copy this picture.” (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.)</td>
</tr>
</tbody>
</table>

30 TOTAL
APPENDIX F

ABILHAND
### ABILHAND - Manual Ability Measure

**Patient ___________________________**

**Date _______________**

<table>
<thead>
<tr>
<th>How DIFFICULT are the following activities?</th>
<th>Impossible</th>
<th>Difficult</th>
<th>Easy</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pulling up the zipper of trousers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Peeling onions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Sharpening a pencil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Taking the cap off a bottle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Filing one's nails</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Peeling potatoes with a knife</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Buttoning up trousers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Opening a screw-topped jar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Cutting one's nails</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Tearing open a pack of chips</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Unwrapping a chocolate bar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Hammering a nail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Spreading butter on a slice of bread</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Washing one's hands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Buttoning up a shirt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Threading a needle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Cutting meat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Wrapping up gifts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Fastening the zipper of a jacket</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20. Fastening a snap (jacket, bag...)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. Shelling hazelnuts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. Opening mail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23. Squeezing toothpaste on a toothbrush</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Université catholique de Louvain, Laboratory of Rehabilitation and Physical Medicine*
APPENDIX G

Grooved Pegboard Test and Jebsen-Taylor Hand Function Test Score Sheet
Grooved Pegboard Test

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dropped pegs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pegs in the holes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Jebsen-Taylor Hand Function Test

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Writing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Simulated Page Turning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Lifting Small Common Objects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Simulated Feeding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Stacking Checkers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Lifting Large Light Objects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Lifting Large Heavy Objects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX H

Training Instruction Sheet
Training Instructions

Right Hand training = Extrinsic Strength Exercises
Left Hand training = Intrinsic Strength Exercise

LEFT HAND

Intrinsic Strength Exercises

The pictures to the left demonstrate how we would like you to hold the DIGIFLEX for the intrinsic (top picture) and Extrinsic (bottom picture) Strength Exercises.

We would like you to do these exercises TWICE a day (once in the morning and once in the afternoon). You should complete TWO lots of 10 exercises with each hand TWICE a day for the next week.

RIGHT HAND

Extrinsic Strength Exercises

Points to Remember

* You are performing the extrinsic training with your RIGHT hand and the intrinsic training with your LEFT hand.

* The DIGIFLEX should be positioned between the two arrows as shown in the pictures (depending on which hand you are exercising).

* The strengthening exercise should consist of a slow and controlled squeeze of the DIGIFLEX until the springs from all fingers are fully compressed then hold the squeeze for 2 seconds and release.
Curriculum Vitae
Halla Bjorg Olafsdottir

Education
Ph.D 2008, Penn State University, University Park, PA. Major in Kinesiology (Motor Control).
M.Sc 2004, Penn State University, University Park, PA. Major in Kinesiology (Motor Control).
B.Sc 2000, University of Iceland, Reykjavik, Iceland. Physical therapy.

Scholarships
2002 Fulbright fellowship from the Iceland-United States Educational Commission.
2006 Leifur Eiriksson Foundation Scholarship.

Peer-Reviewed Publications

Book Chapters