ABSTRACT

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The current dissertation addresses the central nervous system (CNS) strategies to solve kinetic redundancy in multi-digit static prehension under different geometries of hand-held objects and systematically varied mechanical constraints such as translation and rotation of the hand-held object. A series of experiments conducted for this dissertation tested the following hypotheses suggested in the current literatures for multi-digit human static prehension: *Hierarchical organization hypothesis*, *principle of superposition hypothesis*, *proximity hypothesis*, and *mechanical advantage hypothesis*. (1) Forces and moments produced by fingers during circular object prehension were grouped into two independent subsets: one subset related to grasping stability control and the other associated with rotational equilibrium control. This result supports the *principle of superposition hypothesis*. Individual fingers acted synergistically to compensate each other's errors. This result confirms *the hierarchical organization hypothesis* in circular object prehension. (2) During fixed object prehension of a rectangular object, the closer the non-task fingers positioned to the task finger, the greater the forces produced by the non-task fingers.

However, during free object prehension, the non-task fingers with longer moment arms produced greater forces. The former and latter results support the *proximity hypothesis* and the *mechanical advantage hypothesis*, respectively. (3) The grasping stability control and rotational equilibrium control were decoupled during fixed object prehension as well as free object prehension. This result supports the *principle of superposition hypothesis* regardless of the mechanical constraints provided for these two prehension types. (4) During torque production, the fingers with longer moment arms produced greater forces when the fingers acted as agonists for the torque production. Therefore, the *mechanical advantage hypothesis* was supported for agonist fingers. (5) Coupling of thumb normal force and virtual finger normal force was not necessitated when horizontal translation of hand-held object was mechanically fixed. However, the coupling of two normal forces was always observed regardless of given translational constraints, and these two normal forces were independent to other mechanical variables such as tangential forces and moments. This result supports the *principle of superposition hypothesis* in static prehension under varied combinations of translational constraints.

MULTI-DIGIT HUMAN PREHENSION

By

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"I praise you because I am fearfully and wonderfully made;
your works are wonderful, I know that full well."
- Psalms 139:14 -

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Chapter 1: Introduction

1.1. Problem statement

Holding an object stably is a one of the basic functions of the hand and is required for dexterous actions of hand and fingers. The dexterous actions of hand and fingers have been known to be affected by the internal constraints (i.e., biomechanical and central constraints) and the external constraints (i.e., mechanical constraints). While many previous studies have shown that the grasping behaviors are influenced by biomechanical connections of muscles and tendons and neuronal connections, little is known how the grasping behaviors are affected by the mechanical constraints. For instance, the central nervous system (CNS) needs to control or restrict the translational and rotational actions of a hand-held object during a stable static prehension. Therefore, the central nervous system (CNS) needs to satisfy a set of static constraints in order to maintain stable static grasping of hand-held objects. The CNS often uses multiple fingers in static grasping tasks and it needs to control a set of finger forces/moments to satisfy the static constraints. However, when the number of forces/moments to be controlled by the CNS is greater than the number of constraints, infinite combinations of finger forces and moments can produce exactly the same motor outcomes (Pataky, Latash, & Zatsiorsky, 2004a; Shim, Latash, & Zatsiorsky, 2003b, 2004a; Zatsiorsky, Gregory, & Latash, 2002). This problem has been known as motor redundancy in human movement science. In order to solve the motor redundancy problem, the CNS needs to make decisions of what combinations of finger forces and moments will be used for a given motor task. The Principle of Superposition, originally suggested in robotics (Arimoto & Nguyen, 2001), was recently suggested as a strategy used by the CNS to solve the motor redundancy within a multi-digit grasping system. According to the Principle of Superposition, a complex action can be decomposed into independently controlled sub-actions. Previous studies showed that the controls for translational and rotational equilibriums could be decoupled in the human grasping task (Shim, Latash, & Zatsiorsky, 2005b; Zatsiorsky, Latash, Gao, & Shim, 2004).

The aim of this dissertation is to investigate how the systematic changes of static external constraints affect the multi-finger grasping actions and the Principle of Superposition. This dissertation specifically investigated the following topics: (1) Is the principle of superposition still valid during a circular object grasping task? Because the previous studies employed the rectangular object prehension in which the geometric shapes of the objects do necessitate the coupling of mechanical variables (e.g., the grasping forces of a thumb and fingers should cancel out to be zero, and the sum of load forces of all digits should be the same as the weight of a grasped object), the generalizability of the principle of superposition is questionable for grasping objects in another geometric shape. (2) Although many previous studies have shown that the independent actions of fingers are affected by internal constraints, little is known how external constraints affect independent finger actions of multi-digit grasping. (3) It is currently unknown whether the decoupled control of grasping stability and rotational equilibrium are affected by static constraints during human hand prehension. (4) Although moment production on fixed and free objects has been studies, relatively little attention has been paid to investigate different mechanical constraints imposed in prehension tasks are affecting the synergistic actions of fingers during grasping tasks. This dissertation will investigate the changes in synergistic finger actions under systematically manipulated conditions of external constraints.

1.2. Study objectives

This dissertation has the following objectives.

(1) to test a hypothesis on the generalizability of the principle of superposition and hierarchical organization (see Chapter 2.4.1 for more details on hierarchical organization of prehension synergy) of prehension synergies in human hand prehension (Part 1 in Fig.1.1).

(2) to investigate the independent actions of individual digits and the interactions of multiple digits while holding a mechanically fixed object or a free object (Part 2 in Fig. 1.1).

(3) to test a hypothesis on the hierarchical organization of prehension synergy and applicability of principle of superposition in human prehension (see Chapter 2.4.1 for more details on hierarchical organization of prehension synergy and principle of superposition) during mechanically fixed object and free object prehensions (Part 3 in Fig. 1.1).

(4) to test the mechanical advantage hypothesis (see Chapter for more details on mechanical advantage hypothesis) during mechanically fixed object and free object prehensions (Part 4 in Fig. 1.1).

(5) to investigate separated effects of horizontal and vertical translations constraints on multi-digit synergies (part 5 in Fig. 1.1).

1.3. Organization of dissertation

In Chapter 2, the following issues on previous literatures were reviewed and discussed: the motor redundancy, movement constraints, prehension mechanics, and prehension control. The dissertation was composed of series of sub-studies (Chapter 3 to 7) that are systematically linked (Fig. 1.1).

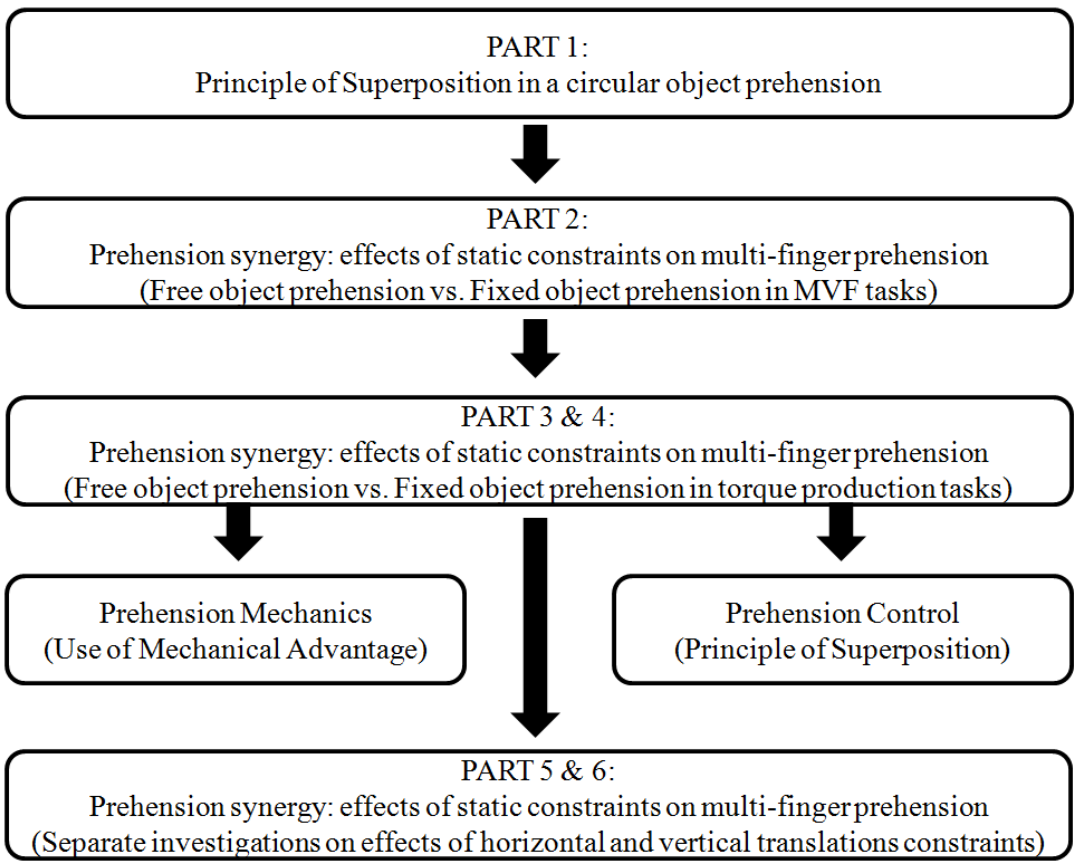


Figure 1.1. Organization of dissertation

Chapter 2: Background of Literature Review

2.1. Motor redundancy (degree of freedom problem)

In many of voluntary human movements, the number of elemental variables is greater than the number of elements minimally required for the successful completion of the task. For example, the end-point trajectories for an arm reaching out to grasp an object can be performed by many different combinations of joint-angle trajectories. Even when a person simply holds an object still, an infinite number of joint-angle combinations and finger-tip force combination can be the solution for the successful completion of that task. Because of this, CNS should govern more degrees of freedom (DOF) than what is now currently provided by tasks.

The DOF is defined in classical mechanics as the minimum number of independent coordinates used to describe a system's position. The main questions in contemporary motor control theories concern what is actually being controlled within the human movement system and how the various actions of the units come together to perform a motor-task successfully. Bernstein (1967) tried to solve this issue in terms of the DOF in human movement (Bernstein, 1967). He argued that the number of elemental variables is greater than the number of elements required for most tasks. This issue has been dubbed a motor redundancy problem, or a Bernstein's problem. The existence of motor redundancy suggests that the central nervous system (CNS) governs many more degrees of freedom (DOF) than most tasks require. The redundancy problem also manifests in joints, muscles, and motor unit levels. If we consider muscle or motor units as variables to be controlled, the redundancy problem becomes even more apparent. However, there are some assumptions and approaches explaining how the CNS solves the DOF problem in order to perform motor task successfully.

2.1.1. Uncontrolled Manifold (UCM) Analysis

Synergy has been defined as having multiple effectors work together to achieve a common goal or a set of given tasks. The notion of synergy has been widely used as a strategy to solve the DOF problem. As already stated, the human body system is very redundant in terms of DOF. The elimination of redundant DOF would reduce the amount of effort expended by the CNS. Turvey (1977) considered cooperation between effectors to be dependent upon a functional and anatomical factor . Turvey referred to this phenomenon as “freezing” redundant DOF. Gelfand and Latash, however, have introduced a different view on the solution (Gelfand & Latash, 1998; Latash, Gelfand, Li, & Zatsiorsky, 1998) . They argued for the existence of a principle of motor abundance, suggesting that the CNS utilizes all DOF in the system so that an abundant set of solutions would be formed. This principle of motor abundance relies on error compensation and synergies among elemental variables. The elemental variables do not act independently, but rather act together to compensate for the error created by individual variables so that they can achieve specific goals (i.e., various level of resultant force or resultant moment).

The notion of synergy has been facilitated by the recent development of uncontrolled manifold hypothesis (UCM). This approach has been tested in the multi-joint coordination (Scholz, Schoner, & Latash, 2000; Tseng, Scholz, & Schoner, 2002), finger movements (Latash, Scholz, Danion, & Schoner, 2001; Scholz, Kang, Patterson, & Latash, 2003; Shinohara, Scholz, Zatsiorsky, & Latash, 2004), and postural control (Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2003, 2004). The idea is that the CNS controls the elemental variables in the null space. In other words, if the value of elemental variables varies within UCM, this action can be considered as the action of error compensation without change of performance variables. Thus, the notion of synergy in UCM hypothesis does not mean that the redundant DOF in the system is either eliminated or has been frozen. Multi-digit synergy in prehension has been described as co-variation of force mode (i.e., a hypothetical latent variable as a desired involvement of individual variables into the performance variables). Two types of synergies have been analyzed in multi-finger pressing tasks: total force stabilization synergy and total moment stabilization synergy.

2.1.2. Synergy from motor programming and reflex

The equilibrium point hypothesis (EPH) offers a physiological mechanism to solve the problem of motor redundancy (DOF problem). In other words, the EPH is based on a major principle of the design of the neuromuscular system. In particular, the equilibrium point hypothesis (EPH) combines the principles from “reflex” and “motor programming.” Sherrington (1906) argued that the control of movement is performed by changing the parameters of reflex; this idea is very close to the concept of the EPH (Sherrington, 1906). The EPH is also associated with Bernstein’s engram. That is, the patterns of motor commands are stored in the memory and constitute voluntary movements. The EPH suggests a reduction of redundant DOF through a combination of efference commands, muscle characteristics, external loads, and reflex functions. The EPH also assumes that the human body is arranged such that the structure is dependent upon the tension and position of individual muscles. In terms of single muscle control, the EPH would be a typical example of multi-element synergy with motor units. The hierarchical structure control model (the idea that a particular group of muscles is controlled by its lower center, rather than its higher center) offers a very attractive addition to the idea of motor synergy through EPH. According to the hierarchical structure control, individual joint control is a secondary, meaning that a higher level control (i.e., end-point position control) does not specify the unique combination of lower level variables (i.e., individual joint trajectories). A controller only governs a certain characteristics of motor action, while others may handle the secondary considerations. For example, the end-point position (or trajectory) can be considered a primary consideration, and would be an important performance variable.

Polit and Bizzi (1979) suggest that the mass spring analogy of muscles employed in EPH can be explained by examining movement control through programming concepts (Polit & Bizzi, 1979). In their experiment, Polit and Bizzi found that the monkey, after having learned a simple one-joint movement to pointing a target, was able to point correctly with its vision occluded and following de-afferentation (i.e., the elimination of sensory nerve impulse). Their findings imply that the information about muscle tension is based around the end position, the act of pointing act the target. In Bizzi's papers, the idea of synergy has been replaced by the idea of muscle activation patterns. Each of the synergies referred to by this concept is modulated by an amplitude scaling and onset delay parameter (Bizzi, Cheung, d'Avella, Saltiel, & Tresch, 2008). He found that functional synergy (i.e., module or functional unit) in the spinal cord, where a specific motor command is generated by imposing a specific pattern of muscle activation, reduces the redundant DOF in the system. Similarly, Ting & Macpherson (2005) defined a muscle synergy as a specific pattern of muscle co-activation (Ting & Macpherson, 2005). She suggested that each muscle synergy is presumed to be controlled by a single neural command signal. This assumption was supported by employing hip or ankle strategy as a way to restore force for a corrective movement against unexpected perturbation.

2.2. Movement constraints

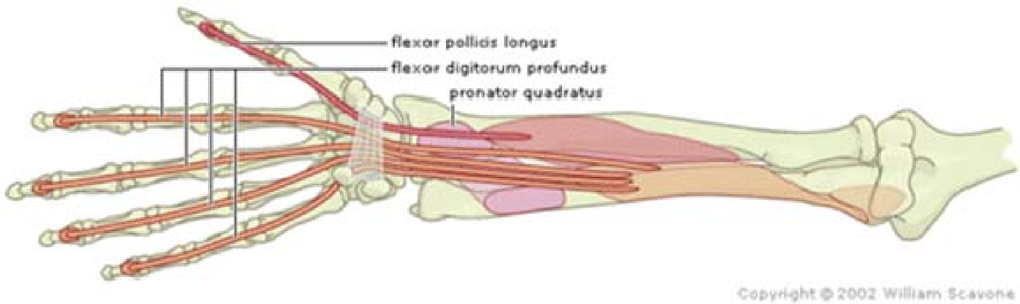
There are four groups of holonomic (geometrical) constraints in human movements: anatomical, actual, mechanical, and motor task constraints (Zatsiorsky, 2002). The examples of holonomic constraints in daily life include pushing a cart, bicycle pedaling, and opening doors. All these examples include the directional difference between the applied force to the object and the outcome motions. Anatomical constraint is based on the structure of the musculoskeletal system, such as a coupled joint movement. Actual constraint is created by a direct physical obstacle, such as the interaction between foot and pedal when pedaling a bicycle. Mechanical constraint describes the indirect ways movement geometry is restricted, such as an intentional movement restriction in order to prevent accidents like slipping. Motor task constraint is imposed voluntarily and involuntarily by performers, and is executed to create the desired movement or to fulfill the given motor tasks. On the level of kinetic constraints, end-effector constraints guide the direction of exerted force, which is distinct from the direction of motion. In this session, the movement constraints on human hand system will be discussed. Generally, the movement constraints on human hand system have been classified into internal and external constraints.

2.2.1. Internal constraints in human Hand system

Unlike robotic hands where each finger has separate effectors, the fingers of the human hand cannot move or produce forces independently (Hager-Ross & Schieber, 2000; Lang & Schieber, 2004). Indeed, when a person voluntarily moves or produces force with one finger (the task finger), the other fingers (non-task fingers) produce involuntary motions and various levels of force. The involuntary force or motion produced by non-task fingers is called finger enslaving (Li, Dun, Harkness, & Brininger, 2004; Zatsiorsky, Li, & Latash, 1998; Zatsiorsky, Li, & Latash, 2000b). Enslaving has been used as an index of finger interdependency and attributed to biomechanical and central (neurological) factors (Hager-Ross & Schieber, 2000; Schieber & Santello, 2004). Therefore, the independent actions of finger are hampered by internal constraints. Internal constraints on human hand system include biomechanical and central constraints.

Biomechanical constraints

(a)



(b)

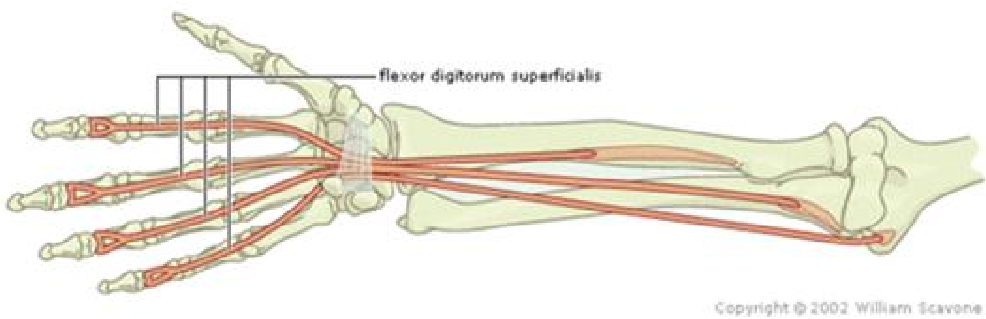


Figure 2.1. Anterior view of the (a) tendons of the forearms and hand and (b) flexor digitorum superficialis tendon (Scavone, 2002)

The biomechanical factors include anatomical connections within the hand and forearm. In involuntary (passive) movements, the architecture of the hand and forearm mechanically couples the actions of fingers, resulting in enslaving and finger interdependency. The soft tissues of the webbed spaces between fingers cause finger interdependence between adjacent digits (Hager-Ross and Schieber, 2000; Schieber and Santello, 2004). Also, the extrinsic hand muscles flexor digitorum profundus

(FDP) (Fig. 2.1) and flexor digitorum superficialis (FDS) (Fig. 2.2) are connected to multiple tendons within the fingers. These multi-tendinous connections to extrinsic muscle can result in the movement of non-task fingers during voluntary flexion of task fingers (Leijnse, 1997). Interconnected tendons of certain muscles, such as the juncturae tendinium, which connects the extensor digitorum communis (EDC) to different fingers, can also contribute to finger interdependency (Schieber & Santello, 2004). Anomalous other interconnections can also play a role in the mechanical coupling of adjacent fingers, such as the tendinous band between flexor pollicis longus and the FDP portion in the index finger (Hager-Ross & Schieber, 2000). Stretch reflexes activated during high frequency, large-arc movements from the spinal column, without central nervous intervention, can also cause finger interdependency.

Central constraints

Neurological factors include interdependent finger control by the central nervous system (CNS) due to overlapping digit representation in the hand area of the primary motor cortex, the synchronous firing of cortical cells, and a common neuronal input to multiple muscles. These factors have been investigated during previous studies employing isometric force pressing tasks and kinematic finger movement tasks. Finger interdependence can also be attributed to poor central nervous system control (CNS) during voluntary (active) movements. Primary motor cortex (M1) plays a fundamental and essential role in the control of voluntary movement performed by the muscles. In particular, the individuated movements are produced by the different parts of M1. Generally, the movements evoked by electrical stimulation of the motor cortex are mediated by the pyramidal tract (i.e., massive collection of axons that travel between the cerebral cortex of the brain and the spinal cord). A large part of the M1 is devoted to control of hand, especially the thumb and index, as well as the lips and the tongue -- most of the distal parts of body need dexterous movement control.

Recent experimental studies have indicated that the somatotopy of M1 is not as spatially segregated as might be suggest by the homunculus or simiusculus (Schieber, 1990). Indeed, most stimuli activate several muscles, with muscles rarely being activated individually. A series of studies performed by Marc Schieber have argued against the labeled-line hypothesis. According to the labeled-line hypothesis, each finger is assumed to be moved by its own set of flexor and extensor muscles, and in turn each set of muscles is assumed to be controlled from a somatotopically distinct region of the primary motor cortex (M1). However, Schieber's recent studies have indicated that the primate hand is controlled differently. Whenever any target finger is moved, many different muscles are active so that unintended fingers also create a certain amount of force. Fig. 2.2 shows the distributed activation in M1 during finger movements (Schieber & Hibbard, 1993). Colored spheres each represents a single neuron recorded in the left hemisphere M1 as a monkey engaged in individuated finger movements (flexion and extension). When the monkey performs the individuated movement of each finger and of the wrist, specific neurons were found to discharge in relation to the movements of several different fingers.

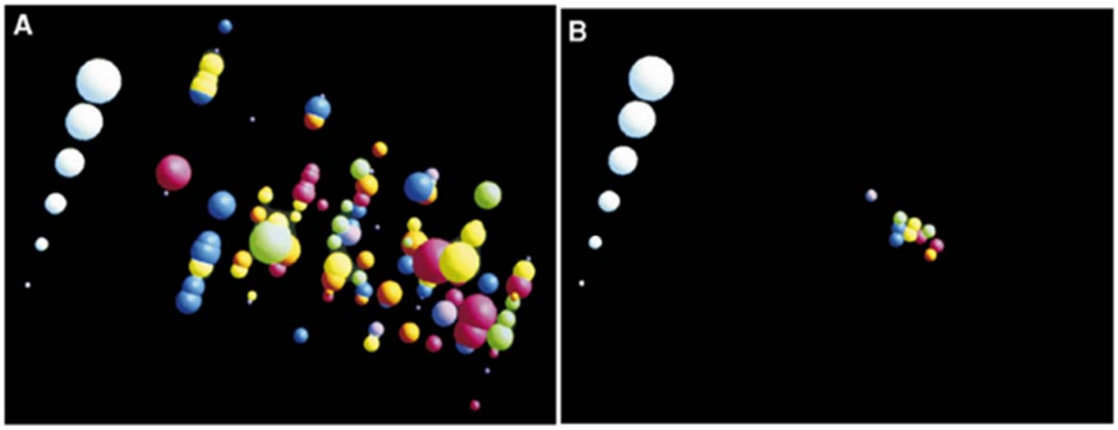


Figure 2.2. Distributed activation in M1 during finger movement. A: colored spheres each represents a single neurons recorded in the left hemisphere M1 as a monkey performed individuated movements of each right-hand digit and of the right wrist. B: centroids of discharge frequency changes calculated for each flexion movement and each extension movement are shown in the same coordinated system as in A. (Schieber & Hibbard, 1993 as modified in Schieber, 2001). This figure is used with permission from AAAS.

This result is obviously opposed to the traditional view, in which the movements of different fingers could be represented in spatially distinct regions of M1. The labeled-line hypothesis (i.e., the traditional view of human body control by the primary motor cortex) does not fully explain the involuntary force production by non-task finger. The neuron activity in the primary motor cortex to control hand (fingers) muscles can be explained by the three sub-factors of the central constraints. These constraints explain why the somatotopy of M1 is not spatially segregated. The three sub-factors in the central constraints are the convergence of output from large, overlapping cortical territories onto single muscle; the divergence of output from any given cortical site to multiple muscles; and the extensive horizontal interconnections between the sub-regions of the M1 hand area.

Evarts (1968) suggests that M1 firing is more correlated with isometric force than with limb position (Evarts, 1968). However, later studies observed that in multi-joint movement tasks the majority of M1 neurons encode not the acceleration, which is proportional to force, but the direction (Georgopoulos, Schwartz, & Kettner, 1986) or the velocity of hand movements (Schwartz, 1994). Also, Scott (1997) found that M1 neurons and muscles display similar patterns of directional variation in their onset time and activation magnitudes. The distribution of preferred direction of both M1 neuron and muscles are roughly uniform in the natural posture when the arm is constrained to the horizontal plane. Heavier representation of the distal parts (digits, wrist, and forearm) was shown posterolaterally and the heavier representation of more proximal parts (shoulder and elbow) were shown at anteromedial region. This result is similar evidence to the convergence shown in the distal part of body (finger). Stimulating a limited number of widely spaced points along the central sulcus demonstrated a progression from shoulder movement medially to finger and thumb movement laterally. In addition, a recent study documented that the functional connection of single M1 neuron may diverge to the include the muscles moving the fingers and shoulders (McKiernan, Marcario, Karrer, & Cheney, 1998). This divergence suggests that hand muscle control is not the sole feature of M1.

2.2.2. External constraints (mechanical constraints)

When we investigate the control aspects of human movements with given conditions, interactions with external world should be considered in order to explain the CNS control strategies for given tasks. From this point of view, mechanical constraints can be defined as the movement constraints (not restriction) such as rotational or translation constraints imposed by externally. For example, the free object static prehension has six different mechanical constraints (three directional and three rotational), and the subject intentionally control all three linear translations and rotations in order to maintain static position of the hand-held object. These constraints hamper the independent action of digits and alter finger interdependency strategies.

2.2.3. Multi-finger prehension with mechanical constraints (Proximity hypothesis and mechanical advantage hypothesis)

There have been two hypotheses on non-task finger force productions. The first is the proximity hypothesis, and the other is the mechanical advantage hypothesis. Previous studies on fixed object pressing tasks, where only internal constraints exist in the system, have commonly revealed that the closer the non-task finger is positioned from the task finger, the greater enslaving force was produced by non-task finger. (Olafsdottir, Zatsiorsky, & Latash, 2005; Zatsiorsky et al., 1998, 2000b). This finding has supported the proximity hypothesis.

When it comes to grasping a free object, where the object is in the air and grasping it requires using multiple digits, the strategy explained by the proximity hypothesis is not fully satisfactory because the larger enslaving force exerted by the neighboring finger would not be helpful in maintaining movement equilibrium, particularly in the case of same direction movements by two neighboring effectors.

The alternative explanation for static prehension involving moment equilibrium is the mechanical advantage hypothesis. According to the mechanical advantage hypothesis, the effectors located farther away from the axis of rotation generate larger force (Devlin & Wastell, 1986; Frey & Carlson, 1994; Gielen & Zuylen, 1988; Shim et al., 2004a; Zatsiorsky et al., 2002).

The fact that the effectors with greater mechanical advantage showed a larger involvement has been shown in muscle activation (Buchanan, Rovai, & Rymer, 1989; Gielen & Zuylen, 1988; Prilutsky, 2000), multi-digit torque production (Shim et al., 2004a; Zatsiorsky et al., 2002). The changes of effectors' actions with greater mechanical advantages are more effective to lead the changes of whole system's status. Although the previous studies documented that the mechanical advantage hypothesis was applied to the torque production task during free object prehension (Zatsiorsky et al., 2002) as well as the fixed object prehension (Shim et al., 2004a), it has not been investigated whether and how sharing patterns among finger forces during torque production task is affected by mechanical constraints imposed in tasks.

2.3. Prehension mechanics

2.3.1. Prehension forces

Internal force

A previous study performed by Gao et al (2005) reported that there are only two internal force factors: grasping force and the internal movement in the planar grasping task (Gao, Latash, & Zatsiorsky, 2005). Internal force has been defined as a set of contact forces (not a single force) applied to an object by the individual digits, which does not disturb the equilibrium of the system. Specifically, the force vectors in the system acts in opposite directions and cancel each other out. Because of this, the internal forces generate a zero resultant force and moment. In contrast, manipulation forces generate the translation or rotation of the system. In multi-digit grasping, a vector of contact forces and moment can be decomposed into two orthogonal vectors: the resultant force vector (manipulation force) and the vector of the internal force. The grasping force (two coupled normal forces created by the thumb and the virtual finger) can act as the internal force during multi-digit prehension task. The virtual finger (VF) acts as a functional unit to produce the same mechanical effects as combined forces and moment by all four fingers. Thus, VF force is the vector sum of all four fingers. In terms of tangential force, coupled tangential force can be created by any two fingers and can act as the internal forces.

Manipulation force

In prehension tasks, normal finger force is defined as the grasping force produced through moment in the direction of pronation or supination, since the finger forces themselves do not pass through the center of mass (COM) of the object. This moment is called a secondary moment. The previous studies (Li, Latash, & Zatsiorsky, 1998; Zatsiorsky et al., 2000b) reported that the CNS tried to minimize the secondary movement in the pressing task. This phenomenon is described as the principle of minimization of the secondary movement. This principle can give an additional constraint on the system so that remaining DOFs in need of control are decreased. The validity of the principle of minimization of the secondary moment in prehension tasks has not been investigated yet.

Tangential force is acting in parallel to the contacted surface. Tangential force contributes to manipulation force as a force component that compensates for the weight of the object or generates the movement. The sharing pattern of tangential finger forces is not associated with the load magnitude, but with the load direction (Pataky et al., 2004a, 2004b).

Force couple system in grasping

In the prehension task, there is the thumb and VF normal force couple (i.e. two equal and opposite forces, but not along the same line, that generate a moment). In the free object prehension tasks, the line of action of the VF normal force is not collinear with the line of action of the thumb normal force so that the VF and the thumb normal forces are equal and opposite resulting in a force couple that generates rotational effects. It is known from mechanics that an arbitrary set of forces acting on a rigid body can be reduced to a wrench, a resultant force and a corresponding force couple. A force couple generates a moment (i.e., free moment) about any axis that is not in the plane of the couple. Since the moment of the couple depends only on the distance between the forces, the moment is a "free vector". It can be applied at any point on the body, and have the same external effects on the body. Thus the resultant moment about a fixed axis (M) is obtained by the sum of the moment of force and the free moment (i.e., $\vec{M} = \vec{M}_{free} + \vec{d} \times \vec{F}$ where d is the moment arm of force $\vec{F}$). In many practical situations, free moment Mfree is generated by pronation or supination efforts of the hand, while the moment of force $(\vec{d} \times \vec{F})$ is due to pushing the object in a certain direction. The moment arm of the normal VF can be computed from the Varignon theorem (Eq. 1).

$$D_{vf}^{n} = \sum F_{f}^{n} d_{f} / \sum F_{f}^{n} \tag{1}$$

According to the varignon theorem, the distributive property of vector products can be used to determine the moment of the resultant of several concurrent forces.

2.3.2. Equilibrium state in grasping

For an object to be at rest in multi-digit prehension (i.e., static equilibrium), the vector sum of all force and the vector sum of all moments acting on the system should be equal to zero. The sum of the individual digits force along each axis should be equal to zero and the total moment of digit force (Eq. 2) and external force should be equal to zero (Eq. 3).

$$\sum_{p=1}^{n} \vec{F}_{p} = [0,0,0]^{T} \tag{2}$$

$$\sum_{p=1}^{n} (\vec{M} + \vec{T}) = [0,0,0]^{T} \tag{3}$$

If the external load creates the moment about Z-axis, the following condition should be satisfied.

$$\sum_{q=1}^{5}\vec{M}_q = \vec{M}^{vf} + \vec{M}^{th} + \vec{m}^{(C)} + \vec{m} + T\vec{q}$$

$$= [M_X^{th(Y)} + M_X^{vf(Y)} + M_X^{vf(Z)}, M_Y^{th(X)} + M_Y^{vf(X)} + M_Y^{vf(Z)}, M_Z^{vf(X)} + M_Z^{vf(Y)} + m_Z^{vf(C)} + m_Z^{th} + m_Z^{vf} + Ta]^T$$

or

$$M_x = \sum_k (d_Y^k F_Z^k - d_Z^k F_Y^K) = 0$$

$$M_Y = \sum_k (d_Z^k F_X - d_X^k F_Z^k) = 0$$

$$M_Z = \sum_k (m_z^k + d_X^k F_Y^k - d_Y^k F_X^k) = m_Z^{th} + m_Z^{vf} + m_Z^{vf(C)} + M_Z^{vf(X)} + M_Z^{vf(Y)} = -Tq$$

, where subscript *T* stands for vector transpose. *M* and *m*, respectively, represent a moment of force and a free moment. The subscripts *x*, *y* and *z* signify the moment axes, and the superscripts *vf* and *th* stand for the virtual finger and the thumb, respectively. $\vec{T}$ is an external moment generated by geometrical position of the center of mass of the system where the gravitational acceleration is acting on. The VF force generates a moment of force about any axis. The VF force also produces a free moment on the object. The total moment produced by digit forces and digit local free moment about the Z-axis has four sources (Fig. 2.3a).

1) Local free moment of thumb and fingers (Fig. 2.3b-A)

2) Moment of a VF-couple in the X-Y plane. This is generated by non-collinear individual finger force. For example, index and little finger can generate opposite force along the X-axis and Y-axis (Fig. 2.3b-B).

3) Moment of the VF tangential horizontal force (Fig. 2.3b-B)

4) Moment of the VF tangential vertical force (Fig. 2.3b-D)

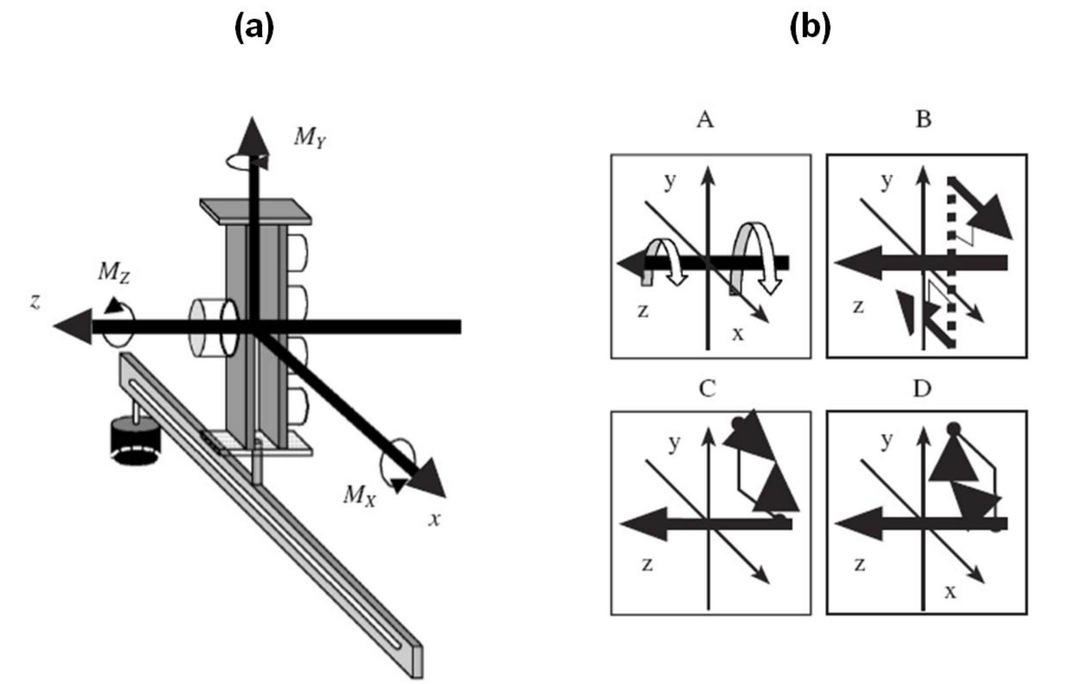


Figure 2.3. **(a)** Experimental setup and **(b)** four source of the total moment by digits about z-axis (Shim, Latash, & Zatsiorsky, 2005a). This figure is used with permission.

2.3.3. Multi-link serial chain in human hand system

Statics deal with the balance of forces and torques required when the object does not move. In two-dimensional coordinate system, the degree of freedom (DOF) of an arbitrary force at the tip of device is two. Controlling the torque applied to the object would add an additional DOF. In terms of the three links chain, the DOF of the system is three, which is larger than the required DOF (two). This means that it is possible to control the torque. In dynamics, the joint torque control is associated with the angular accelerations of the link and the given joint torque varies with the link configuration determined by the joint angles. In statics, the torques and forces used to accelerate the links can be ignored.

The equilibrium condition should satisfy the following conditions. Firstly, resultant force and resultant couple should be equal to or close to zero. Secondly, equilibrating torque is generated as a resistive action when the external end point force is applied to the system.

End point force and joint moment

The analysis is based on the stick-figure model, which represents the body segment as rigid links with ideal revolute joints. The general assumption of the kinematic chain system is that the joints are assumed to be ideal (i.e., frictionless, and no gravity effect). The purpose this process is to calculate the equilibrating torques applied at specific joints which are serially connected. These joints are the metacarpophalangeal (MCP), proximial interphalaengial (PIP), and distal interphalangeal (DIP) joint. A kinematic chain (transformation analysis) can be created to calculate the end-point force or joint torques. If an external end-point force is given and the task is to obtain the joint torques, the mathematical process of calculating each joint torque is called inverse static analysis. Two methods have been developed: the link-isolation method and Jacobian method. The relationship between the joint torques and the force and moment at the end effector is given by

$$T = J^T \vec{F}$$

, where T is a N by 1 vector of the joint torques and J^T is a N by 6 transposed Jacobian matrix obtained by the partial derivatives of the endpoint displacement with respect to the joint displacement. This means that infinitesimal joint displacements $d\alpha$ of infinitesimal end-point displacement dP. In other words, the Jacobian matrix represents the moment arms of the external force F with respect to the individual joint (i.e., F is projected on the plane *X-Y* in two-dimensional planar analysis). F is a 6 by 1 vector of the force and moment at the end effector, and N is the number of joints. The purpose of inverse static is to find joint torques that exactly balance forces in the static situation. When forces act on a mechanism, the work is done if the mechanism moves through a displacement. The principle of virtual work allows us to make certain statements about the static case by allowing the amount of this displacement to go to the infinitesimal. Virtual displacement is a small hypothetical displacement of a body or system, which presumably disturbs the equilibrium of the system. Virtual work, then, is the work done by a force over a virtual displacement (Zatsiorsky, 2002).

Work has units of energy, and it must be the same measured in any set of generalized coordinates. Specifically, we can equate the work done in Cartesian terms with the work done in joint space terms. Because of this, the following equation should be satisfied (i.e., the virtual work is equal to zero).

$$\vec{F}\delta P = T\delta\alpha$$

is a 6x1 Cartesian force-moment vector acting at the end effector, δP is a 6x1 Cartesian displacement of the end effector, τ is a 6x1 vector of torques at the joints, and $\delta\alpha$ is a 6x1 vector of infinitesimal joint displacements. $\vec{F}$ is a Cartesian forces and moment, and δP is a vector of Cartesian end-point displacement. *T* is a vector of individual joint torques, and $\delta\alpha$ is an infinitesimal joint displacement. If we use a three-link planar chain to represent the configurations of finger in a given coordinate system (Fig.2.4), the equation of the balanced force and torques (Fig.2.4) for each link in static state are as follows. The vector $\vec{F}$ is given either in the global reference system (GRS) or local reference system (LRS). If $\vec{F}$ is expressed in GRS then the following equation can be applied. If $\vec{F}$ is expressed in LRS, the transportation matrix should be added on the equation.

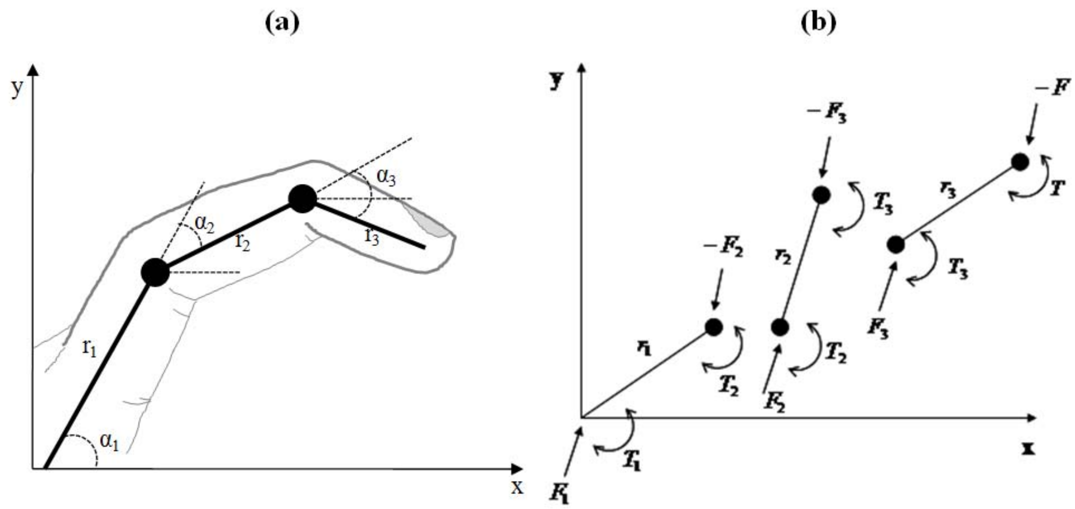


Figure 2.4. Two dimensional model of three-link chain in human finger

$$\vec{F} = \vec{F}_1 = \vec{F}_2 = \vec{F}_3$$
$$T_3 = T + \vec{r}_3 \times \vec{F}$$
$$T_2 = T_3 + \vec{r}_2 \times \vec{F}_3$$
$$T_1 = T_2 + \vec{r}_1 \times \vec{F}_2$$
$$T_1 = T + (\vec{r}_1 + \vec{r}_2 + \vec{r}_3) \times \vec{F}$$
$$T_2 = T + (\vec{r}_2 + \vec{r}_3) \times \vec{F}$$
$$T_3 = T + (\vec{r}_3) \times \vec{F}$$

The vectors of the moment arm for individual links are

$$\vec{r}_1 = \begin{bmatrix} l_1 C_1 & l_1 S_1 \end{bmatrix}$$
$$\vec{r}_2 = \begin{bmatrix} l_2 C_{12} & l_2 S_{12} \end{bmatrix}$$
$$\vec{r}_3 = \begin{bmatrix} l_3 C_{123} & l_3 S_{123} \end{bmatrix}$$

α is a joint angle. For example, in $\sin\alpha_{12} = \sin(\alpha_1 + \alpha_2)$, $\sin\alpha_{12}$ represents the 2nd segment angle.

$$T_1 = (l_1C_1 + l_2C_{12} + l_3C_{123}) \cdot F_y - (l_1S_1 + l_2S_{12} + l_3S_{123}) \cdot F_x + T$$

$$T_2 = (l_2C_{12} + l_3C_{123}) \cdot F_y - (l_2S_{12} + l_3S_{123}) \cdot F_x + T$$

$$T_3 = (l_3C_{123}) \cdot F_y - (l_3S_{123}) \cdot F_x + T$$

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \begin{bmatrix} -(l_1S_1 + l_2S_{12} + l_3S_{123}) & (l_1C_1 + l_2C_{12} + l_3C_{123}) & 1 \\ -(l_2S_{12} + l_3S_{123}) & (l_2C_{12} + l_3C_{123}) & 1 \\ -(l_3S_{123}) & (l_3C_{123}) & 1 \end{bmatrix} \cdot \begin{bmatrix} F_x \\ F_y \\ T \end{bmatrix}$$

T is the external couple moment. Now, the matrix contains three linear equations with three unknown variables. Gaussian elimination is an efficient algorithm for solving systems of linear equations. Therefore, the transpose of the Jacobian matrix for a planar three link kinematic chain is

$$\begin{bmatrix} -(l_1S_1 + l_2S_{12} + l_3S_{123}) & (l_1C_1 + l_2C_{12} + l_3C_{123}) & 1 \\ -(l_2S_{12} + l_3S_{123}) & (l_2C_{12} + l_3C_{123}) & 1 \\ -(l_3S_{123}) & (l_3C_{123}) & 1 \end{bmatrix}$$

If an external force applied to the end-point is given, the individual joint torques can always be calculated (i.e., three unknown and three equations). In order to calculate the end-point force and couple with given individual joint-torques, the following equation is necessary:

$$(J^T)^{-1} \cdot T = (J^T)^{-1} \cdot J^T \cdot \vec{F}$$

$(J^T)^{-1}$ is the inverse matrix of the Jacobian transpose. This process is only possible when the Jacobian matrix is not singular. In other words, if the determinant of the Jacobian matrix is zero, then the direct static process is not possible. For the three-link kinematic chain analysis, the determinant of the Jacobian matrix is $-l_1l_2S_1$.

This implies that the direct solution would not be possible in cases when the 2nd segment angle is either 0 or π. The unique combination of individual joint torques with a given external end-point force and couple could be obtained, while an unique combination of external force with the given set of individual joints torques is not possible. This implies that many different combinations of joint torques (i.e., link configurations) can be formulated with the same external end-point force and coupled in the direct static analysis.

In addition, if the external force is given in the local reference system (LRS), the rotation matrix should be added in the equation. The equation including the rotation matrix is

$$T = J^T \cdot R \cdot \vec{F}$$

, and the rotation matrix in three-dimensional space is

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ Lx & \cos_{Xx} & \cos_{Xy} & \cos_{Xz} \\ L_Y & \cos_{Yx} & \cos_{Yy} & \cos_{Yz} \\ L_Z & \cos_{Zx} & \cos_{Zy} & \cos_{Zz} \end{bmatrix}$$

2.3. Prehension control

2.4.1. Hierarchical organization in human hand prehension

The hierarchical control (i.e., the control of reflexes without higher control centers) offers a very attractive concept to the idea of motor synergy. That is, if the controller governs only certain characteristic of a motor action, other characteristics may be only a secondary consideration. For example, the end-point position can be considered primary consideration as an important performance variable during a multi-joint coordination task. According to the concept of hierarchy control, then, the individual joints (i.e., joint or segment angle trajectories) are secondary considerations, meaning that a higher hierarchical level (i.e., the end point position trajectories) does not specify the unique combination of the lower level variables (i.e., individual joint angle) in the redundant system. The previous studies reported that particular lower level trajectories can be decided by the feedback mechanism (Todorov & Jordan, 2002) or a feedforward mechanism (Goodman & Latash, 2006). Todorov and Jordan proposed optimal feedback control. The optimal strategy in the face of uncertainty is to allow variability in redundant (task-irrelevant) dimension. This does not enforce the desired trajectory instead uses feedback more intelligently, correcting only those deviations of variables that interfere with task goals. Goodman and Latash described a model of feed-forward control of redundant motor system (multi-finger pressing task). Their results showed that changes in the two indices of variance prior to the force pulse production may lead to an anticipatory drop in the synergy index. Tonic-stretch reflex is an example of a feedback system that produces co-variation among individual motor units (this is a physiological feedback). Thus, the hierarchical control scheme supports the control structure of motor synergy as well as provides possible solution for DOF problem by dividing control levels hierarchically.

Previous theoretical studies (Cutkosky & Howe, 1990; Iberall, 1997; Yoshikawa, 1999) as well as experimental studies on hand and finger actions (Baud-Bovy & Soechting, 2001; Santello & Soechting, 1997; Shim et al., 2003b, 2005b) have suggested a hierarchical control of multi-digit prehension based on the notions of the VF and IF, i.e., at the higher level (VF level) the thumb and VF are coordinated to satisfy task mechanics whereas at the lower level (IF level) the individual fingers are coordinated to generate a desired task-specific outcome of the virtual finger during multi-digit manipulation tasks. Previous studies on multi-digit pressing (Li et al., 1998; Shinohara, Li, Kang, Zatsiorsky, & Latash, 2003) and all-digit rectangular object prehension (Shim, Lay, Zatsiorsky, & Latash, 2004; Shim, Olafsdottir, Latash, & Zatsiorsky, 2005; Shim, Park, Zatsiorsky, & Latash, 2006a) used the indices of covariation (ΔVar and ΔVar_{norm}; these variables are similar to negated covariations between elemental variables; see Methods for computational details) between finger forces and moments of force, and showed that the CNS makes fine adjustments of IF forces/moments at the lower level to stabilize VF forces/moments at the higher level. Both multi-digit pressing and multi-digit prehension of a rectangular object offer parallel actions of fingers. Therefore, it is currently unknown whether the hierarchical control hypothesis is valid for other multi-digit manipulation tasks, especially for a task encouraging non-parallel actions of fingers such as multi-digit prehension of a circular object.

2.4.2. Principle of superposition

According to the principle of superposition, originally suggested in robotics (Arimoto & Nguyen, 2001; Arimoto, Tahara, Yamaguchi, Nguyen, & Han, 2001), skilled actions can be decoupled into a few sub-actions (i.e., stable grasping and regulating the posture and the position of the object). Arimoto et al. (2000) configured the mathematical model of soft finger tip by using two effectors (i.e., pinch grip) (Arimoto, Nguyen, Han, & Doulgeri, 2000). They found that the overall control inputs can be designed by linear superposition and the net results is caused by two or more independent phenomena. In other words, each individual phenomenon is independent and the behavior of linear physical system can be performed by combining the separate behavioral components (i.e., grasping and object orientation) to satisfy the stable grasping task. The previous studies revealed that the principle of superposition was valid in the human hand grasping task (Shim et al., 2005b; Zatsiorsky et al., 2004). The validity of principle of superposition in human hand grasping was supported by the virtual finger level analysis. It has been hypothesized and tested that there is a hierarchy between individual finger level and virtual finger level. The higher level (VF level) the thumb and VF are coordinated to satisfy task mechanics whereas at the lower level (IF level) the individual fingers are coordinated to generate a desired task-specific outcome of the virtual finger during multi-digit manipulation tasks. The previous studies tested and confirmed the validity of principle of superposition in human hand prehension, but the geometry of hand-held object was limited to a 'rectangular/parallelepiped shape' which necessitates the coupling of grasping forces (e.g., the grasping forces of a thumb and fingers should cancel out to be zero) and the coupling of load forces and moments of forces (e.g., the sum of the load forces of all digits should cancel out the weight of a grasping object).

Due to the pre-imposed relationship between the mechanical variables during prehension of a rectangular object, the generalizability of the principle of superposition is currently questionable for prehension of objects in systematically manipulated conditions of constraints and in other geometric shapes, which do necessitate the coupling of mechanical variables.

Chapter 3: Prehension synergy: Principle of Superposition and hierarchical organization in a circular object prehension

Chapter 3 contains the following original paper reprinted by the permission from Springer Science + Business Media: Jae Kun Shim, **Jaebum Park** (2007) Prehension synergies: Principle of superposition and hierarchical organization in a circular object prehension. ***Experimental Brain Research***, 180: 445-450

3.1. Abstract

This study tests the following hypotheses in multi-digit circular object prehension: the principle of superposition (i.e., a complex action can be decomposed into independently controlled sub-actions) and the hierarchical organization (i.e., individual fingers at the lower level are coordinated to generate a desired task-specific outcome of the virtual finger at the higher level). Subjects performed 25 trials while statically holding a circular handle instrumented with five six-component force/moment sensors under seven external torque conditions. We performed a principal component (PC) analysis on forces and moments of the thumb and virtual finger (VF: an imagined finger producing the same mechanical effects of all finger forces and moments combined) to test the applicability of the principle of superposition in a circular object prehension. The synergy indices, measuring synergic actions of the individual finger (IF) moments for the stabilization of the VF moment, were calculated to test the hierarchical organization. Mixed-effect ANOVAs were used to test the dependent variable differences for different external torque conditions and different fingers at the VF and IF levels. The PC analysis showed that

the elemental variables were decoupled into two groups: one group related to grasping stability control (normal force control) and the other group associated with rotational equilibrium control (tangential force control), which supports the principle of superposition. The synergy indices were always positive, suggesting error compensations between IF moments for the VF moment stabilization, which confirms the hierarchical organization of multi-digit prehension.

3.2. Introduction

Everyday motor tasks demand the central nervous system (CNS) to be capable of coordinating multiple effectors involved in achieving the task objectives. This often requires the CNS to govern more effectors than are minimally necessary. This problem has been known as the ‘motor redundancy/abundance’ (Bernstein, 1935, 1967; Latash, 2000; Turvey, 1990). Multi-digit prehension is performed by a kinetically redundant system, e.g., there are typically more digits involved in the process of turning a door knob or holding a glass of water than the two digits which are minimally required. The redundant hand system allows an infinite number of solutions for a same prehension task (Santello & Soechting, 2000; Shim et al., 2005b, 2006a; Zatsiorsky, Gao, & Latash, 2003b). Thus, the central nervous system (CNS) needs to decide what specific solution(s) of forces and moments of force to be used to solve the redundancy problem. Previous studies have suggested that the CNS solves the problem of motor redundancy not by having one specific solution but by allowing a family of solutions that satisfy task requirements (d'Avella, Saltiel, & Bizzi, 2003;

Gelfand & Tsetlin, 1966; Latash, Olafsdottir, Shim, & Zatsiorsky, 2005; Scholz & Schoner, 1999; Shim et al., 2004, 2005).

Recent studies on multi-digit prehension of rectangular objects employed trial-to-trial variability analysis and provided evidences of two independent groups of mechanical variables in static prehension (Shim et al., 2003b, 2005b; Zatsiorsky et al., 2004): one group contains grasping forces (normal forces) that are related to the "stability of grasping" and the other group includes load forces (tangential forces) and moments of normal and tangential forces that are associated with the "rotational equilibrium" of the hand-held object. This claim was made by showing coupling of variables in each group and decoupling of variables between the two groups. This type of decoupled control was first suggested in robotics and called the 'principle of superposition' (Arimoto & Nguyen, 2001; Arimoto et al., 2001; Doulgeri, Fasoulas, & Arimoto, 2002). According to the principle of superposition, some sub-actions (e.g., grasping a hand-held object and rotating the object) can be controlled by independent control processes and the total processing/computation time can be reduced by employing this strategy. The present context of grasping stability has been limited to slip prevention.

Although previous experiments showed that the principle of superposition was also supported in static human prehension (Shim et al., 2003b, 2005b; Zatsiorsky et al., 2004), the geometry of the hand-held objects used in the previous experiments was limited to a 'rectangular/parallelepiped shape' which necessitates the coupling of grasping forces (e.g., the grasping forces of a thumb and fingers should cancel out to be zero) and the coupling of load forces and moments of forces (e.g., the sum of the load forces of all digits should cancel out the weight of a grasping object). Due to the pre-imposed relationship between the mechanical variables during prehension of a rectangular object, the generalizability of the principle of superposition is currently questionable for prehension of objects in other geometric shapes which do necessitate the coupling of mechanical variables. Here an interesting question arises. Will the principle of superposition still be valid when grasping force of the thumb (e.g., the thumb normal force) and the grasping force of individual fingers (e.g., the sum of individual finger normal forces) are not mechanically coupled?

In this study we used a circular object to study the generalizability of the principle of superposition because prehension of a circular object presents a geometry in which the scalar sum of the individual finger (IF) normal forces (defined as the virtual finger (VF) normal force) is not necessarily required to be the same as the thumb normal force. In prehension of a circular object, therefore, it is not clear whether the thumb and VF normal forces would even form a group of coupled variables. If the CNS controls the thumb and VF normal forces using one command regardless of the geometry of the hand-held objects, we may expect to find a coupling of thumb and VF normal forces and a decoupling of normal and tangential forces during circular object prehension, thus supporting the generalizability of the principle of superposition in a circular object prehension.

Previous theoretical studies (Cutkosky & Howe, 1990; Iberall, 1997; Yoshikawa, 1999) as well as experimental studies on hand and finger actions (Baud-Bovy & Soechting, 2001; Santello & Soechting, 1997; Shim, Latash, & Zatsiorsky, 2003b; Shim et al., 2005b) have suggested a hierarchical control of multi-digit prehension based on the notions of the VF and IF, i.e., at the higher level (VF level) the thumb and VF are coordinated to satisfy task mechanics whereas at the lower level (IF level) the individual fingers are coordinated to generate a desired task-specific outcome of the virtual finger during multi-digit manipulation tasks. Previous studies on multi-digit pressing (Li et al., 1998; Shinohara et al., 2003) and all-digit rectangular object prehension (Shim et al., 2004, 2005, 2006a) used the indices of covariation (ΔVar and ΔVar_{norm}; these variables are similar to negated covariations between elemental variables; see Methods for computational details) between finger forces and moments of force, and showed that the CNS makes fine adjustments of IF forces/moments at the lower level to stabilize VF forces/moments at the higher level. Both multi-digit pressing and multi-digit prehension of a rectangular object offer parallel actions of fingers. Therefore, it is currently unknown whether the hierarchical control hypothesis is valid for other multi-digit manipulation tasks, especially for a task encouraging non-parallel actions of fingers such as multi-digit prehension of a circular object.

We asked subjects to statically hold a circular handle multiple times under systematically varied external torques and recorded forces and moments of force at each digit contact. Although the terms ‘torque’ and ‘moment of force’ are used interchangeably in mechanics, in this paper we will use ‘torque’ to designate the external torque (the rotational force externally imposed by locating a load at different positions; see Methods for details) and use ‘moment of force’ or ‘moment’ to signify a rotational force produced by a subject to overcome the external torque during static prehension. We analyzed intra-subject trial-to-trial variability of forces and moments of force produced by hand digits. This approach is based on the idea that the CNS prefers a family of solutions rather than one specific solution for a redundant motor task. Thus, studying a family of solutions recorded from multiple trials for the same motor task may reveal the strategies used by the CNS to resolve the motor redundancy. The previous work as well as the theoretical position, which support the idea that the strategies utilized by the CNS in multi-digit grasping should be invariant to tasks, leads the hypothesis that the principle of superposition and the hierarchical organization of multi-digit control are also valid in circular object prehension task.

3.3. Method

3.3.1. Subject

Eight right-handed males participated in this study as subjects (age: 27.3 ± 2.7 years, weight: 70.9 ± 3.8, height: 177.2 ± 5.1 cm, hand length: 20.1 ± 2.2 cm, and hand width: 9.0 ± 2.7). The hand lengths were measured between the distal crease of the wrist and the middle finger tip when a subject positioned the palm side of the right hand and the lower arm on a table with all finger joints extended. The hand width was measured between the radial side of the index finger metacarpal joint and the ulnar side of the little finger metacarpal joint. All subjects gave informed consent according to the protocol approved by the University of Maryland after the purpose and the involved experimental procedures of the study were explained to them.

3.3.1. Equipment

Five six-component sensors (Nano-17, ATI Industrial Automation, Garner, NC) were attached to a circular aluminum handle to which an aluminum beam (3.8 x 52.0 x 0.6 cm) was fixed (Fig. 3.1a). The recorded angular positions of the digits from the wooden circular object prehension were used to specify the angular positions of five force sensors. The sensors were aligned in the X-Y plane (a vertical plane). Aluminum caps were attached to the surface of each sensor. The bottom of the cap was flat and mounted on the surface of a sensor while the top part was round (the curvature k = 0.22 cm–1) to accommodate the curvature of the circle shown as a dotted circle in Figure 1A. Sandpaper [100-grit; static friction coefficients between the digit tip and the contact surface was 1.5; measured previously (Zatsiorsky et al., 2002)] was placed on the round contact surface of each cap to increase the friction between the digits and the caps. The radius (r_o^l) between the centre of the circular handle (OG) and the contact surface was 4.5 cm for each sensor. The force components along the three orthogonal axes and three moment components about the three axes in the local reference system (LRS) for each sensor were recorded (Fig. 3.1b). A load (0.41 kg) was attached to the beam with an eyehook that could be positioned at seven different positions of the long beam with 10 cm intervals between adjacent positions. Positioning the weight at different positions produced different external torques on the handle system about the Z-axis (see the caption for Fig. 3.1). A plastic bubble level (Hi Vis Line Level, Stanley Tools, New Britain, CT) was positioned at the center of the horizontal beam so that subjects could monitor the consistent angular position of the handle and beam (Shim et al., 2003b). The total weight of the system, which consisted of the circular handle, beam, transducer, and suspended load, was 14.9 N. A total of 30 analogue signals from the sensors were routed to two synchronized 12-bit analogue-digital converters (PCI-6031 and PCI-6033, National Instrument, Austin, TX) and processed and saved in a customized LabVIEW program (LabVIEW 7.1, National Instrument, Austin, TX) on a desktop computer (Dell Dimension E510, Austin, TX). The sampling frequency was set at 50 Hz.

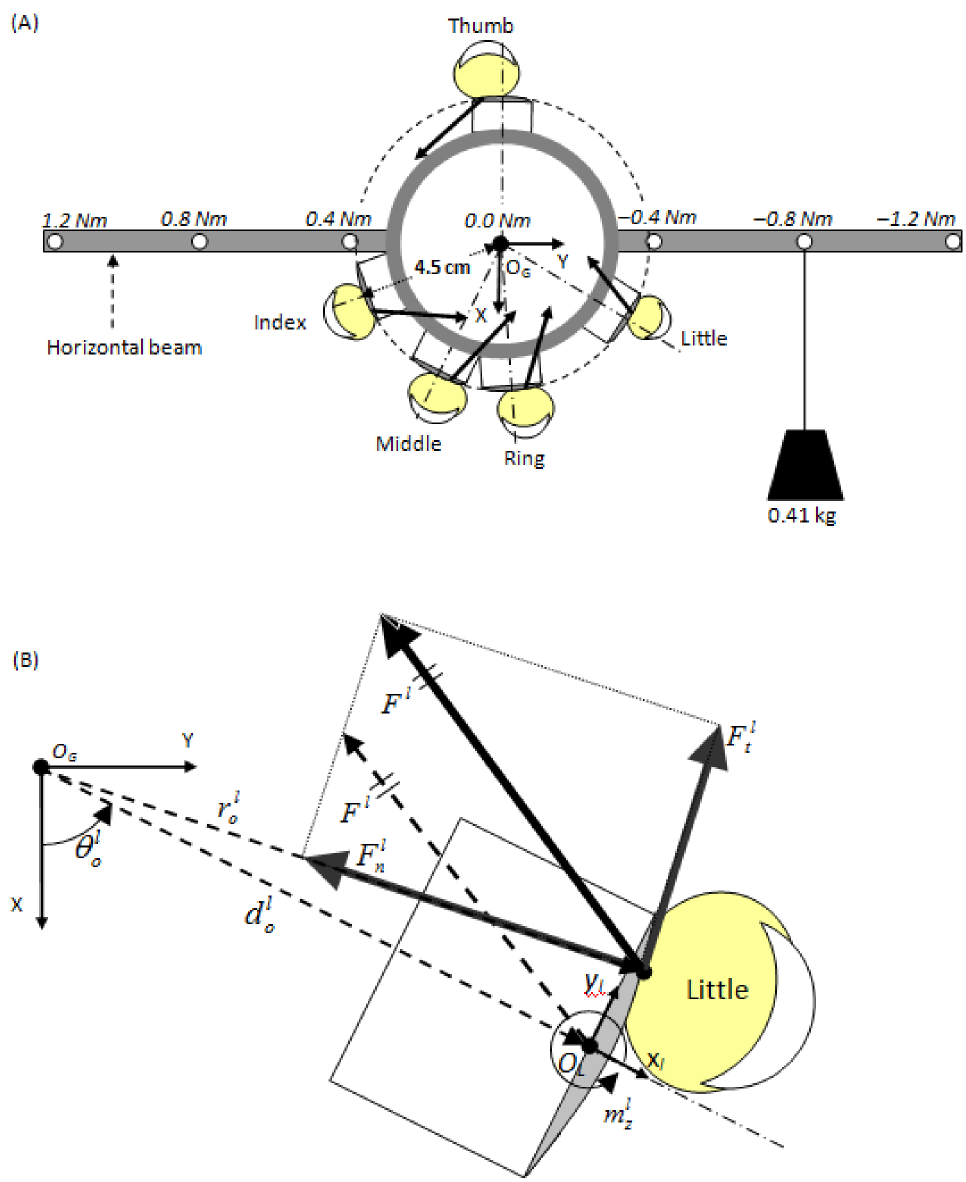


Figure 3.1. **(a)** Schematic illustration of an aluminum handle (gray circle with a large hollow inside) and six-component sensors (white rectangles) at digit contacts and **(b)** detailed schematic illustration of the little finger producing a force at a contact. O_G: origin of the global reference system of coordinates (GRS), X: X-axis in GRS, Y: Y-axis in GRS (Z-axis is not shown, but its direction follows the right-handed coordinate system and its positive direction is from paper to the reader), O_L: origin of local reference system of coordinates (LRS) of the little finger sensor, x_l: x-axis in LRS of little finger sensor, y_l: y-axis in LRS of the little finger sensor, m_z^l: moment about z-axis in LRS of little finger sensor (z-axis in LRS for each sensor is parallel to Z-axes in GRS), F^l: little finger force, F_n^l: little finger normal force, F_t^l: little finger tangential force, d_o^l: position of LRS origin in GRS, r_o^l: position of little finger centre of pressure (CoP) in GRS, θ_o^l: angular position of d_o^l in GRS. The LRS origin (O_L) was fixed to the center of the contact surface of the sensor and a cap (shown gray) was fixed on the sensor surface. The distance between the apex of the cap and O_L was ~ 0.81 mm. External torques were systematically changed by hanging the load at different positions along the horizontal beam. (B) shows –0.8 Nm external torque condition. The figures are not drawn to scale.

3.3.3. Experimental procedures

The subjects washed their hands with soap and warm water to normalize the skin condition. The subjects were asked to hold a wooden circular handle (radius = 4.5 cm; the same size as the experimental handle used for force and moment recording) and the relative finger positions with respect to the thumb position were measured (index: 109.0º±12.6º, middle: 156.3º±11.2º, ring: 187.0º±8.2º, and little: 240.8º±15.4º; Mean±SD across subjects are presented). The subjects had a pre-testing session (two trials for each external torque condition) to be familiarized with the experimental procedure and testing-device. During the trials, the subjects sat in a chair and positioned their right upper arm on a wrist-forearm brace that was fixed to a table. The forearm was held stationary with Velcro straps. The upper arm was flexed 20° in the sagittal plane and the forearm was aligned parallel to the sagittal axis of the subject. For each trial, the subjects placed each digit on each six-component sensor and held the circular handle with the thumb at the top (Fig. 3.1a). The task for the subjects was to hold the handle with minimum effort while keeping the horizontal beam parallel to the transverse plane and maintaining the handle system in equilibrium. The task was achieved by monitoring and maintaining a bubble at the center of the bubble level (Shim, et al., 2003b). The 0.41 kg load was located at seven different positions along the horizontal beam to create seven different external toques about Z-axis (i.e., –1.2, –0.8, –0.4, 0, 0.4, 0.8, 1.2 Nm). The positive and negative torques required subjects to generate pronation and supination efforts, respectively. The pronation and supination efforts are respectively compatible to opening and closing efforts for a door knob and a jar cap in everyday circular object manipulations. To help the subjects achieve a stable trial-to-trial performance, the forearm, wrist, and hand positions were fixed and checked before every trial. In addition, the subjects were instructed to hold the circular handle exerting minimal force while placing the fingertip centers at the center of the sensor caps. Hyperextended joint configurations were not allowed for any phalangeal joints of the hand. Each subject performed twenty-five trials for each external torque condition. There were a total of 175 trials for each subject. Data recording started when a subject announced comfortable holding of the handle. Before each trial, all signals from 30 channels were zeroed. The sampling frequency was 50Hz and each trial was recorded for 6-s. A rest interval was given to the subject between trials and torque conditions to minimize fatigue. The minimum rest interval between trials and between torque conditions were 10-s and 5 min, respectively. The order of the external torque conditions was randomized and balanced.

3.3.4. Data analysis

The recorded force and moment data were averaged over the second half of the 6-s period for each trial for the following analysis. We analyzed normal and tangential forces in the X-Y plane and moments of tangential forces orthogonal to the plane. Since sticking a digit tip to the contact surface was not possible in this experiment [so-called ‘soft contact model’ (Arimoto et al., 2001; Mason & Salisbury, 1985; Nguyen & Arimoto, 2002; Shimoga & Goldenberg, 1996)], a free moment (Shim et al., 2005a, 2005b; Zatsiorsky, 2002) about the direction of a normal force was possible only due to the friction between the digit tip and the contact surface. However, we did not consider this component because it did not contribute to the task moment about the Z-axis and the magnitude of this component recorded was ignorable. The moment produced by each digit about the Z-axis could be expressed as the sum of the moment produced by the force along the y-axis in LRS (F_y^j; directly recorded from the sensor) and moment about the z-axis at the center of the sensor surface (m_z^j) (Eq. 1). In the present experiment, the digits were not in direct contact with the sensors, but rather in contact with the sensor caps. The moment m_z^j is due to the distance from the LRS origin (OL) where m_z^j was measured to the point on the sensor cap where the digit force was applied.

The force components measured in the LRS origin (OL) were converted into the components in GRS using the direction cosines (Eq. 2). These components and the moment values about the Z-axis in GRS (M_Z^j) computed from Equation 1 were then used to compute the tangential force components (F_t^j) at the digit contact on the cap (Eq. 3). The normal force component was calculated from Equation 3. Note that the force measured at the LRS origin is equivalent to the force produced by the digit in terms of its magnitude and direction.

$$M_Z^j = m_z^j + d_o^j \times F_y^j \,,\; j = \{thumb, index, middle, ring, little\} \tag{1}$$

$$\begin{bmatrix} F_X^j \\ F_Y^j \end{bmatrix} = \begin{bmatrix} \cos\theta_o^j & -\sin\theta_o^j \\ \sin\theta_o^j & \cos\theta_o^j \end{bmatrix} \begin{bmatrix} F_x^j \\ F_y^j \end{bmatrix},\; j = \{thumb, index, middle, ring, little\} \tag{2}$$

$$F_t^j = M_Z^j / r_o^l$$

$$\text{and}\, F_n^j = \sqrt{(F_X^j)^2 + (F_Y^j)^2 - (F_t^j)^2} \,,\; j = \{thumb, index, middle, ring, little\} \tag{3}$$

VF normal and tangential forces (F_n^{vf} and F_t^{vf}) were calculated, respectively, as the sum of IF (index, middle, ring, and little) normal forces and the sum of IF tangential forces (Eq. 4). Note that the VF normal and tangential forces calculated in Eq. 4 are scalars. The IF normal forces or VF normal force do not produce a moment of force about the axis of rotation (OG) because all IF normal forces pass through the axis of rotation and have zero moment arms (Eq. 5). VF normal and tangential forces are the sums of normal forces (i.e., grasping forces) and tangential forces (i.e., forces causing moments of force about OG) of IF in each LRS, respectively. Hence, VF normal and tangential forces are not horizontal (Y-axis) and vertical (X-axis) forces in GRS because each axis in LRS is not parallel to the corresponding axis in GRS except Z-axis.

$$\begin{bmatrix} F_n^{vf} \\ F_t^{vf} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{4} F_n^{j} \\ \sum_{j=1}^{4} F_t^{j} \end{bmatrix}, \; j = \{index, middle, ring, little\} \quad (4)$$

$$M_Z = M_Z^{th} + M_Z^{vf} = r_o \times F_t^{th} + r_o \times F_t^{vf} = -T, \; T \text{ represents an external torque} \quad (5)$$

For the 25 trials for each external torque condition, the variances of IF moments (Var_j , $j = \{index, middle, ring, little\}$) and the variance of the VF moment (Var_{tot}) were computed across 25 trials for each external torque condition and each subject. The sum of the variances of IF moments ($\sum_{j=1}^{4} Var_j$) was also computed across the trials. For further analysis, the difference between $\sum_{j=1}^{4} Var_j$ and Var_{tot} was computed (Eq. 6) and normalized by $\sum_{j=1}^{4} Var_j$ (Eq. 7) .

$$\Delta Var = \sum_{j=1}^{4} Var_j - Var_{tot}, \; j = \{index, middle, ring, little\} \quad (6)$$

$$\Delta Var_{norm} = \left[\sum_{j=1}^{4} Var_j - Var_{tot} \right] \Big/ \sum_{j=1}^{4} Var_j, \; j = \{index, middle, ring, little\} \quad (7)$$

Note, when $\Delta Var > 0$ and $\Delta Var_{norm} > 0$, negative covariations among the individual finger moments dominate, whereas when $\Delta Var < 0$ and $\Delta Var_{norm} < 0$, positive covariations among the individual finger moments prevail. These indices have been used as multi-digit synergy strength in previous studies to investigate covariation profiles between individual finger normal forces (Li et al., 1998; Shim, Latash, & Zatsiorsky, 2003a; Shim et al., 2004, 2005, 2006a; Shinohara et al., 2003, 2004). In this study, however, the indices are used to study synergic actions between individual finger tangential forces.

3.3.5. Statistics

Mixed-effect ANOVAs with the factors of EXTERNAL TORQUE (7 levels: –1.2 Nm, –0.8 Nm, –0.4 Nm, 0 Nm, 0.4 Nm, 0.8 Nm, and 1.2 Nm), THUMB-VF (2 levels: thumb and VF), and FINGER (4 levels: index, middle, ring, and little fingers) were used to investigate the differences of dependent variables between experimental conditions and fingers at different hierarchical levels.

Linear regression was used to characterize the relations of variables. Pearson coefficients of correlation (r) were computed and then corrected for noise and error propagations (Taylor, 1997) in MatLAB. The uncertainty or error affects the values of coefficients of correlation, i.e., the magnitudes of coefficients decrease with error propagations. The true coefficients of correlation, after the errors were eliminated, were computed [see Shim et al. (2003b) for computational details]. The true coefficients of correlation are usually larger in magnitude than the coefficients initially computed. In order to test the differences between two regression lines for negative and positive torque conditions, the slopes of the regression lines were statistically compared (Neter & Wasserman, 1974).

For each external torque condition, sets of variables at the VF level (thumb and VF normal and tangential forces) were grouped, and coefficients of correlation between the variables were computed and corrected for noise and error propagations. The corrected correlations were used to construct a correlation matrix. This matrix was used to perform a principal component analysis (PCA) with a variance maximizing (varimax) rotation in MatLAB. The eigenvectors with eigenvalues >1 (Kaiser Criterion) were extracted as principal components (PCs) (Kaiser, 1960) and the loading coefficients for each variable were calculated in the PCs. A customary cutoff loading coefficient of 0.4 was used as a minimal significant loading coefficient (Krishnamoorthy et al., 2003; Shim et al., 2005b).

3.4. Results

3.4.1. The Virtual Finger (VF) level

At the VF level of analysis, only the thumb and VF normal and tangential forces were considered, but the moments of normal and tangential forces were not included: moments of thumb and VF normal forces are always zero because the normal forces pass through the center of rotation (OG in Fig. 3.1a) and the moment arms are all zero. The moments of thumb and VF tangential forces were not included because of the perfect linear relationship between the moments and the forces [i.e., the moments of tangential forces are simply calculated by multiplying the constant moment arm (ro = 4.5 cm) and the tangential forces].

VR and thumb force changes with external torques

The normal force magnitudes of both VF and thumb increased systematically with the external torque magnitude (Fig. 3.2a). For each external torque condition, the VF normal forces were always larger than the thumb normal forces. This finding is expected from the circular geometry of the handle which causes the non-parallel normal forces of individual fingers. These findings were supported by two-way Repeated-measures ANOVA with the factors of EXTERNAL TORQUE and THUMB-VF, which showed the significant effects of EXTERNAL TORQUE [$F(6,42)=187.7$, $p<.001$], THUMB-VF [$F(1,7)=1133.5$, $p<.001$], and EXTERNAL TORQUE x THUMB-VF [$F(6,42)=19.7$, $p<.001$]. The tangential forces of the VF and thumb also increased with the external torque. The VF tangential force was larger than the thumb tangential force for the negative external torque conditions (supination effort by subjects) whereas the VF and thumb tangential forces for positive torque conditions (pronation effort by subjects) showed similar values. These findings were supported by two-way Repeated-measures ANOVA with the factors of EXTERNAL TORQUE and THUMB-VF, which showed the significant effects of EXTERNAL TORQUE [$F(6,42)=7321.6$, $p<.001$], VF force [$F(1,7)=30.2$, $p=.001$], and EXTERNAL TORQUE x THUMB-VF [$F(6,42)=64.3$, $p<.001$]. Thumb and VF normal forces increased linearly together for each torque direction (Fig. 3.2c). It was also true for the thumb and VF tangential forces (Fig. 3.2d). The ratios of the VF normal force to the thumb normal force were larger for positive torque conditions than for negative torque conditions (Fig. 3.2c) while the tangential forces were larger for negative torque conditions (Fig. 3.2d). These findings were supported by the significant (p<.01) differences of the slopes (1.0952 versus 0.8841 in Fig. 3.2c and 2.4624 versus 1.0576 in Fig. 3.2d) between the positive and negative torque conditions.

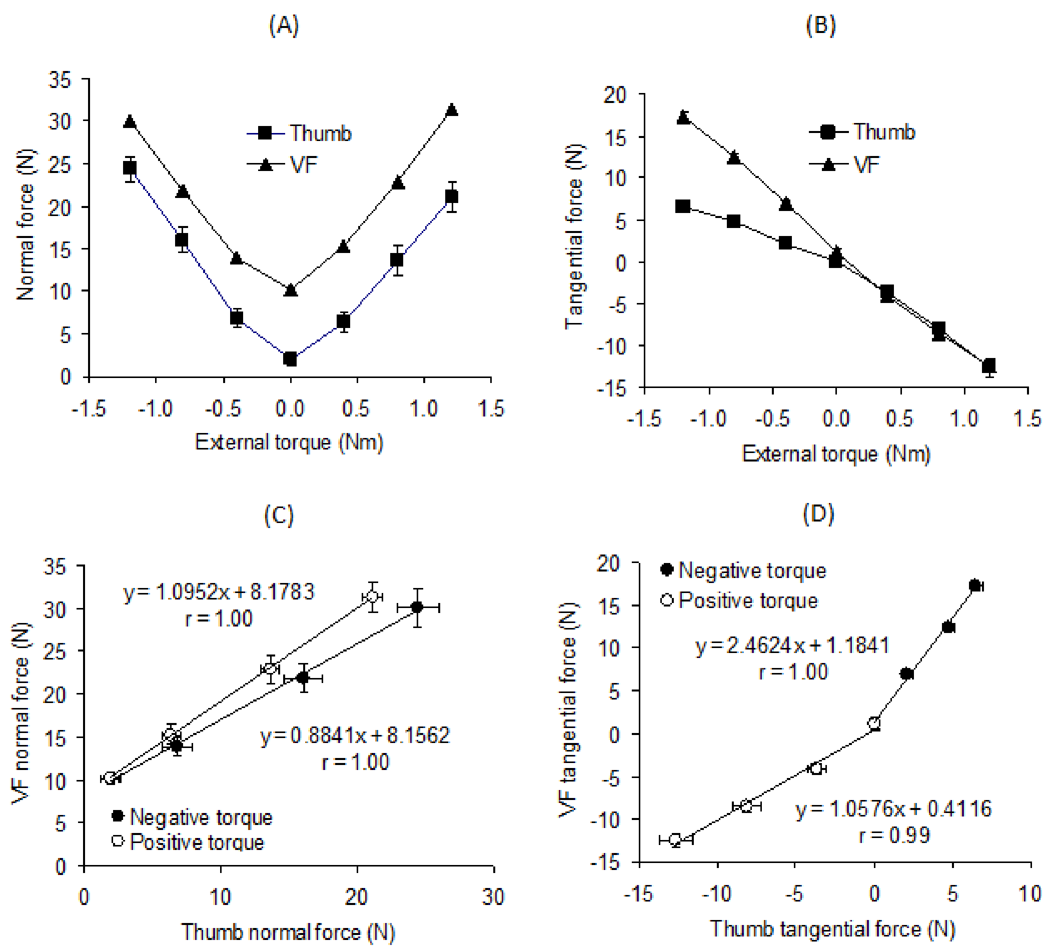


Figure 3.2. Relations among forces under different external torque conditions at the virtual finger (VF) level. **(a)** thumb and VF normal forces (F_n^{th} and F_n^{vf}), **(b)** thumb and VF tangential forces (F_t^{th} and F_t^{vf}), **(c)** the VF normal forces vs. thumb normal forces, and **(d)** VF tangential forces vs. thumb tangential forces. The positive and negative directional conventions are used for tangential forces to specify the directions of the moments produced by the tangential forces (e.g., a positive tangential force produce a positive moment). Averaged across subjects data are shown with standard error bars (some of the error bars are too small to be seen).

Inter-relations among VF and thumb normal and tangential forces

The trial-to-trial relations between the VF and thumb forces are shown in Figure 3.3. The VF and thumb tangential forces are mechanically coupled in static equilibrium (Fig. 3.3b) because an increase in VF tangential force should accompany a decrease in thumb tangential force with the same magnitude and vice versa due to their relationship in static mechanics to keep the resultant moment equal and opposite to the external torque (Eq. 5). Thus, the high coefficients of correlation found between the VF and thumb tangential forces are expected (Fig. 3.3b). The large coefficients of correlation between the VF and thumb normal forces (Fig. 3.3a), on the other hand, are not necessitated by mechanics because the VF normal force is not required to be coupled with the thumb normal force (Eq. 4). However, the VF and thumb normal forces showed close-to-perfect coefficients of correlation for each external moment condition for each subject. In general, the magnitudes of coefficients (|r|) between the normal forces were even larger than those between the tangential forces.

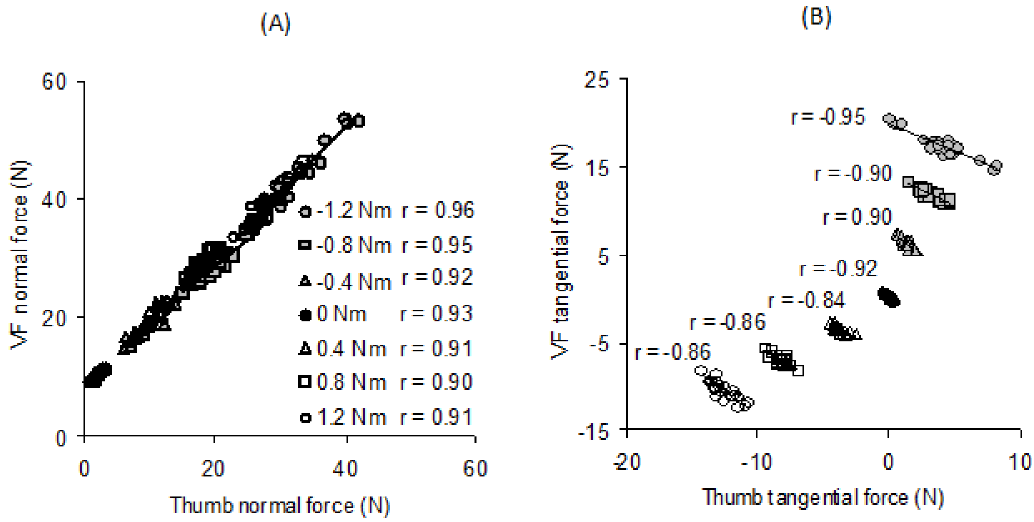


Figure 3.3. Relations between **(a)** the thumb and VF normal forces (F_n^{th} and F_n^{vf}) and **(b)** the thumb and VF tangential forces (F_t^{th} and F_t^{vf}). All coefficients of correlation are significant (p<.01) and large in magnitudes (|r|>0.84). The positive and negative directional conventions are used for tangential forces to specify the directions of the moments produced by the tangential forces (e.g., a positive tangential force produces a positive moment). The data are from a representative subject.

<u>Principal Component Analysis (PCA) on thumb and VF normal and tangential forces</u>

The PCA on all VF level variables (thumb and VF normal and tangential forces; F_n^{th} , F_t^{th} , F_n^{vf} , and F_t^{vf}) revealed two PCs (PC1 and PC2) that accounted for 96.56 ± 0.95% (average ± SD across external torque conditions after the results were averaged across the subjects for each external torque condition) of the total variance. The loadings for each variable were calculated for PC1 and PC2 (Table 3.1). The thumb and VF normal forces had large loadings (absolute values > .64) in the same PCs (e.g. PC1 for –1.2 Nm, –0.8 Nm, 0 Nm, 0.4 Nm, 0.8 Nm, and 1.2 Nm and PC2 for –0.4 Nm in Table 1) and small (absolute values <.35) loadings in the other PCs, whereas the thumb and VF tangential forces had large loadings in the latter PCs and small loading sin the former PCs. This data structure implies a decoupling between the normal forces of thumb and VF and the tangential forces of thumb and VF, which supports the principle of superposition. These findings were true for all external torque conditions in each subject. The large loadings of thumb and VF tangential forces in the same PCs and the opposite signs are necessitated by the static equilibrium: the mechanically necessitated negative correlation between the thumb and VF tangential forces (Eq. 5). However, note that the large loadings of VF and thumb normal forces in the same PC are not completely required by the static equilibrium.

Table 3.1. Loadings of principal components (PC1 and PC2) of all variables at the virtual finger (VF) level.

	Variable	PC1	PC2
–1.2 Nm	F_n^{th}	**0.96**	–0.25
	F_T^{th}	–0.28	**0.94**
	F_n^{vf}	**0.97**	–0.22
	F_t^{vf}	0.20	**–0.97**
–1.8 Nm	F_n^{th}	**0.91**	0.35
	F_T^{th}	–0.34	**–0.84**
	F_n^{vf}	**0.96**	0.24
	F_t^{vf}	0.22	**0.97**
–0.4 Nm	F_n^{th}	–0.29	**0.93**
	F_T^{th}	**0.89**	–0.31
	F_n^{vf}	–0.24	**0.96**
	F_t^{vf}	**–0.96**	0.23
0 Nm	F_n^{th}	**0.98**	0.04
	F_T^{th}	–0.07	**0.98**
	F_n^{vf}	**0.98**	–0.03
	F_t^{vf}	–0.08	**–0.98**
0.4 Nm	F_n^{th}	**0.97**	0.10
	F_T^{th}	–0.24	**–0.85**
	F_n^{vf}	**0.91**	0.28
	F_t^{vf}	0.21	**0.89**
0.8 Nm	F_n^{th}	**0.93**	–0.22
	F_T^{th}	–0.27	**0.89**
	F_n^{vf}	**0.88**	–0.26
	F_t^{vf}	0.32	**–0.64**
1.2 Nm	F_n^{th}	**0.98**	0.03
	F_T^{th}	–0.11	**–0.94**
	F_n^{vf}	**0.97**	0.13
	F_t^{vf}	0.04	**0.97**

F_n^{th} : thumb normal force, F_t^{th} : thumb tangential force, F_n^{vf} : VF normal force (sum of finger normal forces), and F_t^{vf} : VF tangential force (sum of finger tangential forces).

Variability of thumb and VF forces

The trial-to-trial variability of the thumb and VF normal and tangential forces increased with the external torque magnitude. The larger trial-to-trial variabilities for larger magnitudes of external torques are reflected in greater distributions of trial data points along the regression lines for larger magnitudes of external torques in Figures 3.3a and 3.3b. The larger variability was found for the negative external torque conditions than the positive ones. These findings were supported by Two-way Repeated-measures ANOVAs with the factors of EXTERNAL TORQUE and THUMB-VF, which showed the significant effects of EXTERNAL TORQUE [$F(6,42)=9.4$, $p<.001$] and THUMB-VF [$F(1,7)=19.7$, $p<.005$] in normal forces and the significant effect of EXTERNAL TORQUE [$F(6,42)=25.6$, $p<.001$] for tangential forces. The other factors or interaction effects were not significant. When the variability was plotted against the force magnitudes (Fig. 3.4c and 3.4d), the increasing trends of the variability with force magnitude were found.

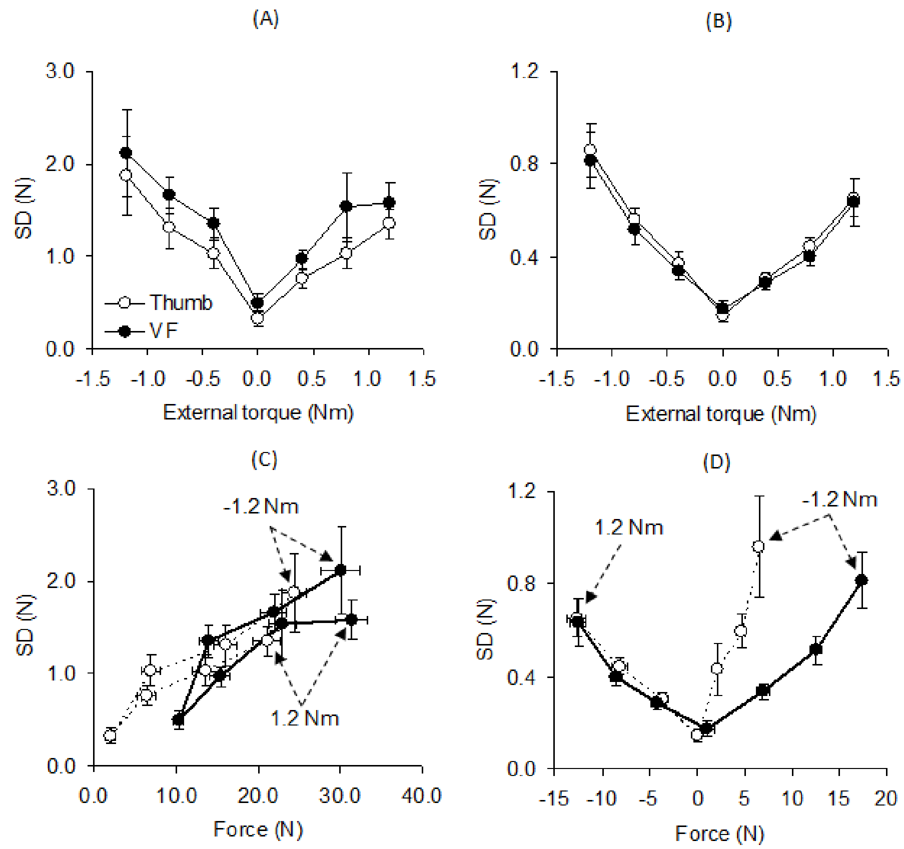


Figure 3.4. Trial-to-trial variability of the thumb and VF **(a)** normal (F_n^{th} and F_n^{vf}) and **(b)** tangential forces (F_t^{th} and F_t^{vf}) under different external torque conditions. Trial-to-trial variability of the thumb and VF normal forces versus thumb and VF **(c)** normal forces and **(d)** tangential forces. The positive and negative directional conventions are used for tangential forces to specify the directions of the moments produced by the tangential forces (e.g., a positive tangential force produce a positive moment). Averaged across subjects data are shown with standard error bars.

In summary, the results from the analysis of thumb and VF showed that the normal and tangential force magnitudes of both VF and thumb increased systematically with the external torque magnitude. PCA showed a decoupling between the normal forces of thumb and VF and the tangential forces of thumb and VF, which supports the principle of superposition. In addition, the larger variability was found for the negative external torque conditions than the positive ones.

3.4.2. The Individual Finger (IF) level

At the IF level of analysis, the individual finger (index, middle, ring, and little) normal (F_n^j and F_n^j, $j = \{index, middle, ring, little\}$) and tangential forces (F_t^j and F_t^j) were considered.

<u>IF force changes with external torque</u>

The IF normal and tangential force magnitudes increased with the external torque magnitude (Fig. 3.5a and 3.5b). This finding was supported by Two-way Repeated-measures ANOVAs with the factors of EXTERNAL TORQUE and THUMB-VF, which showed the significant effects of EXTERNAL TORQUE [F(6,42)=122.6, p<.001], THUMB-VF [F(3,21)=60.6, p<.001], and EXTERNAL TORQUE x THUMB-VF [F(18,126)=46.2, p<.001] for normal forces and significant effects of EXTERNAL TORQUE [F(6,42)=95.7, p<.001], FINGER [F(3,21)=1390.3, p<.001], and EXTERNAL TORQUE x THUMB-VF [F(18,126)=30.0, p<.001] for tangential forces.

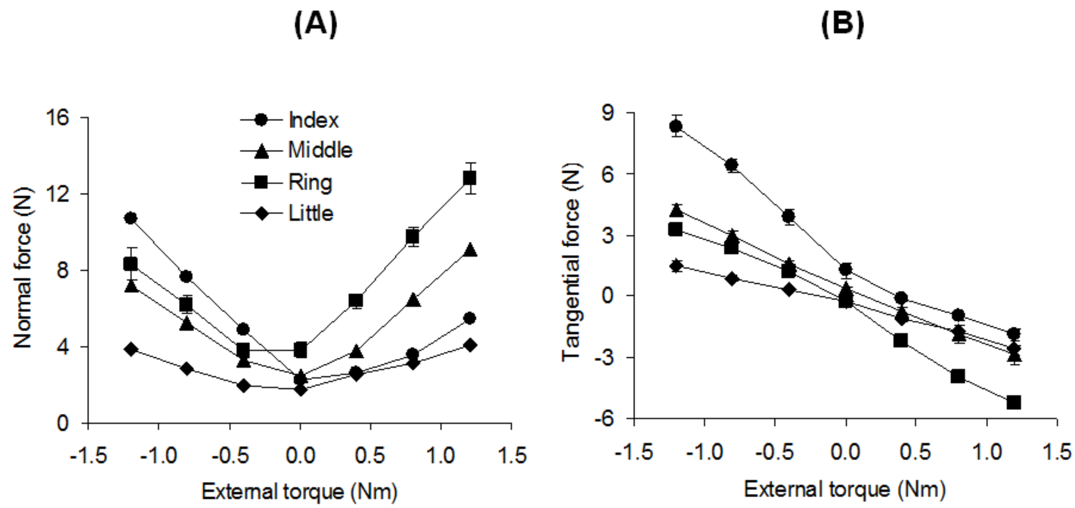


Figure 3.5. Individual finger (a) normal forces (F_n^j , $j = \{index, middle, ring, little\}$) and (b) tangential forces (F_t^j) under different external torque conditions. The positive and negative directional conventions are used for tangential forces to specify the directions of the moments produced by the tangential forces (e.g., a positive tangential force produces a positive moment). Averaged data across subjects are presented with standard error bars (some of the error bars are too small to be seen).

Variability of IF forces

The trial-to-trial variability of IF normal and tangential forces increased with the external torque magnitude (Fig. 3.6a and 3.6b). This finding was supported by Two-way Repeated-measures ANOVAs with the factors of EXTERNAL TORQUE and FINGER, which showed the significant effects of EXTERNAL TORQUE [F(6,42)=15.3, p<.001], FINGER [F(3,21)=19.3, p<.001], and EXTERNAL TORQUE x FINGER [F(18,126)=3.2, p<.001] for normal forces and the significant effects of EXTERNAL TORQUE [F(6,42)=54.7, p<.001], FINGER [F(3,21)=37.6, p<.001], and EXTERNAL TORQUE x FINGER [F(18,126)=12.1, p<.001] for tangential forces. When the variabilities were plotted against the force magnitudes

(Fig. 3.6c and 3.6d), the normal and tangential forces showed 'rotated V-shape' and 'V-shape', respectively.

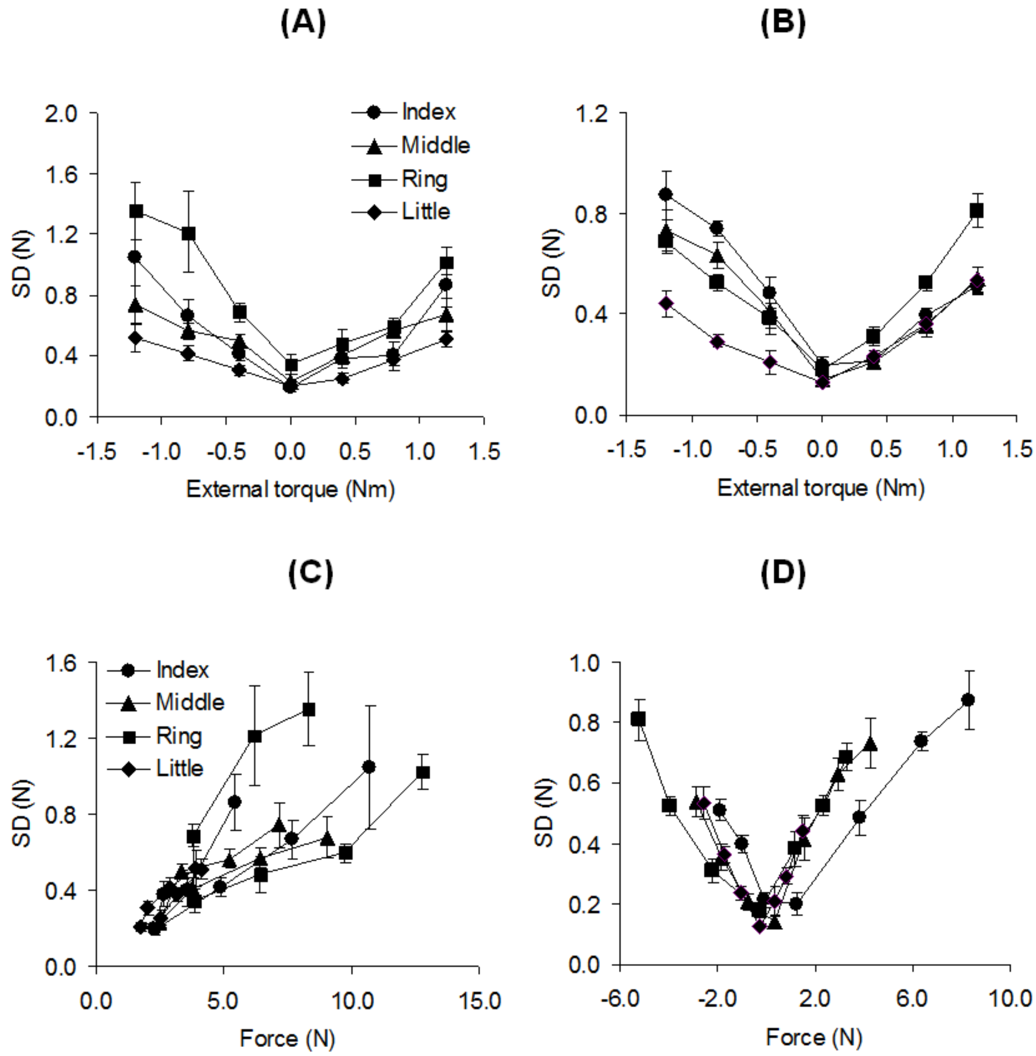


Figure 3.6. Trial-to-trial variability of individual finger **(a)** normal (F_n^j) and **(b)** tangential (F_t^j) forces under different external torque conditions. Trial-to-trial variability of individual finger normal forces versus individual figner **(c)** normal forces and **(d)** tangential forces averaged across all trials. The positive and negative directional conventions are used for tangential forces to specify the directions of the moments produced by the tangential forces (e.g., a positive tangential force produces a positive moment). Averaged across subjects data are shown with standard error .

Finger synergy strength indices (ΔVar and ΔVar_{norm})

To quantify finger interactions during the moment production tasks, the indices (ΔVar and ΔVar_{norm}) reflecting the difference between the sum of the variances of the moments of IF tangential forces and the variance of the resultant moment were computed (Eqs. 6 and 7). Note that ΔVar and ΔVar_{norm} are multi-digit synergy indices. ΔVar and ΔVar_{norm} revealed positive values for all external torque conditions. This suggests that the negative covariations (i.e., "error compensations") between IF moments prevail. ΔVar systematically increased with the external torque magnitude (Fig. 3.7a). ΔVar values were in general larger for negative external torque conditions than positive torque conditions. This finding was also true for ΔVar_{norm} (Fig. 3.7b) although the changes of ΔVar_{norm} ('M-shape') with the external torque were different from those of ΔVar ('V-shape'). These findings were supported by One-way Repeated-measures ANOVAs performed on ΔVar and ΔVar_{norm} with the factors of EXTERNAL TORQUE, which showed significant effects for ΔVar [$F(6,42)=20.4$, $p<.001$] and ΔVar_{norm} [$F(6,42)=3.4$, $p<.005$].

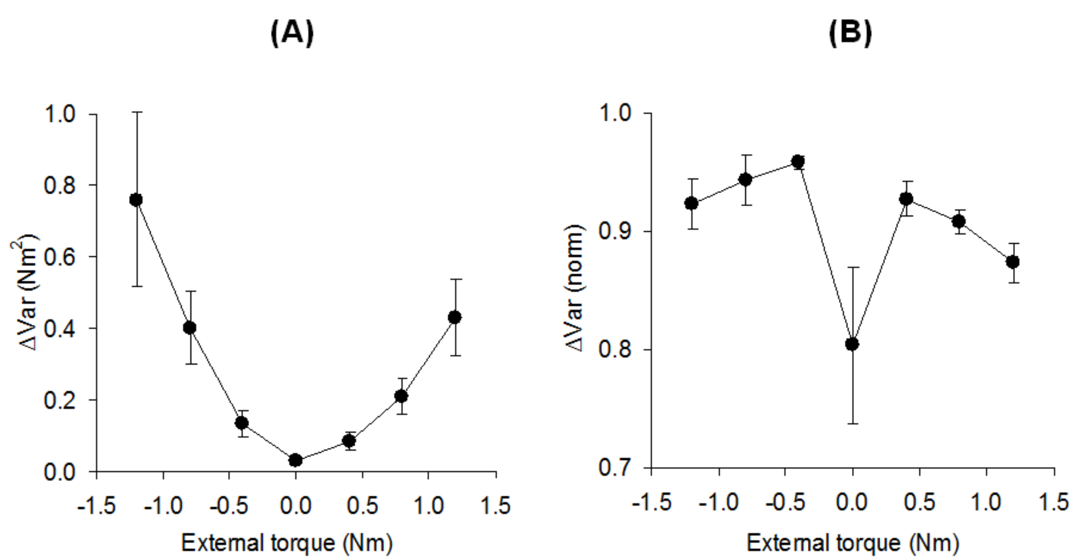


Figure 3.7. **(a)** ΔVar and **(b)** normalized ΔVar (ΔVar_{norm}) computed over 25 trials for static prehension under different external torque conditions. Averaged data across subjects are presented with standard error bars.

In summary, the magnitude and variability of individual finger normal and tangential forces increased with the external torque. The multi-digit synergy strength increased with the external torque magnitude. Generally, synergy strength was greater for negative external torque conditions than positive torque conditions.

3.5. Discussion

In this study, we investigated the trial-to-trial variabilities of digit forces and moments for the same multi-digit prehension tasks in order to test the hypotheses of the principle of superposition and the hierarchical organization of prehension control for circular object prehension. The PCA showed that the elemental variables were clearly decoupled into two groups: one group comprising normal forces and the other group containing tangential forces, which supports the first hypothesis. The synergy indices, ΔVar and ΔVar_{norm}, were always positive (negative covariations between IF moments), which confirms the second hypothesis. The discussion addresses the following topics: the principle of superposition in circular object prehension, hierarchical organization of prehension and the uncontrolled manifold (UCM) hypothesis, and trial-to-trial variability of forces.

3.5.1. Principle of superposition

The principle of superposition was originally suggested in robotics (Arimoto & Nguyen, 2001; Arimoto, Tahara, Bae, & Yoshida, 2003; Arimoto et al., 2001) and has been confirmed in two-dimensional and three-dimensional prehension tasks in humans (Shim et al., 2003b, 2005b, 2006a).

During static prehension of an upright rectangular object, there exist two static constraints to be satisfied: all forces should cancel out to be zero ($\sum \overrightarrow{F^j} = 0$) and all moments should cancel out to be zero ($\sum \overrightarrow{M^j} = 0$) in all three dimensions. At the level of virtual finger (Baud-Bovy & Soechting, 2001; Cutkosky & Howe, 1990; Iberall, 1997; Santello, Flanders, & Soechting, 2002; Yoshikawa, 1999), two groups of the variables are already necessitated by static mechanics during a rectangular object prehension: the thumb grasping force and the VF grasping force (sum of individual finger normal forces) should have the same force magnitudes along the horizontal axis (i.e., $F_n^{vf} = F_n^{th}$; vf and th respectively stand for virtual finger and thumb, and n represents a normal force) while the sum of the thumb tangential force (load force) and the VF tangential force should be equal and opposite to the weight of the hand-held object along the vertical axis (i.e., $F_t^{vf} + F_t^{th} = -$W; t represents a tangential force and W stands for the weight of a hand-held object). The other group of variables, the tangential forces and moments of normal and tangential force, are also coupled. The mechanically necessitated coupling relationship between these variables has been explained using the ‘chain effects’ (i.e., high correlations between seemingly unrelated variables can be explained by chained relations between variables (Gregory, 2002; Shim et al., 2005b; Zatsiorsky et al., 2003b; Zatsiorsky &

Latash, 2004). Therefore, the novel finding of the previous studies (Shim et al., 2003b, 2005b) on the principle of superposition in human prehension was the decoupling of the two groups of variables or two synergies, rather than the coupling of variables in each synergy. Therefore, there are two independent synergies used by the CNS to control two important aspects of the prehension of a rectangular object: grasping stability control by the thumb and VF normal forces and rotational equilibrium control by the thumb and VF tangential forces and the moments of forces. Shim et al. (2006a) recently showed that the stabilizations of grasping forces and grasping moments can be modulated in different directions after mechanical perturbations (sudden changes of weight of the hand-held object and/or sudden changes of external torques) are given. The study suggested that the CNS may be more concerned about rotational equilibrium control than grasping stability control when a mechanical perturbation is given to the hand-held object.

Our study on circular object prehension revealed relationships of elemental variables (thumb and VF normal and tangential forces) similar to the rectangular object prehension tasks of previous studies. The PCA revealed two PCs: thumb and VF normal (tangential) forces had large (small) loadings in one PC, but small (large) loadings in the other. This data structure suggests two null spaces or two independent multi-digit synergies. This finding may not be easily expected without experiments because the relationship between the thumb and VF normal forces are not mechanically necessitated in circular object prehension although it is in rectangular object prehension. It appears that the grasping stability and the rotational equilibrium are controlled by two independent central commands during circular object prehension as it was previously suggested in rectangular object prehension. Thus, this finding supports the principle of superposition for circular object prehension. The findings from PCA and ΔVar and ΔVarnorm analysis also support the previously suggested central neural back-coupling model (CBC-model) for multi-digit actions (Latash, Shim, Smilga, & Zatsiorsky, 2005), because in the CBC-model the performance variables related to 'force stabilization' and 'moment stabilization' can be separately modulated as it was shown in the results from our experiments.

3.5.2. Hierarchical organization of prehension and Uncontrolled Manifold (UCM) hypothesis

The earlier finger movement experiments from skilled telegraphers (Bryan, 1899) and typists (Book, 1908) suggested the hierarchical organization of finger movements by demonstrating that lower level units (e.g., letters) were combined as upper level unit (e.g., word) for typing control. The following physiological and behavioral experiments in the mid 20th centuries (Sherrington, 1947; Turvey, 1977; Weiss, 1941) facilitated the conceptualization and theorization of hierarchical organization of human behavior [see (Gallistel, 1980) for details].

In this study we have shown that there exist positive multi-digit synergy indices for all external torque conditions. This means that the IF moments had dominant negative covariations, resulting in stabilized performance of the VF moment (sum of IF moments). These results conspicuously support the hierarchical organization of prehension, i.e., the individual fingers are acting together to stabilize the functionally important performance of the VF. The stabilization of the overall performance of individual finger actions have been well described for rectangular object prehension (Shim et al., 2003b; 2005b; 2004; 2006a) and far more for multi-finger pressing (Kim, Shim, Zatsiorsky, & Latash, 2006; Latash, Shim, & Zatsiorsky, 2004; Shim et al., 2003a, 2005). All these studies used digit interaction indices to study how the CNS controls multiple digits during prehension and pressing. This approach is similar to previously suggested UCM hypothesis (Kang, Shinohara, Zatsiorsky, & Latash, 2004; Latash, Scholz, & Schoner, 2002; Scholz & Schoner, 1999). According to UCM hypothesis, the CNS specifies a subspace (UCM) in the state space of elemental variables for a redundant motor system and tries to find a solution for a task in the subspace while allowing solutions in the UCM, yet compressing the variability orthogonal to the UCM (UCM_{orth}). Thus, for a successful manipulation task, the sum of the trial-to-trial variabilities (e.g. $\sum_{j=1}^{4} Var_j$ or variability in UCM) of individual finger actions (e.g., forces/moments) may be relatively large, whereas the variability of the combined finger actions (e.g. Var_{tot} or variability in UCM_{orth}) can be small. The previous UCM analysis on multi-digit pressing removed inter-digit dependency [called finger force enslaving (a phenomenon of unintended force production by non-task fingers during a task finger force production) (Reilly & Hammond, 2000; Zatsiorsky, Li, & Latash, 2000a)] in order to extract independent elemental variables, called 'Modes' (Danion et al., 2003; Kang et al., 2004; Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2005). The Modes have been considered as hypothetical independent elemental variables or central commands to fingers, and the UCM analysis for finger force studies used Modes to investigate the synergic actions between the Modes.

The inter-dependent digit actions during pressing are contributed by peripheral and central intrinsic factors such as insertions of a flexor digitorum profundus to multiple fingers (Kilbreath, Gorman, Raymond, & Gandevia, 2002; von Schroeder & Botte, 2001; von Schroeder, Botte, & Gellman, 1990) and motor cortex (M1) outputs diverging to innervate the spinal motor neuron pools of different finger muscles (Buys, Lemon, Mantel, & Muir, 1986; Fetz, Finocchio, Baker, & Soso, 1980; Shinoda, Zarzecki, & Asanuma, 1979). However, during a free object prehension, the inter-dependent digit actions are caused by not only the intrinsic factors but also the external constraints imposed by the task mechanics. For example, when the thumb increases its normal force in static circular object prehension as in our experiment, other fingers will produce enslaving forces due to the intrinsic finger dependency to the thumb (Olafsdottir et al., 2005). However, if the resultant force of the finger enslaving forces is not the same and opposite to the thumb force, the fingers will be required to adjust the forces to compensate the difference between the thumb force and the finger resultant force or VF force. In our study, we did not remove the inter-digit dependency for the investigation of synergic actions between fingers due to technical difficulties (e.g., differentiating the contributions of intrinsic factors from the contributions of the mechanical constraints during prehension of the free circular handle). However, if we assume that the direction of enslaving actions of non-task digits are the same as the direction of task digits as implied by the previous studies (Lang & Schieber, 2004; Shim et al., 2008), removing the inter-digit dependency would have caused changes in ΔVar and ΔVar_{norm} values to be more positive. This would suggest larger error compensations between fingers because the inter-digit dependency makes the finger actions positively covary.

3.5.3. Active control of tangential forces

The tangential force during grasping has been considered to be passively coupled (Flanagan & Wing 1995; Pheasant & O'Neill 1977) by other mechanical constraints such as grasping normal force (Imrhan & Loo, 1988; Nagashima & Konz, 1986; Rohles, Moldrup, & Laviana, 1983), handle diameter (Adams & Peterson, 1988; Imrhan & Loo, 1988; Nagashima & Konz, 1986; Pheasant & O'Neill, 1975), contact surface condition (Amis, 1987a; Gurram, Rakheja, & Gouw, 1995; Hall, 1997; Johansson, 1998; Kinoshita & Francis, 1996; Lee & Rim, 1991), orientation of a handheld object (Pataky, Latash, & Zatsiorsky, 2004), and inertial force (Zatsiorsky, 2005).

It was previously shown that the finger normal forces during pressing and prehension can be synergically controlled by the CNS to stabilize the task-specific performances (reviewed in (Latash, Shim, Gao, & Zatsiorsky, 2004)). Previous studies on synergic finger actions during pressing used the index synergy (i.e., ΔVar) to study the interactions between the finger pressing forces (normal forces) (Li et al., 1998; Shinohara et al., 2003). Other studies on multi-digit prehension of a rectangular object used the index of synergy calculated from the normal forces of individual fingers or the moments of individual fingers (Shim et al., 2004, 2005, 2006a). Contrary to the previous studies on rectangular object prehension, the geometry of a circular object employed in the current study does not allow finger normal forces to produce moments of force about the center of the circular object. Thus, the tangential forces are the only forces contributing to the moments which achieve the rotational equilibrium of the circular object against external torques. The index of synergy calculated from the tangential forces showed synergic actions between individual finger tangential forces for stabilizing the virtual finger tangential force. Thus, this result suggests that finger tangential forces can be actively controlled by the CNS.

3.5.4. Trial-to-trial variability of forces

Due to the obvious importance of accurate force production in everyday activities, the variability of force has been an interest of many researchers in human motor control (Fullerton & Carttell, 1892; Michon, 1967; Moritz, Barry, Pascoe, & Enoka, 2005; Newell & Carlton, 1988; Newell & Corcos, 1993; Sosnoff & Newell, 2006). The experimental tasks employed in the current study were designed to encourage the subjects to produce a consistent prehension performance across multiple trials under the same external torque conditions. Despite the effort, the trial-to-trial variabilities of forces were significant at both VF and IF levels. The thumb and VF tangential force variabilities showed very similar values for each external torque (Fig. 3.4b), whereas the thumb normal force variability was always larger than the VF normal force variability. The identical variability trend of the thumb and VF tangential forces can be simply explained by the moment constraint ($\sum \overrightarrow{M^{j}} = 0$) of static prehension (Eq. 5). Since the resultant moment produced by the thumb and VF should be equal and opposite to the external torque, the moment of thumb tangential force and the moment of VF should show close-to-perfect negative correlations for an ideal performance: an increase in one should be followed by a decrease in the other with the same magnitude. The moments of thumb and VF tangential forces are calculated by multiplying the thumb and VF tangential forces by the constant radius (4.5 cm) of the circular handle. Thus, the thumb and VF tangential forces should also have close-to-perfect negative correlations. Due to this relationship, an increase in thumb tangential force should correspond to a decrease in VF tangential force with the same magnitude, resulting in the same variability (SD) as shown in Fig. 3.4b. The larger variability of the VF normal force than the thumb normal force can be explained from the non-parallel force directions between the thumb and IF normal forces. Since the IF normal forces are not parallel to the thumb normal force, an increase in the thumb normal force with a certain magnitude in the vertical direction should correspond to an increase in the sum of the IF normal forces with a larger magnitude to satisfy the force constraint ($\sum \overrightarrow{F^j} = 0$) in the vertical direction. This relationship resulted in the larger VF normal force variability than the thumb normal force variability. In general, larger force variabilities were found in negative external torque conditions (supination effort for subjects) for both thumb and VF normal and tangential forces (Fig. 3.4a and 3.4b). These findings reflect an ability of the CNS control to the hand and lower arm muscles to generate more consistent force outputs in pronation than supination during static circular object prehension. Previous studies showed that the strength of subject is inversely related to the control of end-effector force or torque (Hamilton, Jones, & Wolpert, 2004; Shinohara et al., 2003; Sosnoff & Newell, 2006). Hamilton et al. (2004) recorded the maximum voluntary torques from four different muscle groups in the arm. They showed that the coefficients of variation of torque decreased systematically as the maximum voluntary torque increases. Sosnoff and Newell (2006) asked subjects to consistent force output of 5% or 25% maximum voluntary force and found that the variability of force output decreased with the maximum voluntary force. A previous study on strength training effects on finger control showed that training finger muscles with heavy loads increased both consistent force outputs and functional hand dexterity (Bilodeau, Keen, Sweeney, Shields, & Enoka, 2000). If muscle strength is a major factor to determine the consistency of finger force outputs as suggested in the previous studies, the large thumb and index finger abductors producing pronation torques during circular object prehension (e.g., thenar muscles of the thumb and dorsal interossei for the index finger) may have played a role in the small variability in the constant torque production tasks during pronation as compared to supination. However, the result of the current study that showed smaller variability during pronation and our previous studies that showed smaller maximum voluntary torque in pronation as compared to supination (Shim, Huang, Latash, & Zatsiorsky, 2006; Shim et al., 2004a) seem to be contradictory to the previous studies by others. Thus, it seems that the different between the pronation and supination torque control found in the current study seems to be contributed to by the specificity of different muscle groups involved in the pronation and supination tasks. The synergy strength indices, ΔVar and ΔVar_{norm}, are similar to negated covariations between the IF moments: the positive and negative ΔVar and ΔVar_{norm} represent prevalent negative and positive covariations between variables, respectively. When the large variability was present for negative external torque conditions, the larger error compensations between IF moments, indexed by the larger ΔVar and ΔVarnorm values for the negative external torque conditions, were observed in our study. Thus, it appears that the CNS uses the strategy to generate larger error compensations between IF moments for the tasks in which larger variabilities are present.

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Chapter 4: Prehension synergy: effects of static constraints on multi-finger prehension

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4.1. Abstract

Previous studies have shown that the interactions of human hand digits are influenced by internal constraints, i.e., biomechanical and central constraints. However, little is currently known about the influence of externally imposed mechanical constraints on multi-finger behavior. This study investigates maximal digit force production during fixed object and free object prehension in statics. The results from the fixed object prehension indicated that the closer the non-task finger was positioned to the task finger, the greater the force produced by the non-task finger, which supports the proximity hypothesis. Conversely, the non-task fingers with longer moment arms showed greater force production during free object prehension, which supports the mechanical advantage hypothesis. During the free object prehension, equal and opposite torques were produced by the digit normal forces and tangential forces, while this phenomenon was not observed in the fixed object prehension. The results also showed that the thumb normal force had a positive linear relationship with task-finger normal forces during fixed object prehension while the thumb normal force remained constant during free object prehension tasks.

We concluded that the CNS employed different strategies when different sets of internal and external constraints are provided during multi-digit prehension tasks.

4.2. Introduction

Previous studies on multi-finger actions have focused on two main topics, the synergistic actions of multiple fingers (Danion, Latash, Li, & Zatsiorsky, 2001; Kang, Shinohara, Zatsiorsky, & Latash, 2004; Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2003; Latash, Li, Danion, & Zatsiorsky, 2002; Santello & Soechting, 2000; Shim, Latash, & Zatsiorsky, 2005; Visser et al., 2003) and the independent actions of the individual fingers (Edin, Westling, & Johansson, 1992; Hager-Ross & Schieber, 2000; Kilbreath & Gandevia, 1994; Schieber, 1995). Many studies on finger independence have shown that the independent actions of fingers are influenced by internal constraints, such as biomechanical and central constraints. For example, biomechanical constraints affecting independent finger actions include the interconnection of tendons in the hand and forearm (Hager-Ross & Schieber, 2000; Leijnse, Walbeehm, Sonneveld, Hovius, & Kauer, 1997). The flexor digitorum profundus (FDP) has insertions in all four fingers. This multi-tendoned extrinsic muscle, when activated, induces the movements or force production of adjacent fingers when another intended finger moves or produces force (Kilbreath, Gorman, Raymond, & Gandevia, 2002; Li, Zatsiorsky, & Latash, 2000; Reilly & Schieber, 2003; Schieber, 1995; Thompson & Giurintano, 1989). One of the central constraints includes the short-term synchronization of motor-units that cause simultaneous actions of multiple fingers. When more than two motor units receive a common neural input, multiple motor units are excited simultaneously (Reilly & Schieber, 2003; Schieber, 1996; Winges, Kornatz, & Santello, 2008). Although many previous studies showed that the independent actions of fingers are affected by these internal constraints created by the human body, it is still largely unknown how external constraints, the constraints provided by the physical world with which the human body interacts, affect finger actions during multi-digit grasping.

Previous studies on multi-finger force production tasks have commonly revealed that greater forces are created in non-task fingers the closer these fingers are to the task fingers, and have suggested that this phenomenon supports the proximity hypothesis (Olafsdottir, Zatsiorsky, & Latash, 2005; Zatsiorsky, Li, & Latash, 2000). Previous studies have also supported the mechanical advantage hypothesis in moment production tasks during the multi-digit grasping of a mechanically fixed object (Shim, Latash, & Zatsiorsky, 2004; Zatsiorsky, Gregory, & Latash, 2002). The normal forces of peripheral fingers (i.e., index and little fingers) are produced mainly in response to the external torques. Consequently, they especially depend on the external torques since they have longer moment arms resulting in greater mechanical advantages. The force productions by central fingers (i.e., middle and ringer fingers with shorter moment arms) depend on the external torques as well as the load magnitudes (Zatsiorsky et al., 2002). This implies that the fingers with longer moment arms are mainly torque generating fingers. According to the mechanical advantage hypothesis, the force effectors located farther away from the axis of rotation have greater mechanical advantages due to the longer moment arm. In other words, the specific functions of motor effectors would be determined by the requirements for the successful completion of the task, such as moment production or rotational equilibrium against external torques (Devlin & Wastell, 1986; Frey & Carlson, 1994; Smutz et al., 1998).

Despite these earlier studies, it is still unknown if the central nervous system (CNS) uses the mechanical advantage hypothesis by applying the force production in non-task fingers during free-object grasping tasks. The multi-finger grasping of a free object and the grasping of a mechanically fixed object are governed by different sets of constraints. In order to engage in the static grasping of a free object, the CNS needs to satisfy the resultant force and resultant moment of force constraints. For example, the sum of all digit forces and moments applied to a free object should be equal to zero, so that there is no movement of the object. However, the CNS does not need to consider these static external constraints when manipulating a mechanically fixed object.

The main purpose of the current study is to investigate the independent actions of individual digits and the interactions of multiple digits while holding a mechanically fixed object or a free object. We assume that the CNS only needs to satisfy internal constraints (i.e., biomechanical and central constraints) when holding a mechanically fixed object, while it is required to satisfy both internal and external constraints (i.e., translation and rotational equilibrium constraints) when holding a free object. This study was specifically designed to investigate the strategies used by the CNS under the rotational equilibrium constraint (see Equipment in Methods) and tests three hypotheses. The first hypothesis under investigation is the proximity hypothesis in mechanically fixed object prehension, which suggests that the CNS will produce greater forces from the non-task fingers closer to the task finger in maximum finger force production tasks during a mechanically fixed object prehension. The second hypothesis under investigation is the mechanical advantage hypothesis in free object prehension, which suggests that the CNS would produce greater forces from the non-task fingers with longer moment arms during free object prehension. Finally, it is hypothesized that the CNS utilizes the tangential force actively in maintaining rotational equilibrium during free object prehension, in contrast to the CNS's control strategy for the tangential force during a fixed object prehension.

4.3. Methods

4.3.1. Subjects

Ten male volunteers (age: 25.2 ± 3.1 years, weight: 71.1 ± 1.2 kg, height: 175.2 ± 3.3 cm, hand length: 19.7 ± 1.4 cm, and hand width: 9.1 ± 0.8cm; mean ± SD across subjects are presented) participated in this experiment. All subjects were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). The hand length was measured using the distal crease of the wrist to the middle fingertip when a subject positioned the palm side of the right hand and the lower arm on a table with all finger joints extended. The hand width was measured using the radial side of the index finger metacarpophalangeal joint to the ulnar side of the little finger metacarpophalangeal joint. Before testing, the experimental procedures of the study were explained to the subjects and the subjects signed a consent form approved by the University of Maryland's Institutional Review Board (IRB).

4.3.2. Equipments

Five six-component (three force and three moment components) transducers (Nano-17s, ATI Industrial Automation, Garner, NC, USA) attached to an aluminum handle were used to measure each individual digit's forces and moments (Fig. 4.1a). In order to monitor the position of the handle and to provide feedback about the handle position to the subject during the free object prehension tasks, a six-component (three position and three angle components) magnetic tracking device (Polhemus LIBERTY, Rockwell Collins Co., Colchester, VT, USA) was used. A Polhemus position-angle sensor was attached to the front edge of a Plexiglas base (0.2 cm × 17.0 cm × 13.5 cm). This Plexiglas base was affixed to the top of the handle. Pieces of 100-grit sandpaper with a friction coefficient of about 1.5 were attached to the surface of each sensor in order to increase the friction between the digits and the force application point. The vertical distance between the adjacent sensors for index, middle, ring, and little fingers was 30mm. The thumb sensor was positioned at the midpoint between middle and ring finger sensors. The horizontal distance between the contact points of the thumb sensor and other sensors was 70 mm. A counter-load (300g) with the same weight as the handle (including the sensors) was used to eliminate the effect of gravity (Fig. 4.1b). Because of this counter-load, the sum of digits' tangential forces did not have to be equal to the weight of the handle when the handle was vertically oriented (Shim, Lay, Zatsiorsky, & Latash, 2004). This preparation was done to focus our investigation on the rotational constraint during subjects' grasping of the handle in the air (i.e., free-object grasping). The analogue signals were routed to a 12-bit analogue-digital converter (a PCI-6031 and a PCI-6033, National Instrument, Austin, TX). LabView programs (LabView 7.1, National

Instrument, Austin, TX) were developed and used to synchronously record the signals from the force/moment sensors and magnetic sensor. The sampling frequency was set at 50 Hz. The sampled data were digitally low-pass filtered with a 2nd order Butterworth filter. The cutoff low frequency was set at 5 Hz (Gao, Latash, & Zatsiorsky, 2005a; Li, Latash, & Zatsiorsky, 1998).

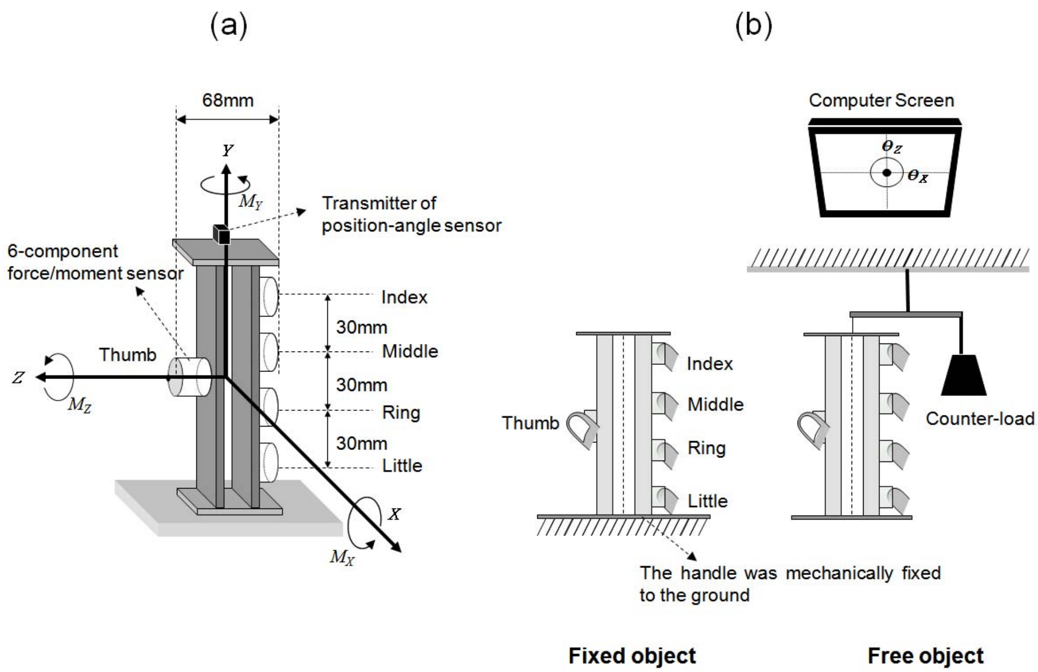


Figure 4.1. **(a)** The customized handle: The force-moment sensors shown as white cylinders were attached to two vertical aluminum bars. The subjects were instructed to place each digit on the designated sensor (i.e., Thumb, Index, Middle, Ring, and Little) and keep all digits on the sensors during trials. The transmitter of a magnetic position-angle sensor, marked out as a small black cube, was attached to the plastic base affixed to the top of the handle. M_X, M_Y, and M_Z are moments produced by the digits about *X*-, *Y*-, and *Z*-axes, respectively. **(b)** For the fixed object, the handle was mechanically fixed to a desk and could not be moved by digits' forces (left). The subject held the handle while monitoring its angular position about *X*- and *Z*-axes during free object prehension (right). These positions were designated θ_X and θ_Z respectively. A counter-load of 300g, the same weight as the handle and sensors, was hung to the long horizontal wooden beam.

4.4.3. Experimental procedures

The subjects sat in a chair facing the computer screen and positioned their right upper arm on a wrist-forearm brace (a semi-circular plastic cylinder) that was fixed to a table (Shim, Latash, & Zatsiorsky, 2003). The forearm was held stationary with Velcro straps to prevent forearm and wrist movements. There were five single-digit maximal voluntary force (MVF) production tasks along Z-axis (T, I, M, R, L) and one multi-digit MVF task along the same axis (TIMRL): These were designated as the T- (thumb); I- (index finger); M- (middle finger); R- (ring finger); and L- (little finger) tasks. The multi-digit task was designated the TIMRL-task. Note that the subjects were instructed to keep all digits on the sensors during each task and were asked to pay attention to the task-digit maximal force production while allowing non-task digit force productions. It was not allowed to lift non-task fingers during the trials. All digit forces were recorded during all trials and tasks. Two different experimental conditions were used in order to investigate the effects of rotational equilibrium constraint on the finger force production during multi-finger grasping. One condition included MVF tasks while holding a fixed object and the other included the same tasks holding a free object. For the fixed object condition, the handle was mechanically fixed to a desk and could not be moved. During the free object condition, subjects watched real-time feedback of the angular position of the handle about the X- and Z-axes. They were instructed to avoid handle rotations and were asked to minimize the angular deviation of the object. If the angular deviation exceeded the pre-defined criteria ($\sqrt{\theta_X^2 + \theta_Z^2} > 1^\circ$) during the trial, the data collection automatically stopped and the subject performed the trial again (Shim et al., 2003).

For each condition, the subject performed three consecutive attempts. Thus, each subject performed a total of 36 trials (2 TASKs × 6 MVF tasks × 3 attempts = 36 trials). The LabView program automatically initialized the values of sensor signals to zero at the beginning of each trial. Two-minute breaks were given at the end of each trial in order to avoid fatigue effects. Prior to the actual experiments, the subjects had a familiarization session, which included an explanation of the experimental procedures and several practice trials. The order of the six MVF tasks was balanced and no subject reported fatigue.

4.3.4. Data analysis

The maximal forces of the task digit and non-task digits at the instant maximal force production of task-digit were obtained. The subjects performed three attempts for each condition, and the average data over three attempts were calculated for further analysis. The analysis was limited to the frontal plane of the subject (the Y-Z plane in Fig. 1a). Forces along Y- and Z-axes, tangential and normal forces respectively, and the moments produced by these two forces (moments about X-axis) were considered. The force application point was calculated from $y = -M_x / F_z$ along the Y-axis, with respect to the center position of the each sensor, where M_x is the moment of force about the local x-axis and F_z is the force along the Z-axis (the normal force component). The total moment exerted by digit forces about X-axis was calculated from Eq.3. The subject performed three attempts in each condition. Their individual trial data were averaged and used for further analyses.

Model

During the fixed object prehension, the handle was mechanically fixed to the immovable table so that there was no rotational equilibrium to be satisfied. During the free object prehension, however, the following three mechanical constraints should be satisfied in order to maintain static equilibrium along Z-axis.

1) The sum of the normal force of all four fingers should be equal to the normal force of the thumb

$$F_{th}^{n} = F_{i}^{n} + F_{m}^{n} + F_{r}^{n} + F_{l}^{n} = \sum_{j} F_{j}^{n}, j = \{i, m, r, l\} \quad (1)$$

2) The sum of the digit tangential forces should be equal to zero. Note that the counter load, which provided the exact same weight as the handle including the sensors, was used. Because of this, the resultant tangential force of all digits should be zero in order to maintain static equilibrium along Y-axis.

$$F_{th}^{t} + F_{i}^{t} + F_{m}^{t} + F_{r}^{t} + F_{l}^{t} = 0 \quad (2)$$

3) The resultant moment created by the digit forces should be zero due to the task constraints (e.g., the rotational constraint).

$$M_{TOT} = \underbrace{-F_{th}^{n} d_{th} + F_{i}^{n} d_{i} + F_{m}^{n} d_{m} + F_{r}^{n} d_{r} + F_{l}^{n} d_{l}}_{\text{Moment of normal force } (M_n)} + \underbrace{F_{th}^{t} r_{th} + F_{i}^{t} r_{i} + F_{m}^{t} r_{m} + F_{r}^{t} r_{r} + F_{l}^{t} r_{l}}_{\text{Moment of tangential force } (M_t)} = 0 \quad (3)$$

, where the subscripts *th, i, m, r*, and *l* stand for the thumb, index, middle, ring and little finger respectively. The superscript *n* and *t* indicate the normal and tangential force components. *d* and *r* are the moment arms, which are orthogonal to the each force component. Theoretically, *d* can be changed during the trials due to finger tip movement along the Y-axis, while *r* is a constant (half of the grip width).

Finger Inter-dependency Index (FII)

The finger inter-dependency (i.e., finger enslaving) was defined as the average non-task finger forces normalized by the task finger MVF (F^{j}_{max}). In order to quantify the digit inter-dependency, the following calculation was used (Shim et al., 2008; Zatsiorsky et al., 2000):

$$FII_j = \left[\left(\sum_{i=1}^{n} F^{ij} / F^{j}_{max} \right) / n - 1 \right] \times 100\% \tag{4}$$

, where $i \neq j, n = 4$. F^{ij} is a force production by non-task finger (i) during the j finger maximum force task. Normal force components of fingers were used for this calculation.

Proximity Index (PXI)

In order to test the proximity hypothesis (the idea that the closer the non-task fingers are to the task finger, the greater the enslaving force produced), a proximity index (PXI_k) was calculated as the average value of non-task finger forces across the anatomical rank from the task fingers (Zatsiorsky et al., 1998, 2000). Non-task finger forces were normalized by the individual finger maximal force measured during the single-finger MVF task (Eq. 5).

$$PXI_k = \left[\sum^{m} (F^{k} / F^{k}_{max}) / m \right] \times 100\% \tag{5}$$

,where *k* represents the first, second, and third adjacent fingers to the task finger. During middle finger task, for example, k=1 for the index and ring fingers and k=2 for the little finger. F^k is a force production by the *k*-th non-task finger. F^{k}_{max} is the maximal force produced by the *k*-th finger during single finger MVF task. *m* indicates the number of non-task fingers within each calculation of the first-, second-, and third-ranked non-task fingers. *PXI* represents the non-task finger force averaged across the finger of the same anatomical ranks. The normal force components of fingers were used for this calculation.

Mechanical Advantage Index (MAI)

In order to test the mechanical advantage hypothesis, non-task fingers were classified into two types of antagonist (ANT) fingers based on the different moment arms caused by parallel finger connections. The moment arm of antagonist 2 (ANT2) is longer than that of antagonist 1 (ANT1). ANT fingers produce the opposite directional moment to the moment of the task fingers. For example, when the task finger is an index finger, the direction of the moment of normal force by the middle finger is equal to that by index finger (i.e., agonist) while the normal forces of the ring and little finger would produce moment in the opposite direction of the moment of the task finger (i.e., antagonist). The ring and little fingers are ANTs for the index finger task. The moment arm of ring finger normal force is shorter than that of little finger so the ring and little fingers are respectively classified as ANT1 and ANT2. The mechanical advantage indices (*MAI*) of the ANT1 and ANT2 for the given conditions were calculated using Eq. 6. We also calculated the *MAI* difference between the fixed and free object prehension conditions using Eq. 7 in order to investigate the effects of the rotational external constraint on static grasping tasks after removing internal constraints.

$$MAI_i^j = \left[\sum^{m} (F^{ij} / F_{\max}^i) / m \right] \times 100\% \quad (6)$$

$$MAI_{residual} = MAI_{fixed} - MAI_{free} \quad (7)$$

,where, i = {index, middle, ring, and little}, j = {ANT1, ANT2}, and m is the number of variables within each calculation. F^{ij} is a force production by the antagonist (j) during the i finger maximum force task. The calculations were performed on the normal forces only. $MAI_{residual}$ was obtained by subtracting the *MAI* of the fixed object prehension condition from the *MAI* of free object prehension condition.

4.3.5. Statistics

ANOVAs were used with the following factors: FINGER (the four levels of task fingers: index, middle, ring and little finger, or two levels: peripheral and central fingers), TASK (the two levels of prehension tasks: the fixed object and the free object), RANK (the three levels of anatomical ranks of fingers: first, second, and third), and ANTAGONIST (two levels of antagonist fingers: ANT1 and ANT2). The factors were chosen based on particular comparisons. Linear regression was employed in order to characterize the relationship between the thumb's normal force and the task-finger's normal force for the fixed and free object prehension tasks. Significance for all statistical tests was set at $\alpha = 0.05$.

4.4. Results

During the free object prehension task, subjects held the handle quasi-statically while receiving feedback regarding the real-time angular position of handle. Although only the real-time feedback of angular position was given to the subjects, the root-mean-square (RMS) errors of linear positions with respect to all three axes were very small for all tasks (T-task: 0.53 ± 0.13cm, I-task: 0.51 ± 0.08cm, M-task: 0.45 ± 0.11cm, R-task: 0.52 ± 0.08cm, L-task: 0.45 ± 0.09cm, TIMRL-task: 0.54 ± 0.11cm). Substantial force production by non-task fingers was apparent during both fixed and free object prehension (Table 4.1).

Table 4.1.Digit normal forces during single digit MVF tasks under the fixed object and the free object prehension.

	Fixed object prehension				
Task-Finger	T	I	M	R	L
T	**100.0 ± 0.0**	43.1 ± 8.3	23.1 ± 6.5	28.0 ± 5.1	37.9 ± 5.3
I	61.4 ± 9.2	**100.0 ± 0.0**	15.2 ± 4.2	15.5 ± 3.7	20.5 ± 4.3
M	54.7 ± 7.0	24.0 ± 1.6	**100.0 ± 0.0**	32.0 ± 3.6	10.1 ± 3.2
R	36.4 ± 6.3	14.3 ± 1.7	29.2 ± 2.9	**100.0 ± 0.0**	33.4 ± 6.5
L	30.6 ± 6.2	15.3 ± 1.8	6.2 ± 1.8	46.0 ± 3.9	**100.0 ± 0.0**
TIMRL	**52.0 ± 14.3**	**29.6 ± 7.6**	**31.3 ± 10.9**	**42.9 ± 9.4**	**54.2 ± 12.8**
	Free object prehension				
Task-Finger	T	I	M	R	L
T	**100.0 ± 0.0**	58.6 ± 3.0	23.8 ± 3.5	38.2 ± 3.1	65.8 ± 6.6
I	100.8 ± 5.6	**100.0 ± 0.0**	12.5 ± 2.3	22.8 ± 3.4	46.6 ± 7.3
M	103.7 ± 7.7	23.9 ± 3.5	**100.0 ± 0.0**	31.1 ± 4.0	17.3 ± 3.3
R	102.9 ± 8.3	21.1 ± 3.0	32.5 ± 2.8	**100.0 ± 0.0**	31.7 ± 5.7
L	102.2 ± 9.0	48.8 ± 5.5	12.3 ± 1.2	37.4 ± 5.9	**100.0 ± 0.0**
TIMRL	**82.9 ± 13.0**	**42.5 ± 4.8**	**28.9 ± 6.2**	**35.5 ± 4.7**	**43.6 ± 6.5**

The values in the table show the digit forces, normalized with respect to the maximum force during the single-digit MVF tasks. The registered values of the multi-digit task (TIMRL-task) were normalized by each single-digit MVF value. The digits investigated during these MVF tasks were the thumb (T), index (I), middle (M), ring (R), and little finger (L). The values above are mean ± SE.

4.4.1. Finger Inter-dependency Index (FII)

In general, the FII values of lower fingers (i.e., ring and little fingers) were greater than those of upper fingers (i.e., index and middle fingers) for both fixed and free object conditions. However, the FII values of peripheral fingers (i.e., index and little finger) under the free object condition were greater than those under the fixed object condition (Fig. 4.2), while the central fingers (i.e., middle and ring) did not show a difference between the two task conditions. These results were confirmed by a two-way repeated-measured ANOVA with the factors FINGER (four levels) and TASK (two levels). The effect of the factors and their interaction were statistically significant [FINGER: $F(3, 27) = 26.380$, $p < 0.005$; TASK: $F(1, 9) = 16.03$, $p<0.01$; FINGER × TASK: $F(3, 27) = 6.70$, $p<0.01$]. Pair-wise comparisons showed that FII values of the fixed and free object conditions were different in the index and little finger tasks ($p<0.01$).

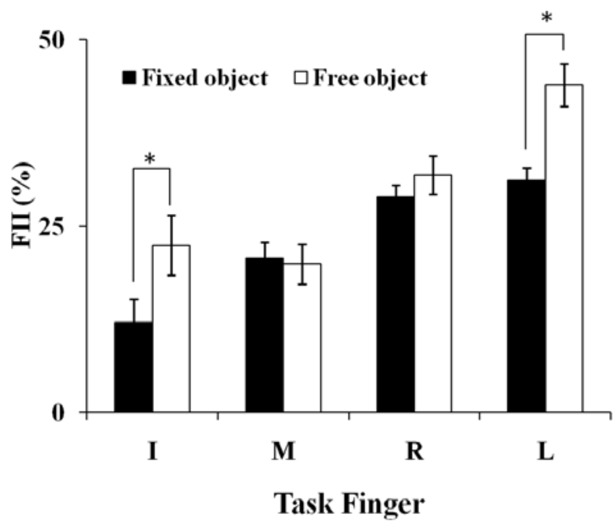


Figure 4.2. Finger inter-dependency indices (FII) of task-fingers during fixed and free object prehension. The average values across subjects are presented with standard error bars. * represents statistical significance (p<.05)

4.4.2. Proximity Index (PXI)

PXI values of the first RANK finger was greater than that of the second and third ($1^{st} > 3^{rd} > 2^{nd}$) during the fixed object prehension. During the free object prehension, however, the PXI of the third was the largest ($3^{rd} > 1^{st} > 2^{nd}$). The PXI values during the free object prehension were greater than those during the fixed object prehension, particularly in the 2^{nd} and 3^{rd} ranked non-task fingers (Fig. 4.3). These results were supported by a two-way repeated-measured ANOVA with the factors RANK and TASK. The effect of these factors and their interaction were statistically significant [RANK: F (2, 18) = 37.79, p<0.01; TASK: F (1, 9) = 33.38, p<0.01; RANK × TASK: F (2, 18) = 56.23, p<0.01]. Pair-wise comparisons showed that PXI values between the two levels of prehension tasks (i.e., fixed and free object) within the second and third RANK non-task fingers were significantly different (p<0.01).

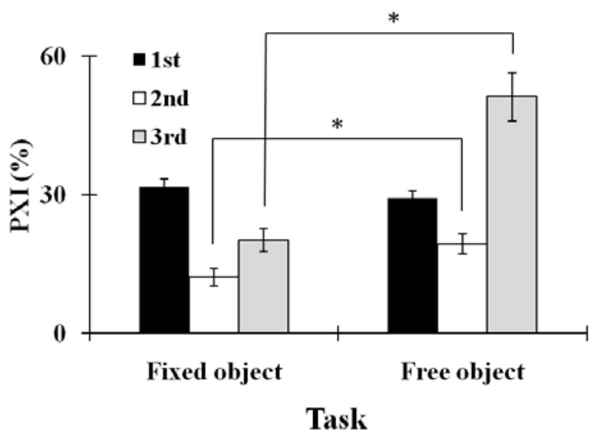


Figure 4.3. Proximity Indices (PXI) (%) during fixed and free object prehension tasks. The anatomical ranks were defined as the anatomical position of the non-task finger from the task-finger. The 1^{st} is the non-task finger that is the closest to the task finger. The average values across subjects are presented with standard error bars. * represents statistical significance (p<.05)

4.4.3. Mechanical Advantage Index (MAI)

During the fixed object condition, the MAI of ANT2 was greater than the MAI of ANT1 during the central finger tasks (i.e., middle and ring finger tasks), while the MAI between ANT1 and ANT2 did not show a significant difference in the peripheral finger tasks (i.e., index and little finger tasks) (Fig. 4.4a). On the contrary, the MAI of ANT2 was greater than ANT1 during the free object prehension peripheral finger tasks, while the MAI of ANT2 is smaller than ANT1 during the central finger tasks (Fig. 4.4b). A significant difference between the $MAI_{residual}$ of peripheral finger tasks and central finger tasks was observed only in ANT2. However, a significant difference between the $MAI_{residual}$ of ANT1 and ANT2 was identified only in the peripheral finger tasks (Fig. 4.4c). A two-way repeated-measured ANOVA with the factor FINGER (two levels: peripheral and central finger tasks) and ANTAGONIST (two levels: ANT1 and ANT2) supported this finding. The effect of the factors and their interaction was statistically significant at $p<0.05$ [FINGER: $F(1, 9) = 43.88$, $p<0.01$; ANTAGONIST: $F(1, 9) = 31.83$, $p<0.01$; FINGER × ANTAGONIST: $F(1, 9) = 29.85$, $p<0.01$]. Pair-wise comparisons between the MAIs of ANT1 and ANT2 within peripheral finger tasks (Fig. 4.4c) showed significant differences ($p<0.01$).

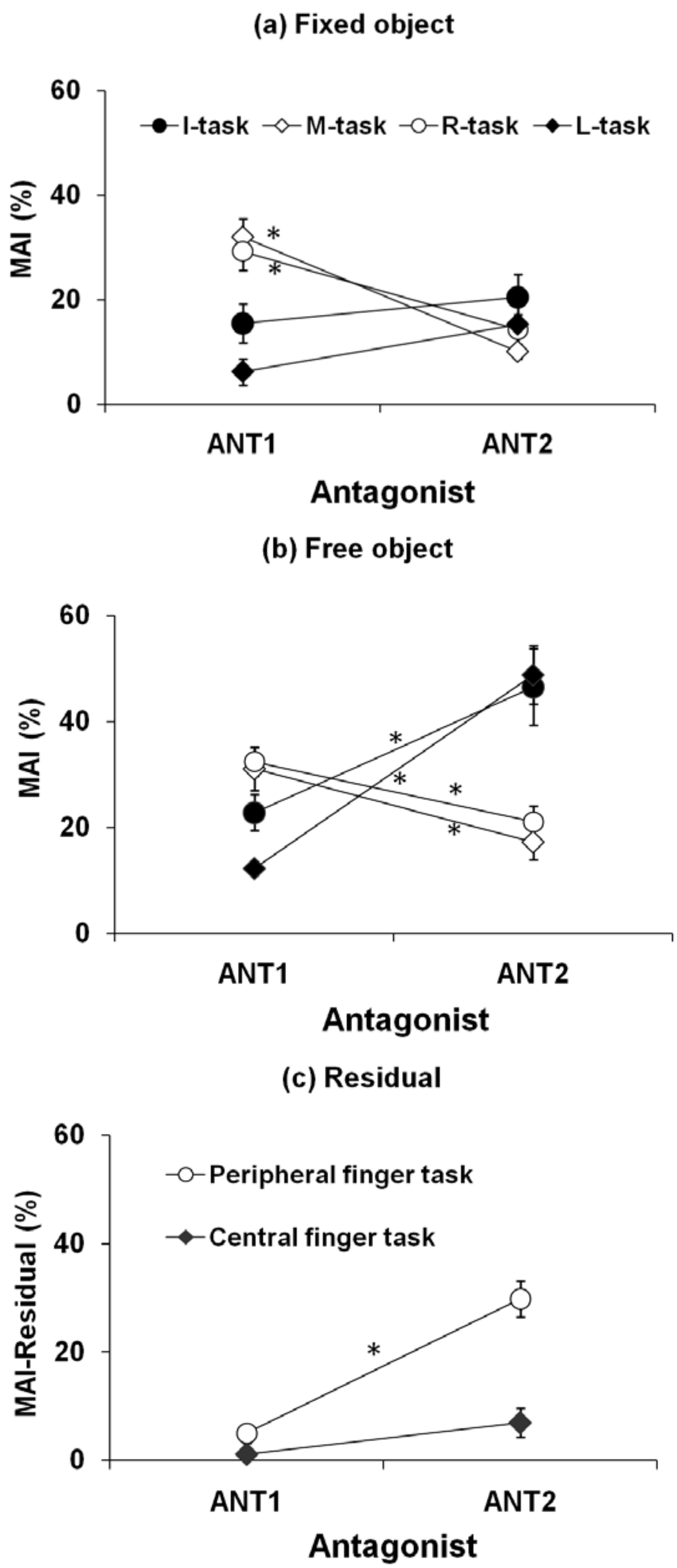
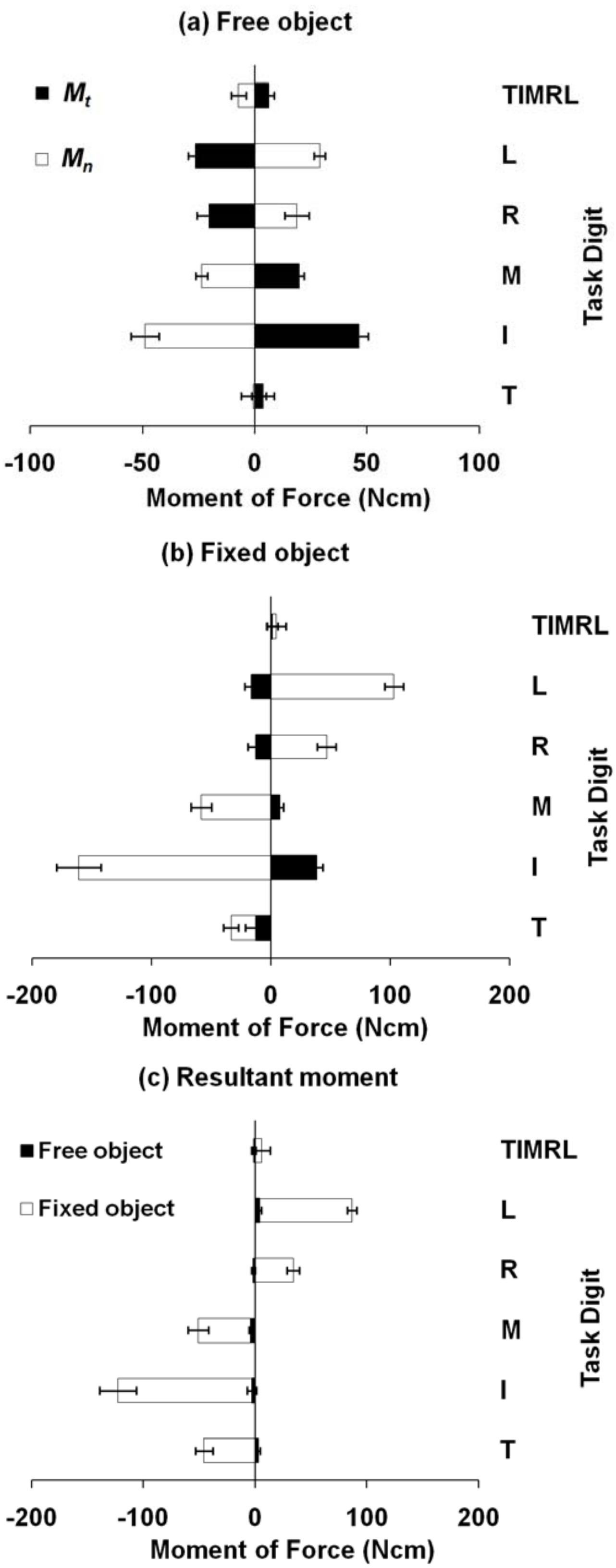

(a) Fixed object
I-task
M-task
R-task
L-task
MAI (%)
60
40
20
0
ANT1
ANT2
Antagonist
(b) Free object
MAI (%)
60
40
20
0
ANT1
ANT2
Antagonist
(c) Residual
Peripheral finger task
Central finger task
MAI-Residual (%)
60
40
20
0
ANT1
ANT2
Antagonist

Figure 4.4. echanical advantage Indices (MAI) of ANT1 and 2 at each finger task during (a) fixed object prehension and (b) free object prehension. (c) $\mathrm{MAI}_{Residual}$ (= $\mathrm{MAI}_{Fixed} - \mathrm{MAI}_{Free}$). The average values across subjects are presented with standard error bars. * represents statistical significance ($p < .05$)

4.4.4. Contribution of moment of normal force and tangential force to the total moment

During the free object prehension, the percent contribution of the moment of the normal forces (M_n) and the moment of tangential forces (M_t) to the resultant moment (M_{tot}) was almost 50% of each (Fig. 4.5a). The normal and tangential moments worked in opposite directions for all tasks. The two moment components canceled each other out, producing the zero resultant moment during the free object condition (Fig. 4.5c). On the contrary, the resultant moment $(M_n + M_t)$ was not zero during the fixed object prehension (Figs. 4.5b and c), as the resultant moment was not required to be zero during the fixed object prehension. Specifically, the pronation moment was produced in the thumb, index and middle finger tasks, whereas the supination moments were generated in the ring and little finger task during the fixed object condition (Fig. 4.5c). All pair-wise comparisons showed significant differences of the resultant moment between two levels of prehension tasks (i.e., fixed and free object) except for TIMRL-task ($p<0.01$).



(a) Free object
M_t
M_n
TIMRL
L
R
M
I
T
Task Digit
-100
-50
0
50
100
Moment of Force (Ncm)
(b) Fixed object
TIMRL
L
R
M
I
T
Task Digit
-200
-100
0
100
200
Moment of Force (Ncm)
(c) Resultant moment
Free object
Fixed object
TIMRL
L
R
M
I
T
Task Digit
-200
-100
0
100
200
Moment of Force (Ncm)

Figure 4.5. Contribution of the moments of normal and tangential forces to the resultant moment of force during single-digit and multi-digit MVF tasks under **(a)** free object and **(b)** fixed object prehension. **(c)** Resultant moment of force during single-digit and multi-digit MVF tasks under fixed object and free object prehension. Positive and negative values represent the direction of produced moment, clockwise (supination) and counter-clock wise (pronation), respectively. The average values across subjects are presented with standard error bars.

4.4.5. Changes of thumb normal force with task finger normal force

In general, MVF of each task finger during the fixed object prehension was significantly greater than MVF during the free object prehension (e.g., Index: 42.83 ± 2.95 (Fixed) > 22.46 ± 1.87 (Free), Middle: 35.34 ± 1.84 > 24.27 ± 2.31, Ring: 27.46 ± 1.85 > 18.88 ± 2.61, and Little: 22.24 ± 1.35 > 15.43 ± 1.59, unit: N, $p<0.05$ for all). During the fixed object prehension, the normal force of the thumb as a non-task digit increased linearly with the target finger normal forces (Fig. 4.6a). In addition, the normal force of the thumb as a non-task digit was the same as normal force of the task fingers in each finger task. During the free object prehension, however, the thumb normal force was quite constant regardless of the magnitude of task finger force (Fig. 4.6b). These findings were confirmed by the linear regression analysis. The thumb normal forces were in direct proportion to the task finger force in the fixed object prehension (slope: 1, $r = 0.98$), while the slope of regression equation of the free object condition was zero (slope: 0, $r = 0.03$).

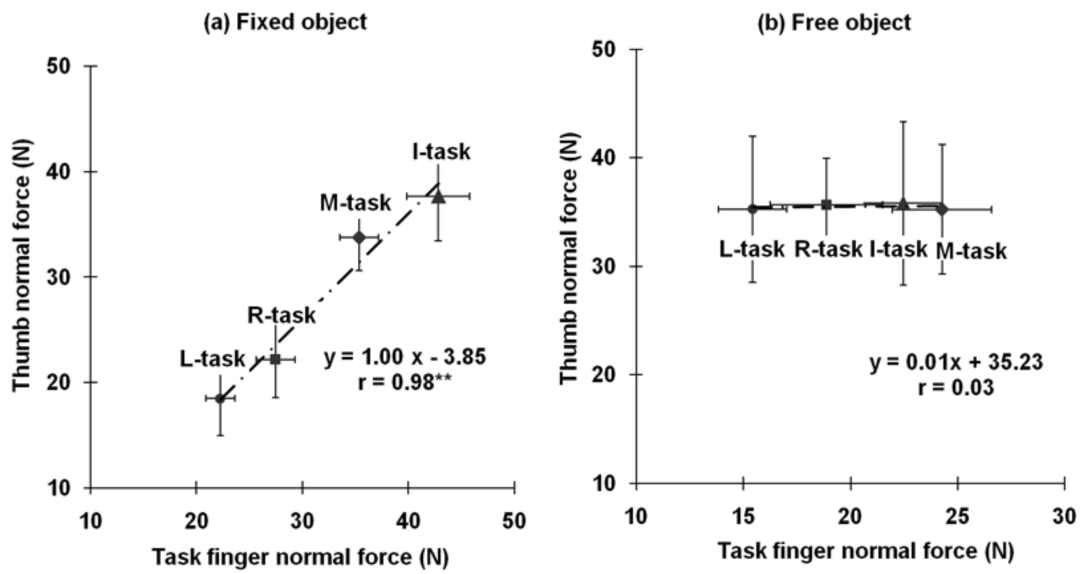


Figure 4.6. Relation between thumb normal force (F_n^{th}) and task finger normal force under **(a)** the fixed object prehension and **(b)** the free object prehension. Data averaged across all subjects are presented here with standard error bars. (**$p < .01$)

<u>*4.5. Discussions*</u>

This study investigated the digit force interactions during single-digit and all-digit maximum normal/grasping force production under a fixed object and a free object prehension conditions. The following topics are addressed in this discussion: (1) the proximity hypothesis vs. mechanical advantage hypothesis, (2) moment control with mechanical constraints, and (3) scaled thumb force with mechanical constraints.

4.5.1. Proximity hypothesis vs. mechanical advantage hypothesis

Previous studies on finger inter-dependency employed finger pressing tasks (Shinohara, Latash, & Zatsiorsky, 2003; Zatsiorsky et al., 1998) rather than more functional grasping tasks. The main purposes of these previous studies were to examine the finger force interaction caused by the internal constraints such as biomechanical and central constraints (Hager-Ross & Schieber, 2000; Latash et al., 2002; Li, Dun, Harkness, & Brininger, 2004; Zatsiorsky et al., 1998, 2000).

In this study, we employed two prehension tasks, i.e., fixed object and free object prehension, to investigate finger inter-dependency with and without the static rotational constraint. In this study, the fixed object condition was similar to pressing tasks against a vertical surface as opposed to pressing a horizontal surface, which involves the thumb. Olafsdottir and her colleagues reported that indices of digit interaction when the thumb acted in parallel to the fingers were similar to those when the thumb acted in opposition to the fingers (Olafsdottir et al., 2005). The task employed in their study was to press the sensors by digits against a horizontal surface, and it is questionable whether there is a significant difference regarding digit interactions between the pressing task against a vertical surface and a horizontal surface. Although it is still questionable whether the fixed object condition can be qualified as prehension task, we considered it as a prehension task because all hand digits were involved in the tasks and formed the opposition (Naiper, 1956, 1962) in the same way as free object condition. The grasping configuration of the hand during the fixed object condition was designed to be similar to that of free object condition in order to compare the two prehension conditions.

Our assumption was that both internal and external constraints (i.e., static rotational constraint) have influences on the actions of non-task fingers during free object prehension while only the internal constraints affect the non-task fingers' actions during mechanically fixed object prehension. During the fixed object prehension, the external force produced by digits engaging with the handle can be of any magnitude and direction because there was no prescribed condition among finger forces during fixed object prehesion (Shim et al., 2004). Supposedly, the force combinations amongst digits would follow the controller's specific principles rather than the mechanical principles during the fixed object condition.

During the fixed object prehension in the current study, it was obvious that the magnitude of non-task finger force by the neighboring fingers was greater than that of other fingers farther away from the task finger. However, the digit force interaction between digit forces during the free object prehension did not follow the finger force profiles observed in the fixed object prehension. We assume that the CNS strategies for controlling the digit force would alter according to the task mechanics (i.e., mechanical constraints) during the static free object prehension. In other words, the CNS employs an alternative strategy which follows mechanical principles such as force and moment equilibrium for the free object prehension.

We hypothesized that the non-task finger force profiles follow the mechanical advantage hypothesis during the free object prehension because using mechanical advantage would be the effective way to reduce the total digit force and satisfy the moment equilibrium. Several previous studies considered mechanical advantage as the CNS's primary strategy to control moment of force during prehension (Shim et al., 2004; Zatsiorsky et al., 2002). However, the results of the current study suggest that only peripheral finger tasks (i.e., index and little finger tasks) follow the mechanical advantage hypothesis, whereas the control of central finger tasks (i.e., middle and ring finger tasks) was supported more by the proximity hypothesis. The digit forces during the free object prehension are presumably explained by both the controller's specific principle for governing the redundant hand system and the mechanical principles in order to satisfy task mechanics. Assuming that both internal and external mechanical constraints are linearly superposed, the $MAI_{Residual}$ should follow the mechanical advantage hypothesis. Theoretically, individual finger force is linearly dependent on the mechanical advantage of the individual fingers during the voluntary torque production task (Shim et al., 2005). However, this expectation was only fulfilled in peripheral finger (i.e., index and little finger) tasks. In other words, the mechanical advantage hypothesis as the CNS's strategy for governing force production by non-task fingers does not apply to all finger tasks, and is not linearly independent from other CNS strategies used during the free object prehension task. We assume that the torque demand by the central finger might not reach a sufficient level for the mechanical advantage strategy, resulting in the continued manifestation of the proximity hypothesis in the control of non-task fingers. If this assumption is true, the level of torque demand indicates the borderline where these two strategies intersect. Investigating this borderline would be an interesting future experiment. Furthermore, the mechanical constraints in the current study contain all three subsets of two-dimensional constraints (e.g., horizontal translation, vertical translation, and rotational equilibrium). The effects of different combinations of sub-mechanical constraints and the relationship with internal constraints remain to be explored.

4.5.2. Moment control with mechanical constraints

Digit normal forces were the primary force components during the tasks in the current study because the task was to produce maximum normal force and tangential force was not required with the counter-balance load. If the gravitational effect of the handle was taken into consideration, the magnitude of tangential force would have been mainly determined by considering the weight of the object. This suggests that the slip prevention associated with relationships between normal and tangential forces could be a meaningful issue (Flanagan, Burstedt, & Johansson, 1999; Johansson, Backlin, & Burstedt, 1999; Pataky, Latash, & Zatsiorsky, 2004; Westling & Johansson, 1984), and that the interpretation of tangential force production should include the force direction in terms of object weight (Kinoshita, Backstrom, Flanagan, & Johansson, 1997; Westling & Johansson, 1984), slip prevention (Wheat, Salo, & Goodwin, 2004; Zatsiorsky, Gao, & Latash, 2003), and moment equilibrium (Gao, Latash, & Zatsiorsky, 2005b; Latash, Shim, Gao, & Zatsiorsky, 2004; Shim et al., 2005; Zatsiorsky et al., 2002). The relationship between grasp force (i.e., normal force) and load force (i.e., tangential force) was linear (Kinoshita, Kawai, & Ikuta, 1995; Monzee, Lamarre, & Smith, 2003) in cases where the load force is a necessary force component during the task. In the present study, however, the task was to produce single-digit or all-digit normal forces, and the tangential force was necessary in neither the fixed object nor free object prehension conditions. This suggests that the tangential force does not have a mechanical reason to be coupled with the normal force. The approaches to answering the role of tangential force in the current study are different from the previous studies. During data analysis, it became clear that the direction of moment of resultant tangential forces $(\sum M_t)$ was opposite to that of the resultant of normal force $(\sum M_n)$ even though the ratios of the moment of normal and tangential force were varied with the experimental conditions. We then investigated how the CNS controls an inevitable tangential force production. The results showed that the percent distributions of normal and tangential force were almost 50% for both components of force throughout all task digits during the free object condition. There are two possible ways to satisfy the moment equilibrium regarding normal and tangential force control for the free object prehension in the current experiment. The first would be to minimize the sum of the moments of the normal forces (Flanagan et al., 1999). The second would be to produce the opposite directional moment of tangential forces to the moment of normal force (Zatsiorsky et al., 2003). Considering the results of the normal and tangential force contributions to the resultant moment (Fig. 4.5), it seems that the CNS utilizes both strategies to maintain the moment equilibrium. The first strategy for moment equilibrium (i.e., the minimization of resultant moment of normal force) can be explained by the mechanical advantage hypothesis. Because the peripheral fingers (e.g., index and little finger) showed the greater *MAI* (i.e., greater non-task fingers normal forces) than the central fingers did and the two peripheral fingers' normal forces produced opposite directional moments, the moment of resultant normal forces during the free object prehension could be less than the moment of resultant normal forces during fixed object prehension. However, the minimization of the moment of resultant normal forces employing the mechanical advantage hypothesis was not enough to produce zero resultant moment of forces. Therefore, the CNS also employed a second strategy for moment equilibrium (i.e., the production of a force of the same magnitude but working in the opposite direction of the tangential force's moment). This finding coincided with the fact that one half of the torque was exerted by the tangential force during the free object prehension in a previous study (Zatsiorsky et al., 2003). In the analysis, we only considered the normal forces of individual digits to compute the mechanical advantage index. The lever arms for the tangential forces of individual digits are the same, meaning that there was no difference on the mechanical advantage of tangential force production among digits.

Mechanically speaking, TIMRL- and T-tasks can be considered a pressing task regarding the action of fingers. In comparing the components of force production seen during the fixed object prehension, the ratio of non-task fingers' normal forces to the tangential force under the free object condition was greater than under the fixed object condition (Fig. 4.5a and 4.5b). The magnitudes of moments either of normal or of tangential force in the TIMRL- and T-tasks were smaller than those of any other tasks. We can infer that the principle of the minimization of the secondary moment, the sharing pattern between finger forces as a way to minimize secondary moments like the pronation and supination moments (Li, Zatsiorsky, Li, Danion, & Latash, 2001; Zatsiorsky et al., 2000), would be valid during prehension. Nevertheless, it is still questionable whether the principle of the minimization of secondary moment is valid during the prehension task when that task includes a gravitational effect.

4.5.3. Scaled thumb force with mechanical constraints

The flexor pollicis longus (FPL) muscle is a flexor of the thumb, and is considered an anatomically independent muscle. This implies that the FPL does not contribute to other fingers' movements (Brand & Hollister, 1999). In other words, it is assumed that there is no known muscle-tendon connection between thumb and other fingers for the flexion. However, the recent investigation by Yu and colleagues revealed the neural coupling between FPL and the flexor of the index finger by showing peripheral force transfer to the index finger (Yu, Kilbreath, Fitzpatrick, & Gandevia, 2007). In this study, there was an evident relationship between thumb enslaving force and task-finger force. Indeed, the force of the thumb as a non-task digit was increased with the task-finger forces under the fixed object prehension. Thumb forces were constant regardless of the task-finger forces during the free object prehension (Fig. 4.6). It is reasonable to interpret this as evidence that the interaction between the thumb and fingers is caused mainly by the central constraints, not the anatomical connection. Earlier studies found in-phase changes between the thumb and finger forces in the frequency domain during prehension tasks (Rearick & Santello, 2002). Combining this previous finding with our results, we can conclude that the interaction between the thumb and the finger forces is explained by the phase-relationship (in-phase) and the scaled amplitude, where amplitude is the scaled finger force incorporating the thumb force during the fixed object prehension. Presumably, these two phenomena are caused by the central constraint. However, when the mechanical constraints were imposed in the hand-held object system, the magnitudes of finger normal forces were not scaled, but were instead limited due to the task constraint (i.e., normal force constraint). It was shown that the thumb normal forces were constant across all single-finger MVF tasks (i.e., I-, M-, R-, and L-tasks), meaning that total normal force produced by all fingers was the same across all single-finger MVF tasks for the free object condition. Therefore, the thumb normal force seems to be a limiting factor for the force production in task fingers during free object prehension. During free object prehension, the CNS considers task mechanics so that the interaction strategy between the thumb and the fingers is different from the strategy employed in the fixed object prehension.

The thumb forces as non-task digits were similar to the thumb maximal force during the free object prehension. This implies that the thumb force remains the same for all task finger conditions in much the same way the maximal force production ability does under the free object condition, whereas finger forces were shared within the thumb force magnitude considering the force and moment constraints. These interactions between the thumb and finger forces could be explained solely by the central constraints. Previous studies performed by Schieber and colleagues have revealed that each set of muscles is not controlled from a somatotopically distinct region of the primary motor cortex (M1) (Schieber, 1996). More recent studies have revealed that the inter-dependency between the thumb and fingers was an evident phenomenon of the human digits' actions (Olafsdottir et al., 2005; Yu et al., 2007). The current study also supports this view. This suggests that an independent set of flexor and extensor muscles for each digit does not fully account for digit movements.

Even the somatotopy of M1 is not spatially segregated; rather, it encompasses several spatially overlapped M1 neurons (Dechent & Frahm, 2003; Schieber, 2001).

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Chapter 5: Prehension synergy: effects of static constraints on multi-finger torque production tasks

Chapter 5 will be submitted to a journal for publication

5.1. Abstract

This study tests the principle of superposition in multi-digit fixed and free object prehension. There were twelve experimental conditions: two task conditions (i.e., fixed and free object prehensions) with two torque direction (i.e., supination and pronation) and three torque magnitudes: -0.70, -0.47, -0.24 Nm). The subjects performed 25 trials while producing assigned task moment during fixed object prehension or maintaining constant position of the hand-held object against external torques during free object prehension. For the 25 trials in each condition, Pearson coefficient correlations between force and moments of the thumb and virtual fingers were computed in order to test the principle of superposition by examining significant correlations necessitated by the task mechanics and significant correlations not required by the task mechanics. For both free and fixed object conditions, the thumb normal force was highly correlated with the VF normal force across 25 trials, meaning the coupling of thumb normal force and VF normal force was not affected by the prescribed condition of grasping force. In addition, grasping stability control and rotational equilibrium control were decoupled during both free object prehension as well as fixed object prehension. During fixed object prehension, coupling of thumb and virtual finger forces was not mechanically necessitated/constrained in either normal direction (equal and opposite grasping forces) or tangential direction

(compensating the weight of the object). This result suggests that the principle of superposition is valid regardless of the mechanical constraints in human static prehension.

5.2. Introduction

In order to maintain stable static grasping and prevent slipping of hand-held objects, the central nervous system (CNS) needs to satisfy a set of static constraints. When the number of independent variables is greater than the number of constraints (i.e., motor redundancy), infinite combinations of digit forces and moments are possible for a static prehension task (Pataky et al., 2004a; Shim et al., 2003b, 2005a; Zatsiorsky et al., 2002). The 'principle of superposition', originally suggested in robotics (Arimoto & Nguyen, 2001), has recently been suggested as a strategy that the CNS uses to control the redundant multi-digit human prehension system. According to the principle of superposition, a complex action can be broken down into two commands, which are linearly superposed so that sub-actions are independently controlled. Recent research suggests that grasping stability control and rotational equilibrium control are decoupled in human static grasping tasks (Shim et al., 2005b; Zatsiorsky et al., 2004). In other words, one set of variables (e.g., normal forces of digits) is associated with grasping force control, while the other subset (e.g., the moment of normal forces, the moment of tangential forces, and tangential forces of digits) is related to the torque control (rotational equilibrium) in a static condition. Further, the 'chain-effect' (i.e., the sequence of local cause-effect adjustment imposed by the task mechanics) of elemental variables in multi-finger free object prehension task provided evidence that the elemental variables (i.e., digit forces and moments) showed a linear relationship while satisfying the task mechanics (Shim et al., 2005a; Zatsiorsky et al., 2004).

Previous studies have employed free object (i.e., the object can be translated or rotated freely in any direction) static prehension to study the principle of superposition and chain effect (Shim et al., 2005a, 2005b; Zatsiorsky et al., 2004). Finger forces and moments during a static multi-finger prehension task change conjointly to satisfy task mechanics such as the linear and rotational equilibriums. It has been reported that there are two independent subsets which were associated with linear and rotational control of a hand-held object. For a free object static prehension, there exist three main sub tasks (constraints) when the forces and moments in the grasping plane (i.e., 2-dimensional plane the finger and thumb contacts form) are considered. In this paper, the term "constraint" is used to describe confined mechanical relation between elemental variables, which are expressed as mathematical equations and supposedly controlled in a certain way. If the relation(s) is not satisfied, the required stasis (e.g., static equilibrium) of the system will not be maintained. The three mechanical constraints for static prehension are (1) the thumb's normal force and the sum of a finger's normal force should be equal in magnitude (horizontal translation constraint), (2) the sum of digit tangential forces should be equal to the weight of the object (vertical translation constraint), and (3) the sum of moments of normal and tangential forces should be equal to zero (rotation constraint). The free object static prehension contains all three mechanical constraints (i.e., task constraints) in a two-dimensional grasping plane. In the multi-digit static prehension tasks, the hierarchical organization of finger force control (i.e., hierarchies of synergy (Latash, 2008)) has been suggested based on the notion of the virtual finger (VF), the vector sum of individual finger forces/moments, and individual finger (IF) levels (Gorniak, Zatsiorsky, & Latash, 2009; Latash, Shim, & Zatsiorsky, 2004; Scholz et al., 2003; Shim et al., 2003b; Shim & Park, 2007). The hierarchical organization during multi-digit control suggests that the CNS coordinates the actions of individual fingers in order to stabilize the actions of the VF (i.e., higher level control), and the coordinated actions of the thumb and the VF directly affect the stabilization of performance variables described by the mathematical constraints equations. The three mechanical constraints mentioned above, therefore, can be expressed by the VF level variables. They describe the performance variables to be stabilized such as stable grasping and rotational equilibrium controls during multi-digit manipulation tasks. Hence, the controls at the IF level and thumb-VF level are performed by forming two control hierarchies: the IF level (lower level) and thumb-VF level (higher level). The number of elemental variables in the lower level are definitely larger than the number of task mechanics for static prehension tasks of a free object in a two dimensional space (i.e., 15 unknown variables > 3 constraints equation). It is a redundant system; an infinite combination of elemental variables can be possible solutions for a static prehension task. When it comes to the VF level, the number of elemental variables (i.e., normal and tangential forces of the thumb and VF, and moment arm of VF normal force) is also larger than the number of constraints, meaning that the system on the VF level is also redundant (or abundant). The notion of synergy has been suggested as a possible solution to the redundant human hand system in either higher level control or lower level control (Kang et al., 2004; Latash, Li, & Zatsiorsky, 1998; Li et al., 1998; Santello & Soechting, 2000; Zatsiorsky et al., 2003). Previous studies on multi-finger pressing (Li et al., 1998; Shinohara et al., 2003), multi-digit rectangular object (Shim et al., 2004, 2005, 2006a) as well as a circular object (Shim & Park, 2007) clearly showed that the CNS makes fine adjustment of IF force or moment to stabilize higher level variables (i.e., VF force and moment).

Prehension tasks employed in previous studies focused on static free object prehension against external torques (Shim et al., 2003b; Zatsiorsky, Gao, & Latash, 2003a; Zatsiorsky et al., 2002), and partially prescribed the relations between VF level variables (i.e., thumb and VF forces and moments) so that the possible solutions of redundant system relied on both controller's specific principles and mechanical principles. If the hand-held object is mechanically fixed, however, the performer does not need to control the translation or rotation of the object. Hence, linear translation and rotation are 'restrained' during fixed object prehension, meaning that there was no mechanically constrained relation among elemental variables. Supposedly, the force combinations amongst digits would follow the controller's specific principles rather than the mechanical principles during the fixed object condition (Shim et al., 2004a). For this reason, some relations of the higher level variables in the hierarchy directly related to the stabilization of performance variables such as grasping forces (i.e., equal in magnitude) and the sum of tangential forces (i.e., equal to the weight of object) are not specified during the fixed object prehension. It has not been investigated whether these unspecified relations among VF level variables under the fixed object static prehension affect the synergic actions of IF level variables for stabilizing higher level variables.

In this study we used a free object and mechanically fixed object to investigate the effect of static constraints during a multi-digit prehension and to investigate how the CNS controls digits' force and moment against the imposed static constraints within tasks. Specifically, it is unknown whether the principle of superposition is valid in fixed object prehension when the scalar sums of IF normal forces and tangential forces are not necessarily required to be equal to the thumb normal force and the weight of object respectively. If the grasping stabilization, which has been proved to have a significantly high correlation between the normal forces of thumb and VF in trial-to-trial changes, is still maintained, and the other variables (excepting the two normal forces in the VF level) are grouped into independent subset, then we may expect to support the claim that the principle of superposition in static human hand prehension is valid regardless of static constraints within tasks. In addition, we tested whether the hierarchical control hypothesis (i.e., hierarchies of synergies) supports the action of IF during the fixed object prehension.

5.3. Methods

5.3.1. Subjects

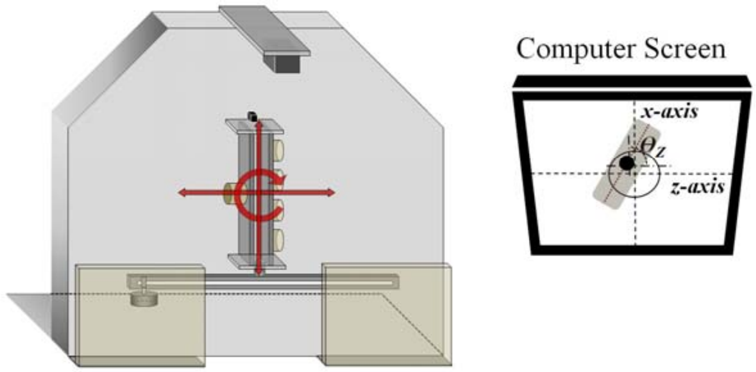
Seventeen right-handed male volunteers (age: 29 ± 3.1 years, weight: 67.1 ± 2.9 kg, height: 174.2 ± 5.3 cm, hand length: 18.7 ± 2.5 cm, and hand width: 8.7 ± 0.9) participated in the current experiment. The handedness was determined by the Edinburgh Handedness Inventory (Oldfield, 1971). No subject had a previous history of neuropathies or traumas to their upper extremities. The hand length was measured using the distal crease of the wrist to the middle fingertip when a subject positioned the palm side of their right hand and the lower arm on a table with all finger joints extended. The hand width was measured from the radial side of the index finger metacarpal joint to the ulnar side of the little finger metacarpal joint. Before testing, the experimental procedures of the study were explained to the subjects and the subjects signed a consent form approved by the University of Maryland.

5.3.2. Equipment

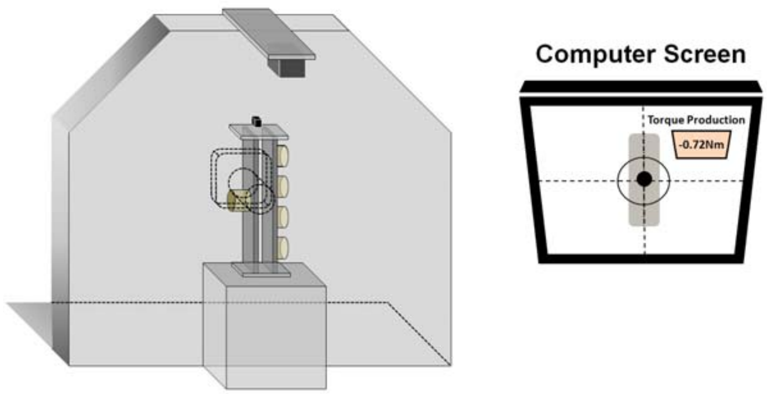
Two types of sensors were used to measure digit force and moment and to provide a real-time feedback to the subjects during trials. Five six-component (three force and three moment components) transducers (Nano-17s, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminum handle (Fig. 5.1c) in order to measure each digit's forces and moments. Pieces of 100-grit sandpaper with a friction coefficient of about 1.5 were attached to the surface of each sensor in order to increase the friction between the digits and the transducers. The vertical distances between the center points of adjacent sensors for fingers were 30mm; the center point of the thumb sensor was positioned at the midpoint between the center point of middle and ring finger sensors in the vertical direction. The horizontal distance between the contact points of the thumb sensor and other sensors was 68 mm. One six-component (three position and three angle components) magnetic tracking sensor (Polhemus LIBERTY, Rockwell Collins Co., Colchester, VT, USA) was mounted to the top of the aluminum handle in order to monitor the position of the handle and to provide feedback about the linear or angular positions of the handle during the free object prehension tasks. A magnetic sensor was attached to the front edge of a Plexiglas base; this Plexiglas construct was affixed to the top of the handle.

For the fixed object prehension task, the handle was mechanically affixed to the table (Fig. 1b) so that the orientation of the handle was kept constant. For the free object prehension task, a horizontal aluminum beam (45cm in length) was affixed to the bottom of the handle in order to hang a load (0.33kg) at different positions along the beam. A load at different positions along the beam generated different external torques due to its different moment arms. The analogue signals were routed to a 12-bit analogue-digital converter (a PCI-6031 and a PCI-6033, National Instrument, Austin, TX). LabView programs (LabView 7.1, National Instrument, Austin, TX) were developed and used to synchronously record the signals from the force/moment sensors and magnetic sensor. The Labview program automatically initialized the values of sensor signals to zero at the beginning of each trial. The sampling frequency was set at 50 Hz. Sampled data were digitally low-pass filtered with a 2^{nd} order Butterworth filter. The cutoff low frequency was set at 5 Hz (Gao, Latash, & Zatsiorsky, 2005a; Li, Latash, & Zatsiorsky, 1998).

(a)


Computer Screen
x-axis
θ_Z
z-axis

(b)


Computer Screen
Torque Production
-0.72Nm

(c)

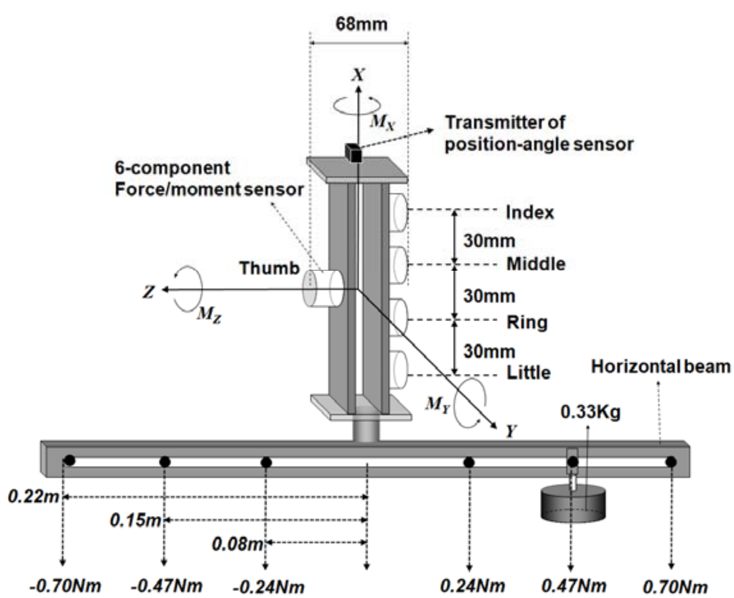

68mm
X
M_X
Transmitter of position-angle sensor
6-component Force/moment sensor
Index
30mm
Middle
Thumb
Z
M_Z
30mm
Ring
30mm
Little
Horizontal beam
M_Y
Y
0.33Kg
0.22m
0.15m
0.08m
-0.70Nm
-0.47Nm
-0.24Nm
0.24Nm
0.47Nm
0.70Nm

Figure 5.1. **(a)** Schematic illustration of experimental setup for the free object prehension (left) and position feedback (right). Arrows on the handle indicate that horizontal and vertical translations. Rotation about the axis orthogonal to the grasping plane are allowed during the free object prehension, but subjects have to maintain the static constraints. Real-time feedback of translation along *z*-axis (horizontal translation), translation along *x*-axis (vertical translation), and rotation about *y*-axis was provided using the magnetic position-angle sensor. **(b)** Schematic illustration of experimental setup for the fixed object prehension and torque feedback. The handle was mechanically fixed to the table so that translations and rotations were now allowed. Real-time feedback of produced moment of force was provided. **(c)** Detailed illustration of experimental 'inverted-T' handle/beam apparatus for the free object condition. The force-moment sensors, shown as white cylinders, were attached to two vertical aluminum bars. The transmitter of a magnetic position-angle sensor, marked out as a small black cube, was attached to the plastic base affixed to the top of the handle. M_X, M_Y, and M_Z are moments produced by the digits about *X*-, *Y*-, and *Z*-axes, respectively.

5.3.3. Experimental procedures

The two prehension conditions included the fixed object prehension and free object prehension. The subjects sat in the chair facing the computer screen with the right elbow joint flexed 90 degrees in the sagittal plane. The forearm was in a neutral position between pronation and supination. A height-adjustable chair was used to keep the right-arm joint configuration of each subject constant throughout the experiments. Prior to the actual experiments, the subject had an orientation session to become familiar with the experimental devices and to ensure that the subjects were able to perform the experimental tasks. There were twelve experimental conditions: two task conditions (i.e., fixed and free object prehensions) with six torque conditions about y-axis (supination efforts: -0.70, -0.47, -0.24 Nm; pronation efforts: 0.24, 0.47, 0.70 Nm). Negative and positive torques were generated by supination and pronation efforts, respectively.

For the fixed object condition, the handle was mechanically fixed to the table (Fig. 5.1b) in such a way that the handle could not be translated or rotated. For the fixed object prehension condition, subjects were asked to produce an assigned task moment as accurately as possible for three seconds (i.e., production of a constant moment). For the free object condition, the handle could be translated or rotated in any direction. The subjects were instructed to place each digit on the designated sensor (i.e., Thumb, Index, Middle, Ring, and Little) and keep all digits on the sensors during overall trials. The task for the subjects was to hold the handle while maintaining the constant linear and angular positions (i.e., maintaining static grasping; production of constant force and moment) of the handle against the given external torques. Thus, the subject had to maintain zero force and moment in order to keep the handle positioned statically. In order to avoid the rotation of the handle about the X-axis, two vertical racks were mounted on the table. These racks provided narrow gaps (1cm) for the horizontal beam. Subjects were asked to keep the horizontal beam inside the gaps. A feedback of real-time linear and angular positions of the handle was provided on the computer screen during the free object prehension task. The subjects were instructed to avoid handle rotation or translation and to minimize the angular and linear deviations of the handle. If the deviations exceeded the pre-defined criteria (rotation: $\sqrt{\theta_x^2 + \theta_y^2} < 1^\circ$ or translation: $\sqrt{x^2 + y^2} < 1\text{cm}$) during each trial, the data collection automatically stopped with beep sound, and the subject was asked to perform the trial again. Subjects were instructed to grasp the handle with as little effort as possible for both fix and free object prehension conditions. For each condition, twenty-five consecutive trials were performed. Thus, each subject performed a total of 300 trials (2 TYPEs × 3 MAGs × 2 DIRs × 25 trials = 300). Prior to the actual experiments, the subjects had a familiarization session, which included an explanation of the experimental procedures and a few practice trials. Two-minute breaks were given at the end of each trial in order to avoid fatigue effects. The order of the twelve four experimental conditions was balanced and no subject reported fatigue.

5.3.4. Data analysis

<u>Task constraints of static prehension in a 2D grasping plane</u>

The constraints model in this study was similar to the model employed in previous studies (Shim et al., 2003b, 2004a; Zatsiorsky et al., 2004). Because the analysis was limited to a static grasping in a two-dimensional grasping plane (i.e., planar static task), the task constraints within the conditions were also limited. The fixed object condition had only one constraint, whereas the free object condition had three. During the free object static prehension, the following three mechanical constraints (i.e., task constraints) had to be satisfied simultaneously in order to maintain a static equilibrium. During the fixed object, however, there was no constraint of linear translations (Eq. 1 and 2). The only task constraint to be satisfied during the fixed object condition was to produce assigned task moments (Eq. 3). The following equations describe these task constraints.

1) The sum of the normal forces of all four fingers should be equal to the normal force of the thumb (i.e., horizontal translation constraint)

$$F_{th}^{n} = F_{i}^{n} + F_{m}^{n} + F_{r}^{n} + F_{l}^{n} = \sum_{j} F_{j}^{n}, j = \{i, m, r, l\} \quad (1)$$

2) The sum of the digit tangential forces should be equal to the weight of the hand-held object (i.e., vertical translation constraint).

$$F_{th}^{t} + F_{i}^{t} + F_{m}^{t} + F_{r}^{t} + F_{l}^{t} = L \quad (2)$$

3) The resultant moment created by the digit forces should be equal and opposite to given external torques during the free object condition and be equal to task torques exerted on the object during the fixed object condition (e.g., the rotational constraint).

$$M_{TOT} = \underbrace{-F_{th}^{n} d_{th} + F_{i}^{n} d_{i} + F_{m}^{n} d_{m} + F_{r}^{n} d_{r} + F_{l}^{n} d_{l}}_{\text{Moment of normal force } (M_n)} + \underbrace{F_{th}^{t} r_{th} + F_{i}^{t} r_{i} + F_{m}^{t} r_{m} + F_{r}^{t} r_{r} + F_{l}^{t} r_{l}}_{\text{Moment of tangential force } (M_t)} = -Tq \quad (3)$$

, where the subscripts *th, i, m, r*, and *l* stand for the thumb, index, middle, ring and little finger respectively. The superscript *n* and *t* indicate the normal and tangential force components. *d* and *r* are the moment arms, which are orthogonal to the each force component. Particularly, *d* can be changed during the trials due to finger tip movement along the Y-axis, while *r,* half of the grip width, is constant.

Eq. 3 (i.e., rotational constraint) should be satisfied throughout all conditions while Eq. 1 and 2 should only be satisfied by the free object condition. Eq.3 is satisfied by producing assigned task torques with a real-time feedback of moment magnitude during the fixed object condition. However, Eq. 3 is also satisfied by maintaining constant handle position (i.e., linear and angular positions) against external torques during the free object condition. There were fifteen unknown variables (i.e., five normal, tangential forces, and the contact point of force application in the vertical direction) for all task conditions. Because the system could have twelve degrees of freedom under the free object condition and fourteen degrees of freedom under the fixed object condition, it is underdetermined system for both fixed and free object conditions. An infinite number of digit force and moment combinations can be possible solutions for the given tasks.

<u>Virtual finger (VF) level analysis</u>

Moment arm of Virtual finger (VF) normal force

The VF normal and tangential forces (F_n^{vf} and F_n^{th}) can be obtained by the vector sum of fingers' normal and tangential forces, respectively. Therefore, the action of the VF can be the same as mechanical effects produced by individual fingers (Arbib, Iberall, & Lyons, 1985; Gentilucci, Caselli, & Secchi, 2003; Iberall, 1997; Santello & Soechting, 1997; Shim et al., 2005b). The moment of the VF tangential forces was obtained by the sum of moment of finger tangential forces. The moment arm of finger tangential forces was constant (i.e., the half of the grip width) so the moment arm of VF tangential force was also constant. However, the moment arm of the normal VF was not constant and can be computed from the Varignon theorem (Eq. 1).

$$D_{vf}^{n} = \sum F_f^n d_f / \sum F_f^n \quad (4)$$

According to the Varignon theorem, the distributive property of vector products can be used to determine the moment of the resultant of several concurrent forces.

Correlations between *experimental variables at the virtual finger (VF) level*

For the 25 trials in each condition, Pearson coefficient correlation between selected experimental variables (e.g., $F_n^{th}, F_n^{vf}, F_t^{th}, F_t^{vf}, F_t, M_n^{vf}, D_n^{vf}, and\ M_t$) constructed simultaneous sequences of local cause-effect adjustments as predicted by the task mechanics (Fig. 5.2) [so called "chain effect"] in order to find a solution in this undetermined system. The 1st (i.e., correlation between the normal forces of the thumb and the VF, $F_n^{th} vs F_n^{vf}$) and 9th local chain (i.e., correlation between the tangential forces of the thumb and the VF, $F_t^{th} vs F_t^{vf}$) were necessitated by the task mechanics of horizontal and vertical translation constraints during the free object prehension. However, these two constraints were not necessitated during the fixed object condition.

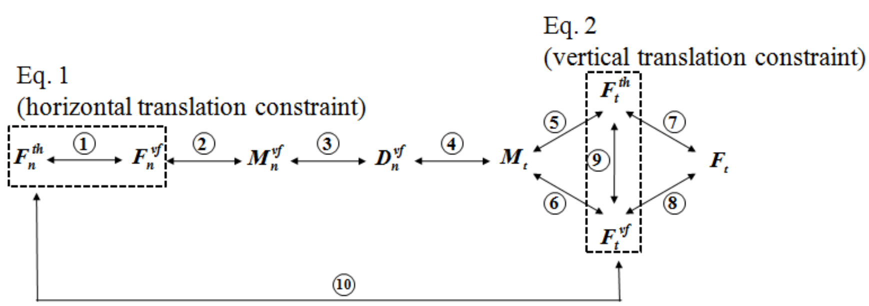


Figure 5.2. Schematic illustration of overall chains among VF level variables during multi-finger torque production tasks. The 1st and 9th local chains represent the constraints of horizontal and vertical translation, respectively.

A principle component analysis with a variance maximizing (varimax) rotation was also performed in order to find the number of linear combinations (principal components) among the variables at the VF level (i.e., thumb and VF normal and tangential forces, and moment arm of VF normal force). The Kaiser Criterion (i.e., extracted PCs should be the eigenvectors whose eigen-values are larger than 1) was employed to extract the principal components (PCs). Then, the number of significant PCs with 0.4 of cutoff loading coefficient (Krishnamoorthy et al., 2003; Shim & Park, 2007), which accounted for more than 95% of total variance, was counted.

The variances in thumb and VF normal forces spaces

The correlations of the 1st local chain ($F_n^{th} vs F_n^{vf}$) should be significant during the free object condition where the horizontal translations were constrained in a static prehension. Particularly, the scatter plot formed by pairs of two forces would be an ellipse or a circle in a two dimensional thumb and VF normal forces coordinates in Newton (N) because the data points cannot be perfectly aligned the null space of '$F_n^{vf} = F_n^{th}$' under the free object condition. Hence, we quantified the variances along (V_{null}) and orthogonal to the null space (V_{orth}) during both the fixed and free object (Fig. 5.3) conditions in order to examine and compare the scattered patterns of trial-to-trial changes of thumb and VF normal forces between experimental conditions.

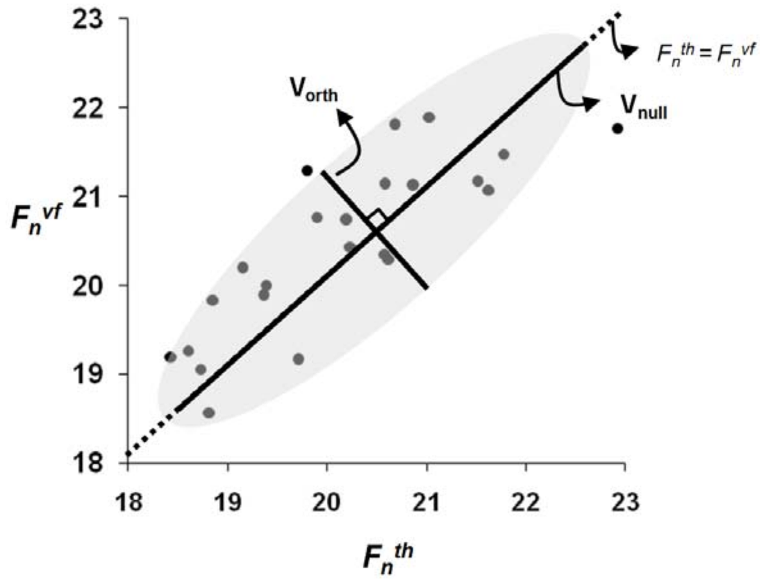


Figure 5.3. The variance in the null space of '$F_n^{vf} = F_n^{th}$' (V_{null}) and orthogonal to the null space (V_{orth})

Individual finger (IF) level analysis

Synergy index (ΔV)

The ΔV was computed in order to examine the synergistic actions of individual fingers. Four components of the ΔV were computed across the 25 trials for each condition: (1) normal force (ΔV_{Fn}), (2) tangential force (ΔV_{Ft}), (3) moment of normal force (ΔV_{Mn}), and (4) resultant moment of force (ΔV_{M}). The ΔV was obtained by subtracting the variance of the VF component (Var_{tot}) from the sum of variances of individual finger components $(\sum_{j=1}^{4} Var_j)$. These variables were normalized by the sum of variance of individual finger components (Eq. 5).

$$\Delta V_{Norm} = (\sum_{j=1}^{4} Var_j - Var_{tot}) / (\sum_{j=1}^{4} Var_j) \quad (5)$$

Agonist and antagonist moments

Both normal and tangential forces created moments about the same axis. Digit forces can create moments in the same or opposite direction to task moments. We defined the agonist and antagonist moment as the respective moment of digits' force in the required and the opposite directions of the task moments. The antagonist moment was calculated by summing up the moment of individual digits' normal and tangential forces that were against the task moments. Similarly, the agonist moment was calculated by summing up the moments of individual digit's normal and tangential forces in the intended direction. Lastly, the 'antagonist/agonist moment' ratio was computed in order to quantify the contributions of 'bad' (negative contributions) and 'good' (positive contributions) moments to task moments (Eq. 6 & 7). This process is represented in the equations below.

$$M_t^{ratio} = M_t^{ant} / M_t^{ago} \quad (6)$$

$$M_n^{ratio} = M_n^{ant} / M_n^{ago} \quad (7)$$

,where *n* and *t* represents normal and tangential forces, respectively; *ago* and *ant* stand for the agonist and antagonist, respectively.

5.3.5. Statistics

ANOVAs were used with the following factors: TYPE (two levels: fixed and free), MAG (three levels: 0.70, 0.47, and 0.23Nm), and DIR (two levels: pronation and supination efforts). These factors were chosen based on particular comparisons. The regression analysis between elemental variables was performed at the VF level, and the Pearson's coefficients of correlation (r) were computed in MATLAB. The p-value of statistical significance was set at p <.01 for both the ANOVA and regression analysis. The sample size (n) of each regression analysis was 25 (i.e., 25 consecutive trials for each condition and subject). We assumed that the correlation coefficients are statistically significant as long as r is larger than 0.5, which gives a power=0.8 (α = .05) with 25 of sample size.

5.4. Results

5.4.1. Normal force production at the virtual finger (VF) level

In general, both thumb and virtual finger (VF) normal force increased systematically with the magnitudes of torques [MAG: F (2, 32) = 370.19, p <.0001 for F_n^{th}; MAG: F (2, 32) = 387.80, p <.0001 for F_n^{vf}], and the normal forces of the thumb and VF under the fixed object condition were smaller than those under the free object conditions for all torque conditions [TYPE: F (1, 16) = 122.12, p < .0001 for F_n^{th}; TYPE: F (1, 16) = 37.21, p < .0001 for F_n^{vf}] (Fig. 5.4a & 5.4b). Both the thumb and the VF produced greater normal forces during the supination efforts rather than during the pronation efforts [DIR: F (1, 16) = 37.90, p < .0001 for F_n^{th}; DIR: F (1, 16) = 23.68, p < .0001 for F_n^{vf}]. The normal force differences between MAG conditions were also greater during supination than during pronation efforts, which was statistically confirmed by a significant interaction of DIR × MAG [DIR ×

MAG: F (2, 32) = 61.67, p <.0001 for F_n^{th}; DIR × MAG: F (2, 32) = 27.95, p <.0001 for F_n^{vf}].

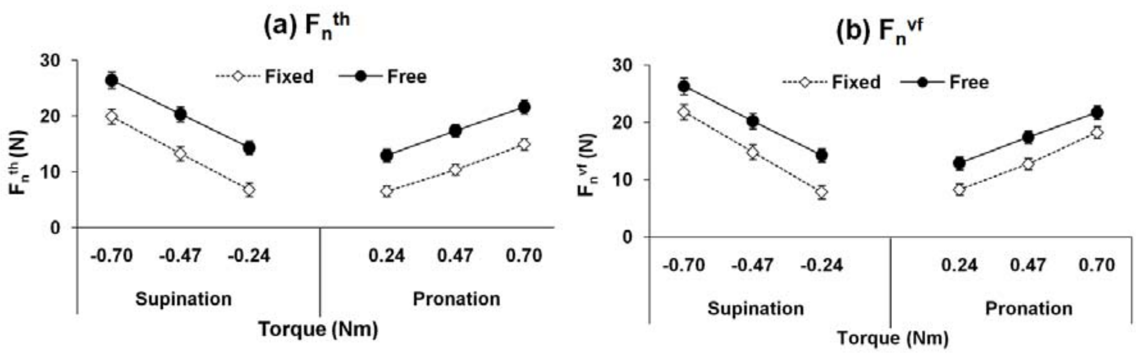


Figure 5.4. **(a)** Thumb normal forces and (**b)** VF normal force under varied conditions of prehension type, torque directions, and torque magnitudes. Averages across subjects data are shown with standard error bars (Some of the error bars are very small to be seen)

5.4.1. Tangential force production at the virtual finger (VF) level

The vertical translation constraint states that the sum of thumb and VF tangential force should be equal and opposite to the weight of the object during a free object conditions. The thumb and VF tangential forces under the free object conditions were always positive except when the VF tangential force was at -0.70Nm torque condition (Fig. 5.5a & 5.5b), while the tangential forces of the thumb produced in the opposite direction of the VF tangential force under the fixed object condition. Generally, both the thumb and VF tangential forces were greater during the free object condition than during the fixed object condition [TYPE: F (1, 16) = 494.18, p < .0001 for F_t^{th}; TYPE: F (1, 16) = 222.95, p < .001for F_t^{vf}], and the thumb and VF tangential forces decreased linearly during pronation. These force increased during supination for both the free and fixed object conditions [DIR: F (1, 16) = 882.10, $p <$ .0001 for F_t^{th}; DIR: F (1, 16) = 597.09, $p < .0001$ for F_t^{vf}].

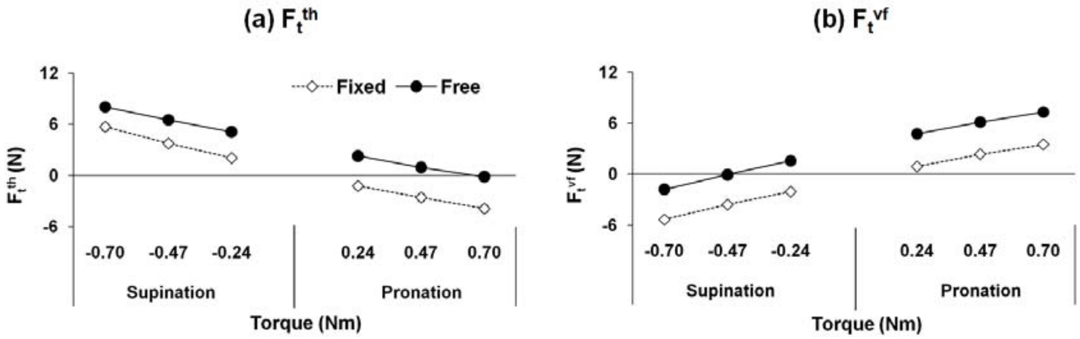


Figure 5.5. **(a)** Thumb tangential force and **(b)** VF tangential forces under varied conditions of prehension type, torque directions, and torque magnitudes. Unlike uni-directional normal force (i.e., pushing direction only, not allowed to produce forces in pulling direction, so-called 'soft-finger' model), the directional conventions (i.e., positive or negative) are used for the tangential forces because the tangential forces could be produced in upward direction (positive) as well as in downward (negative). Averaged across subjects data are shown with standard error bars (some of the error bars are very small to be seen)

5.4.3. Moment arm of virtual finger (VF) normal force

The moment arm of VF normal force (D_n^{vf}) under the fixed object condition was larger than that under the free object condition throughout all experimental conditions [TYPE: F (1, 16) = 10.598, $p < .005$] (Fig. 5.6). D_n^{vf}, which is the distance from the center of the thumb transducer to the force application point of VF force along X-axis, increased during pronation and decreased during supination during the free object condition (Fig. 5.6), while D_n^{vf} was quite constant during a fixed object condition [DIR: F (1, 16) = 369.98, p <.0001; MAG: F (2, 32) = 10.30, p <.01; TYPE × DIR: F (1, 16) = 36.39, p <.0001; MAG × DIR: F (2, 32) = 44.58, p <.0001]. For the fixed object condition, pair-wise comparisons showed that the difference between all pairs of D_n^{vf} s within each DIR (i.e., pronation: -0.70, -0.47, and -0.24Nm; supination: 0.24, 0.47, 0.70Nm) conditions (Fig. 5.6) were not significant (p >.01).

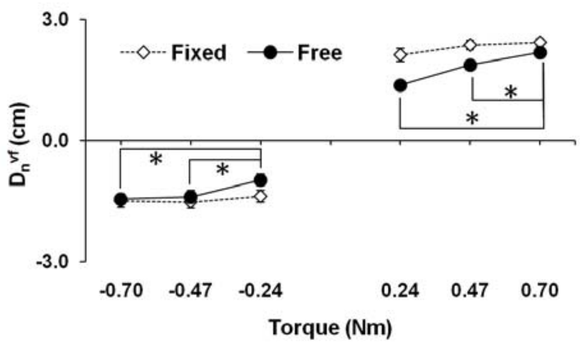


Figure 5.6. Moment arm of virtual finger normal force under varied combinations of experimental conditions. Averaged across subjects data are shown with standard error bars (some of the error bars are too small to be seen).

5.4.4. Moment of normal and tangential forces production at the virtual finger (VF) level

In general, both moments of normal and tangential forces were increased linearly with the magnitudes of produced torques (r > .9) (Fig. 5.7a & 5.7b). This relationship depended mainly on the torque magnitudes and torque directions, and there was no significant difference between fixed and free object conditions on both M_n and M_t . Three-way repeated-measured ANOVAs with the factor TYPE (two levels), DIR (two levels), and MAG (three levels) on M_n and M_t supported these findings, which show significant effects of MAG and DIR with a significant interaction of DIR × MAG at p <.01 [MAG: F (2, 32) = 1418.96, p <.0001; DIR: F (1, 16) = 15.93, p <.001; MAG × DIR: F (2, 32) = 1047.74, p <.0001 for M_n; MAG: F (2, 32) = 13.01, p <.01; DIR: F (1, 16) = 765.10, p <.0001; MAG × DIR: F (2, 32) = 765.94, p <.0001for M_t].

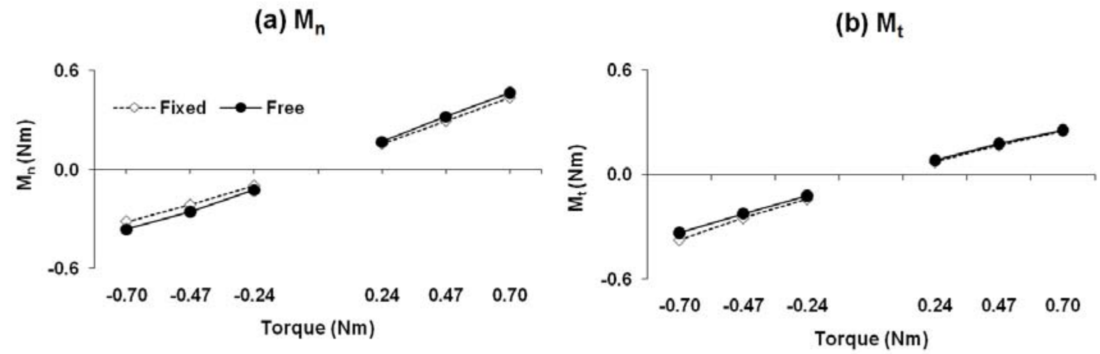


Figure 5.7. **(a)** moment of normal force and **(b)** moment of tangential force under varied combinations of experimental conditions. Averaged across subjects data are shown with standard error bars (some of the error bars are too small to be seen)

5.4.5. Correlations among virtual finger (VF) forces and moments

For both free and fixed object conditions, the thumb normal force was highly correlated with the VF normal force across the 25 trials for each conditions (r > .8, pairs of variables $F_n^{th}\ vs\ F_n^{vf}$; r = {0.87, 1.00}: range of correlation coefficient across all experimental conditions), while the VF normal force across trials was not significantly correlated with the moment of VF normal force (r < .3, pair of variables $F_n^{vf}\ vs M_n^{vf}: r = \{0.04, 0.32\}$) throughout varied conditions of torque directions and magnitudes (Fig. 5.8a). During the free object condition, the 1st $(F_n^{th} vs\ F_n^{vf})$ and 9th local chains $(F_t^{th} vs\, F_t^{vf})$ showed significant correlations as expected by the constraints of linear translations (i.e., the constraints of horizontal and vertical translation) (Fig. 5.8a). However, only task mechanics during the fixed object condition was to produce prescribed moments. Therefore, significant correlations of the 1st $(F_n^{th} vs\, F_n^{vf})$ and 9th chains $(F_t^{th} vs\, F_t^{vf})$ were not mechanically necessitated during a fixed object condition in planar grasping task. The correlation analysis showed that the 9th chain was not significantly correlated ($F_t^{th} vs\, F_t^{vf}$: r = {-0.07, -0.33}). However, the 1st chain showed significant correlation over repetitions ($F_n^{th} vs\, F_n^{vf}$: r = {0.85, 0.92}), which was not mechanically constrained. For the free object condition, the correlations of the 3rd $(M_n^{th} vs\, D_n^{vf})$, 4th $(D_n^{th} vs\, M_t)$, 5th and 6th $(M_t\, vs\, F_t^{th}, M_t\, vs\, F_t^{vf})$ chains, which were serially linked, were all statically significant regardless of varied conditions of torque directions and magnitudes (Fig. 5.8b). For the fixed object condition, the correlations of the 3rd $(M_n^{th} vs\, D_n^{vf})$, 5th $(M_t\, vs\, F_t^{th})$, 6th $(M_t\, vs\, F_t^{vf})$, and 8th $(F_t^{vf} vs\, F_t)$ chains were statistically significant, while the correlation of the 4th $(D_n^{th} vs\, M_t)$ were not significant (Fig. 5.8c). However, the correlations of the direct link from M_n^{vf} to M_t under the fixed object condition rather showed similar (or slightly smaller) to those under the free object condition ($M_n^{vf} vs\, M_t$: r = {-0.49, -0.85}) (not shown in Fig. 5.8c).

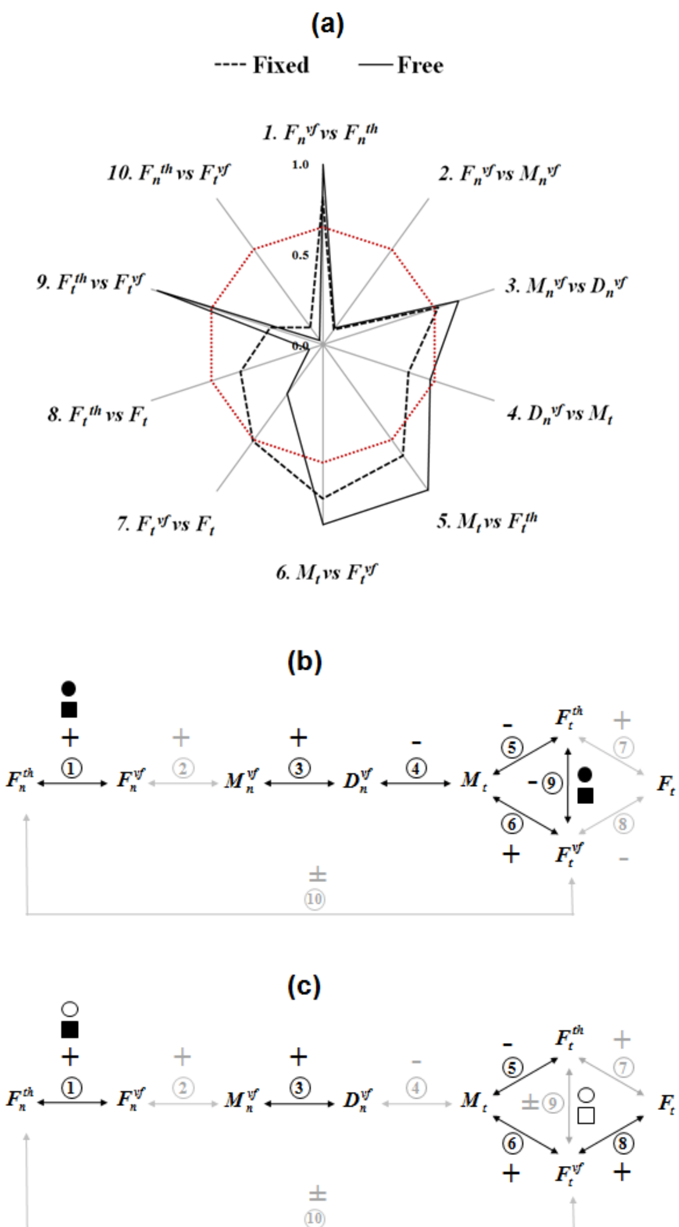

(a)
---- Fixed
— Free
1. F_n^{vf} vs F_n^{th}
2. F_n^{vf} vs M_n^{vf}
3. M_n^{vf} vs D_n^{vf}
4. D_n^{vf} vs M_t
5. M_t vs F_t^{th}
6. M_t vs F_t^{vf}
7. F_t^{vf} vs F_t
8. F_t^{th} vs F_t
9. F_t^{th} vs F_t^{vf}
10. F_n^{th} vs F_t^{vf}
1.0
0.5
0.0
(b)
(c)

Figure 5.8. Capital *F, M* and *D* stand for the digit force, moment of force, and moment arm which is orthogonal to the each force component respectively. The subscripts *th* and *vf* stand for the thumb and virtual finger (VF) respectively. The superscript *n* and *t* indicate the normal and tangential force components. (**a)** The correlation coefficients between ten pairs of elemental variables at the VF level. Averaged data across subjects and experimental conditions in each TYPE (i.e., fixed and free object) are presented. Red dotted line indicates the significant level of correlation coefficients (r = .5) with 25 of sample size. If correlation coefficient is less than .5, the correlation coefficient is not statically significant. (**b)** The cause-effect [so called 'chain effect' (Krishnamoorthy, Slijper, & Latash, 2002; Shim, Latash, & Zatsiorsky, 2005b; V. Zatsiorsky, F. Gao, & M. Latash, 2003)] relations among elemental variables at the VF level under the free object condition. The bold arrows indicate that the correlation coefficients between linked variables by the arrow are significant, while the blurred arrows indicate the correlation coefficient between variables are not significant ($r < .5$). Circles and squares placed on the 1st $(F_n^{th} vs F_n^{vf})$ and 9th $(F_t^{th} vs\, F_t^{vf})$ local chains indicate 'task mechanics (circle)' and 'significance of correlation coefficient by experimental results (square)'. The closed and open circles mean weather the relations of either the 1st $(F_n^{th} vs F_n^{vf})$ or 9th $(F_t^{th} vs F_t^{vf})$ local chains are constrained by task mechanics (closed circle) or not (open circle) imposed in tasks. The closed and open squares indicate the significance of the correlation coefficients of the 1st $(F_n^{th} vs F_n^{vf})$ or 9th $(F_t^{th} vs F_t^{vf})$ local chains from experimental results (i.e., open: not significant, closed: significant). The positive (+) and negative (-) signs represent positive and negative correlations, respectively. (**c)** Cause-effect relations among elemental variables at VF level under the fixed object

5.4.1. Principal Component (PC) analysis on variables at the virtual finger (VF) level

The number of significant PCs which explains more than 95% of total variance was counted for all experimental conditions. On average, the number of significant PCs was greater in the fixed object condition (3.539 ± 0.10; mean ± standard error across all subjects and conditions) than in the free object condition (2.182 ± 0.06; mean ± standard error across all subjects and conditions) (Fig. 5.9). For both the free and fixed object condition, the differences of the number of significant PCs between torque directions as well as torque magnitudes were not statistically significant. A three-way repeated-measured ANOVA with the factor TYPE (two levels), MAG (three levels), and DIR (two levels) showed a significant main effect of TYPE [TYPE: $F(1, 16) = 64.58$, $p < .0001$]. Factor interactions were not statically significant. This implies that the number of significant PCs affected only by prehension types (i.e., fixed and free object prehensions).

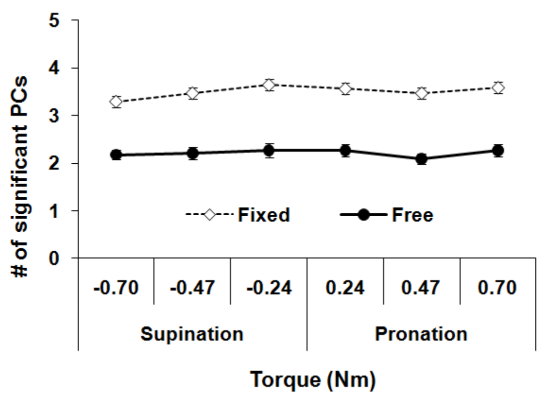


Figure 5.9. The number of significant Principle Components (PCs) which explains more than 95% of total variance under the different TYPE (i.e., fixed and free objects), DIR (i.e., supination and pronation) and MAG (i.e., 0.24, 0.47, 0.70Nm) combinations. The averages across all subjects data are presented with standard error bars (some of the error bars are too small to be seen)

For both fixed and free object conditions, the thumb and VF normal forces had large loadings (|loading| > 0.7) in the same PCs and small loadings in the other PCs throughout all conditions (Table 5.1). The large loadings in the same PCs for the rest of variables (e.g., thumb and VF tangential forces and the moment arm of VF normal forces) were only observed in the free object condition (PC2). The number of significant PCs during the fixed object condition was larger than three. Because two tangential forces had large loadings in the different PCs and two normal forces had large loading in the same PCs, the number of significant PCs was at least three (Table 5.1). The moment arm of VF normal force occasionally had large loadings in the same PC with either the thumb tangential force or the VF tangential force during the fixed object condition.

Table 5.1. Groups of elemental variables at the virtual finger (VF) level which showed high loadings (|loading| > 0.7) in the same PCs. Note that the table represents the general trend of grouping elemental variables from PCA across subjects and experimental conditions. F_n^{th} thumb normal force, F_n^{vf} VF normal force, F_t^{th} thumb tangential force, F_t^{vf} VF tangential force, D_n^{vf} moment arm of VF normal force.

	PC1	PC2	PC3	PC4
Free	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, F_t^{vf}, D_n^{vf}\}$		
Fixed	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, D_n^{vf}\}$ or $\{F_t^{vf}, D_n^{vf}\}$	$\{F_t^{vf}\}$ or $\{F_t^{th}\}$	$\{D_n^{vf}\}$

5.4.1. Variance in thumb and virtual finger (VF) normal forces spaces

The correlations between the thumb and VF normal forces over repetitions were significantly high (p >.8) throughout all experimental conditions. The variances of the trial-to-trial changes in the null space of '$F_n^{vf}=F_n^{th}$' (V_{null}) and orthogonal to the null space (V_{orth}) were varied with combinations of prehension type, torque directions, and torque magnitudes (Fig. 5.10). There were no significant different of V_{null} between TYPEs, while V_{orth} of free object condition were dramatically smaller than that of the fixed object condition throughout all experimental conditions [TYPE: $F(1, 16) = 35.56$, $p < .0001$ for V_{orth}] (Fig. 5.10b). V_{null} systematically increased with torque magnitudes for both fixed and free object condition without a significant difference between two directional conditions (i.e., supination and pronation) [MAG: $F(2, 32) = 23.05$, $p < .0001$], while systematic increases of V_{orth} with torque magnitudes were shown only in the fixed object condition [MAG: $F(2, 32) = 23.30$, $p < .0001$; TYPE × MAG: $F(2, 32) = 24.40$, $p < .0001$].

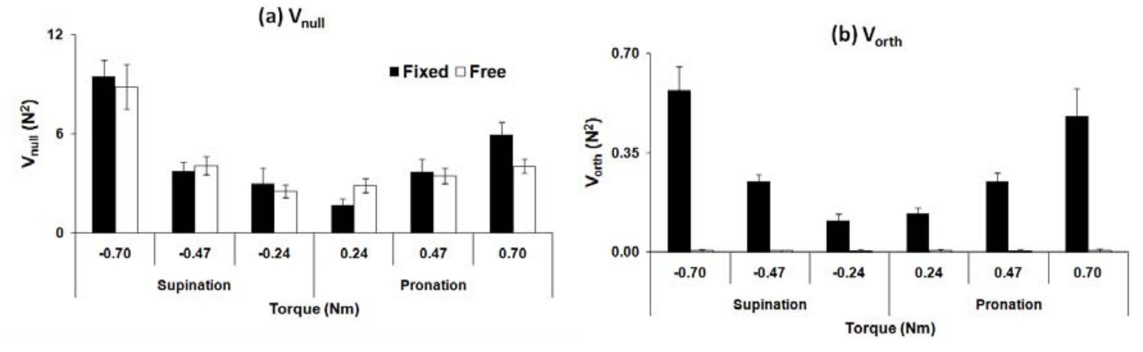


Figure 5.10. **(a)** The variance in the null space of '$F_n^{vf} = F_n^{th}$' (V_{null}) and **(b)** orthogonal to the null space (V_{orth}) under varied combinations of prehension types, torque directions, and torque magnitudes. Averaged across subjects data are presented with standard error bars. V_{orth} under free object condition was very small to be seen.

5.4.8. Agonist and antagonist moments

It was obvious that individual digit generated moments not only in the required direction (i.e., agonist moment), but also in the opposite direction (i.e., antagonist moment). If an antagonist moment of force was not exerted during the trials, then the ratio (i.e., antagonist moment / agonist moment) would be zero. Generally, the ratio of both M_n and M_t under the free object condition was greater than that under the fixed object condition especially when a smaller torque production was required (e.g., 0.24Nm) [TYPE: F (1, 16) = 84.28, p < .0001 for the ratio of M_t; TYPE: F (1, 16) = 21.75, p < .0001 for the ratio of M_n] (Fig. 5.11). In terms of the ratio of M_t (Fig. 5.11a), there was no significant difference between pronation and supination for both the fixed and free object conditions, while the ratio decreased with the torque magnitudes under the free object condition [MAG: F (2, 32) = 230.4, p <.0001; TYPE × MAG: F (2, 32) = 72.85, p<.0001]. For the free object condition, pair-wise comparisons showed that the difference between all pairs of M_t ratios within each DIR (i.e., pronation: -0.70, -0.47, and -0.24Nm; supination: 0.24, 0.47, 0.70Nm) conditions (Fig. 5.11a) were significant (p <.01). For the ratio of M_n, the ratio decreased with torque magnitudes under the free object condition (Fig. 5.11b), and the ratios during supination efforts were greater than during pronation effort [MAG: F (2, 32) = 40.92, p <.0001; DIR: F (1, 16) = 9.50, p <.001; TAKS × MAG: F (2, 32) = 48.85, p<.0001] (Fig. 11b).

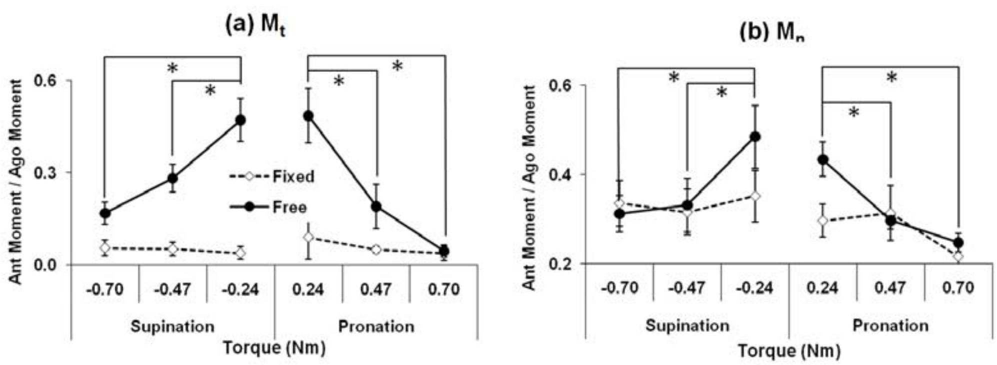


Figure 5.11. The ratio of antagonist moment to agonist moment on **(a)** moment of tangential force, and **(b)** moment of normal force under the different TYPE (i.e., fixed and free objects), DIR (i.e., supination and pronation) and MAG (i.e., 0.24, 0.47, 0.70Nm) combinations. Antagonist and agonist moments were obtained from Eq. 6 & 7 at IF level. The Averages from all subjects data are presented with standard error bars.

5.4.9. Delta variance

In general, the normalized ΔV_{Fn} was negative regardless of experimental conditions (Fig. 5.12a). However, ΔV_{Ft} were positive during the free object condition, while close to zero during the fixed object condition (Fig. 5.12c). ΔV_{Mn} and ΔV_{M} were positive for all experimental conditions ($\Delta V_{Mn} < \Delta V_{M}$) (Fig. 5.12b and 5.12d). Again, the positive ΔV reflects the dominant positive co-variances among IF actions so that the performance variable (VF level variables), if any, do not change, thus resulting in a stabilization of the performance variable. Conversely, a negative ΔV is obtained when there are dominant negative co-variances among IF actions, presumably the results of an error compensation strategy for stabilizing performance variables. ΔV_{Fn} of the free object condition was smaller than that of the fixed object condition, meaning that there were stronger positive co-variances among IF normal forces under the free object condition [TYPE: $F(1, 16) = 12.51, p < .003$], and ΔV_{Fn} increased with the torque magnitudes (three level: 0.24, 0.47, 0.70Nm) for both fixed and free object conditions [MAG: $F(2, 32) = 8.90, p < .01$] (Fig. 5.12a). There was no significant effect of DIR (i.e., supination and pronation) without an interaction of any factors. ΔV_{Ft} was positive (i.e., dominant negative co-variances among IF tangential forces) only when the vertical translation was constrained (i.e., free object condition) [TYPE: $F(1, 16) = 61.87, p < .0001$] (Fig. 5.12c). There were no significant differences of ΔV_{Ft} between pronation and supination as well as torque magnitudes.

ΔV_{Mn} was positive in general (i.e. dominant negative co-variances among IF moment of normal forces) (Fig. 5.12b). Particularly, ΔV_{Mn} was larger when the pronation efforts were required rather than supination efforts [DIR: F (1, 16) = 21.58, p <.0001]. However, a ΔV_{Mn} difference between fixed and free object conditions was not shown in any torque conditions (Fig. 5.12d). ΔV_M was also positive and quite constant within each type of prehension. ΔV_M was also greater during the free object condition than the fixed object condition regardless of either torque directions or magnitudes [TYPE: F (1, 16) = 19.00, p < .0001].

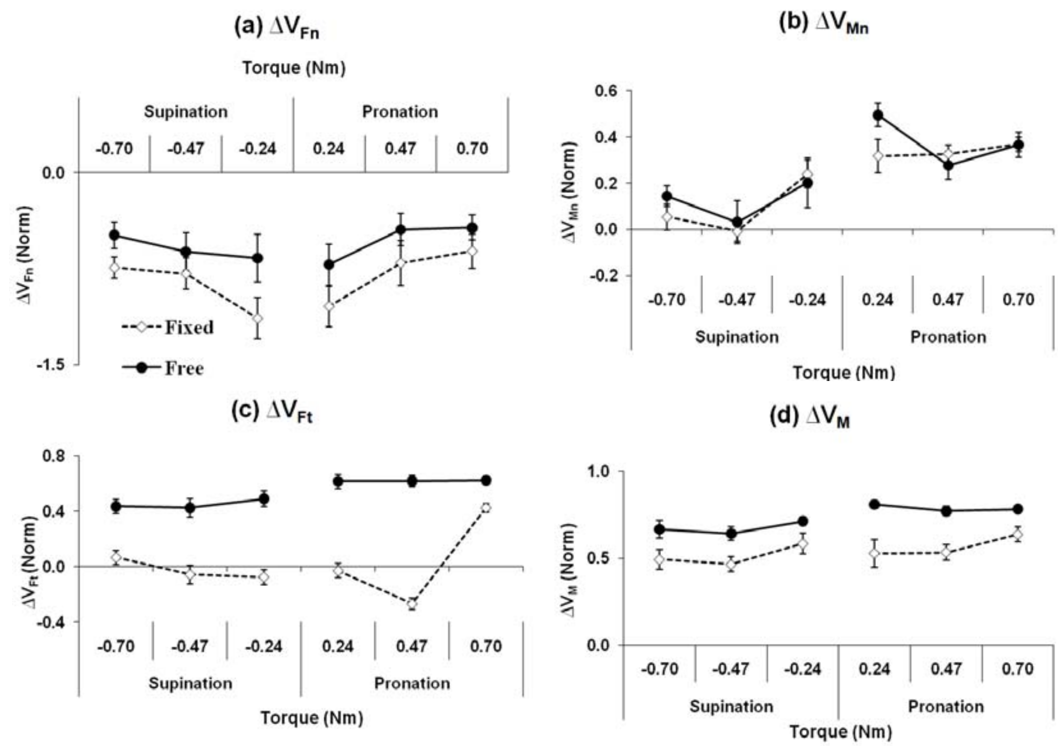


Figure 5.12. Normalized delta variances (ΔV) of **(a)** normal force (ΔV_{Fn}), **(b)** moment of normal force (ΔV_{Mn}), **(c)** tangential force (ΔV_{Ft}), and **(d)** moment of force (ΔV_M). ΔV was computed over 25 repetitions for each condition and subject, and the averages data across all subjects with standard error bars are presented. (Some of the error bars are very small to be seen)

5.5. Discussions

5.5.1. Coupling of thumb and VF normal forces in static prehension

One of the most functionally important actions of the human hand is opposition (Naiper, 1956, 1962). In human hand movements, opposition is that the thumb is placed in opposite to the remaining (Naiper, 1956) digits so that the human can perform various types of prehension such as a precision grip, power grip, etc. The investigation into the control aspects of hand digits' grasping forces in opposition has been of interest to many researchers in human motor control (Gao et al., 2005; Pataky et al., 2004a; Shim et al., 2005b) as well as in robotics (Bicchi, 2000; Kim, Nakazawab, & Inookac, 2002; Nguyen & Arimoto, 2002).

In the current study, we focused more on the ways of the CNS controls digits' forces with and without the static constraints of hand-held object. We investigated this by employing a fixed and free object prehension tasks. As the results clearly showed (Fig. 5.10), most of data points of normal forces lie in the null space of '$F_n^{vf} = F_n^{th}$' with relatively small variances orthogonal to the null space. We can consider the variance orthogonal to the null space an error variance during the free object condition. Nevertheless, the CNS still has the freedom to select the size of variance in the null space since the system is still redundant even if we only consider the normal force constraints at the VF level (i.e., two unknown variables and one equation). However, if the horizontal translation is not constrained, the selection of thumb and VF normal forces in magnitude is perfectly free.

In the results, the scattered patterns of multiple trials data of two normal forces were to elongate the variance in the null space of '$F_n^{vf} = F_n^{th}$', and suppress the variance orthogonal to the null space during both free and fixed object conditions. In terms of variance in the null space, there was no significant difference between two prehension conditions (Fig. 5.10a), while the variance orthogonal to the null space under the free object condition was smaller than that under the fixed object condition (Fig. 5.10b).

The presence of a variance in the null space larger than the variance orthogonal to the null space implies that the CNS strategizes to select the normal forces of the thumb and VF in static prehension under the fixed object condition. This strategy centers on the coupling of two normal rather than the independent control of normal forces in the absence of constraints regarding the selection of the thumb and VF normal force such as the fixed object condition. Indeed, regression analysis in this study revealed that the correlation coefficients between the normal forces of the thumb and VF were significant. The PCA showed that high loadings of two normal forces were always observed in the same PC even under the fixed object condition (Table 5.1). This supports the finding that the normal forces of the thumb were coupled with the VF normal force even when the relation of two normal forces was not constrained by task mechanics in static prehension of a rectangular object. Hence, we can confirm that the coupling of two normal forces (i.e., grasping stability) was maintained without considering linear translational constraints, which prescribe the relation of thumb and VF normal forces. Previous studies have documented that the CNS utilizes grasping stability as one of its multi-digit synergies (controls) used to prevent slipping (Burstedt, Flanagan, & Johansson, 1999; Flanagan, Burstedt, & Johansson, 1999; Pataky et al., 2004b). Because many of previous studies of the investigations on multi-digit prehension synergy employed the free object static prehension, which was oriented vertically, the investigation of grasping force control by the CNS focused partially on slip prevention (Pataky et al., 2004b; Saels, Thonnard, Detrembleur, & Smith, 1999) , tilt prevention (Flanagan et al., 1999; Salimi, Hollender, Frazier, & Gordon, 2000), and perturbation resistance (Frak, Paulignan, Jeannerod, Michel, & Cohen, 2006; Kim et al., 2006; Shim et al., 2006a). The object (handle) had its own weight, and the external load (L) was commonly applied to provide the external torques in the free object prehension. The production of tangential forces was required to orient an object vertically in the air and the magnitude of normal force, which was sufficiently large above the slipping threshold, was adjusted. In most of cases in the previous studies as well as in this current study, the normal forces were sufficient to prevent slipping and showed high correlations to the effect of gravity on the object. However, the coupled and highly correlated normal forces were also observed when the slip prevention was not directly issued in the task (i.e., fixed object condition). Again, the performers were perfectly free to select the IF normal forces without considering the task mechanics (i.e., horizontal translation constraint) and slip prevention during the fixed object condition. Nevertheless, two normal forces were still highly correlated, although the significant level was relatively lower than that of free object condition. Therefore, we can infer that the grasping stability in the static prehension might not be affected by task constraints, which confines the relation between those two normal forces (i.e., equal in magnitude and opposite), and the slip prevention, which prescribes the threshold of normal forces.

However, it might be too impetuous to generalize this finding because the fixed object prehension was constraint free, both horizontal and vertical translations were not constrained. Instead, they were restrained. Separate investigations on the effects of horizontal and vertical translational constraints would be necessary in order to confirm the claim that grasping stability is always maintained in a static prehension task regardless of linear translational constraints during the tasks.

5.5.2. Principle of superposition

In multi-finger human prehension, the 'principle of superposition' explains the decoupled controls (or synergies) of grasping stability and rotational equilibrium (Shim et al., 2005b; Shim & Park, 2007; Zatsiorsky et al., 2004). In other words, the CNS might control these two synergies independently by showing high correlations among elemental variables in each control synergy, but there are not significant correlations between any variables in one synergy and variables in the other synergy.

The previous studies that employed free object prehension clearly revealed that there were two sub-sets in which the correlations among elemental variables in each sub-set were significantly high (Shim et al., 2005b; Shim & Park, 2007; Zatsiorsky et al., 2004). The grasping stability control is governed by the first sub-set composed of two normal forces (i.e., the thumb and VF normal forces). The rotational equilibrium is controlled by the second sub-set, which include two tangential forces (i.e., the thumb and VF tangential forces), the moment of the thumb and VF normal forces, the moment of tangential forces, and the moment arm of VF normal force.

The ‘chain effect’ explained the coupled relations among elemental variables within each sub-set. These significant correlations among variables formed a mechanically necessitated “cause-effect” chain (Zatsiorsky et al., 2003b, 2004). Therefore, there are two important findings on the inter-relations among variables in the multi-digit human prehension. These findings are (1) the existence of two independent controls (i.e., grasping stability control & rotational equilibrium control), and (2) the high correlation among elemental variables in each chain.

The first finding (i.e., decoupled controls of grasping stability and rotational equilibrium) might be enough to support the validity of principle of superposition in human hand static prehension because the mode of production associated with the assigned moment of force (i.e., rotational equilibrium control) would vary according to the given task constraints. This means that the configuration of the cause-effect chains for rotational equilibrium might be affected by the task constraints. Especially, the cause-effect chains among elemental variables in each synergy partially reflect the required mechanics within a task, and not directly mirror unknown CNS control strategies. If the principle of superposition is the specified control strategy used by the CNS to manipulate redundancy in a static human hand prehension, the decoupling of two control synergies is a fact that cannot be explained by the task mechanics of static prehension tasks.

In this study, the correlations analysis and PCA on elemental variables of the free object prehension clearly confirmed that elemental variables were grouped into two sub sets at the VF level as described by previous studies (Shim, Latash, & Zatsiorsky, 2005a; Shim et al., 2005b; Zatsiorsky & Latash, 2004; Zatsiorsky et al., 2004). Two normal forces (i.e., thumb and VF normal forces) comprised the first sub-set. The second sub-set is formed by the thumb and VF tangential forces, the moment of the thumb and VF normal forces, the moment of tangential forces, and the moment arm of VF normal force. However, the VF normal force and the moment of VF normal force, which were seemingly correlated, did not correlate significantly throughout all experimental conditions. Rather, the trial-to-trial tuning of moment of VF normal force was achieved by variations of moment arm of VF normal force, which was not correlated with the VF normal force. This broken local chain can be a point where one subset is separated from the other subset. Despite this, the ‘chain effect’ and the two sub sets of variables were still maintained when the horizontal translation was not constrained (i.e. fixed object condition).

Unlike the mechanically constrained tangential force production in the free object, the sum of thumb and VF tangential forces can be of any magnitude when the vertical translation is not constrained (e.g., fixed object prehension). However, both tangential force components were highly correlated with moment of tangential force and moment of normal force as well as moment arm of VF normal force. In other words, the CNS might alternate “cause-effect” relationships within the second sub-set under the fixed object condition, possibly due to unconstrained relationship of two tangential forces.

The point of separation of two sub-sets in the fixed object condition is the same as the point shown in the free object condition. Therefore, the two separated sub-sets of elemental variables, which explain the grasping stability and rotational equilibrium, were still maintained when the vertical translation was not constrained. In the fixed object condition, the only mechanical constraint within a task was to produce assigned moment of force against external torques, but the two normal forces were highly correlated, and the two sub-sets were clearly separated. We can conclude that the independent controls of grasping stability and rotational equilibrium are not affected by the translational constraints within tasks supporting the validity of principle of superposition in human hand static grasping task.

5.5.3. Synergy and hierarchical organization of finger forces/moments in human prehension

As previously mentioned, the grasping stability was maintained even when the horizontal translation was not mechanically constrained (i.e., fixed object condition). The higher level, thumb-VF level, was stabilized in terms of the control of normal forces.

However, it seemed that the actions of individual finger (IF) normal forces (i.e., IF level variables) did not show the error compensation strategies amongst them. In other words, the delta variance, which has been an indicative of a synergy index (Li et al., 1998; Shim et al., 2003b; Shinohara, Latash, & Zatsiorsky, 2003), of individual normal forces were negative as the result of dominant positive co-variation among individual fingers' normal forces. Although the horizontal translation was constrained during static prehension task, the horizontal translational constraint did not prescribe the value of the sum of individual finger forces as the weight of object prescribed the sum of digit tangential forces. As long as the two normal forces were equal in magnitudes, then we can consider it a successful performance. One might think that the thumb normal force can be the prescribed value of the sum of the finger normal forces because there was no known peripheral connection between the thumb and fingers (Brand & Hollister, 1999), so the actions of the thumb and fingers are independent of each other. However, there has been a claim that the central constraints explain the interconnection between the actions of the thumb and fingers (Yu, Kilbreath, Fitzpatrick, & Gandevia, 2007). It is that inter-relation among action of the thumb and fingers that can be explained mainly by the central connections, rather than the anatomical muscle-tendon connections. Indeed, the somatotopy of the primary motor cortex (M1), which is not spatially segregated but instead overlaps (Dechent & Frahm, 2003; Schieber, 2001), and the central signals from M1 to the several hand muscles diverge from the same area (or spot) on M1. Thus, the actions of the thumb and fingers might not be independent. Although the synergic actions among digit normal forces were not observed on the individual finger level, an apparent coupling of normal forces was shown in the thumb-VF level. Therefore, we can say that the hierarchical organization was not applied in the grasping force control in a static prehension task. Rather, the CNS seems to control the normal forces of the thumb and individual fingers as a whole in order to stabilize grasping forces.

In terms of tangential forces, the synergic actions among the tangential forces of individual fingers was evident during the free object condition in the positive value of the delta variances of IF tangential forces. However, this phenomenon was not clearly shown during the fixed object condition. Because vertical translation was not constrained during the fixed object condition, there was no target force value to be stabilized on the VF level of tangential forces. In the PCA, high loadings of the tangential forces of the thumb and VF were not shown in the same PC, implying independent controls of two tangential forces in a static fixed object prehension. During the free object static prehension, the sum of tangential forces should be equal to the weight of object (Eq.2). This means that the sum of IF tangential forces is also prescribed by the task mechanics. Thus, the synergic actions of IF tangential force could be a CNS strategy to stabilize the VF tangential force; the higher level synergy controls the vertical translational constraints during a static free object prehension. In other words, the stabilizing VF tangential force is functionally important to stabilize the total tangential force (i.e., the stabilization of vertical orientation), which conspicuously supports the hierarchical organization of the tangential force control.

In this study, the production of assigned moments of force was a common task (i.e., mechanical constraint) during both free and fixed object condition. The results showed that the delta variances of moment of normal force and resultant moment of force were positive for most of the torque and task conditions varying their levels. In particular, IF normal forces had dominant positive co-variations; this supposedly did not stabilize the VF normal force. However, positive co-variances among IF normal forces can be a strategy to stabilize moment of normal forces. Because the stabilization of the resultant force and torque require negative and positive co-variations among elemental variables (Latash et al., 2001, 2002), one of the sub-tasks does apparently conflict with the other. For example, during a two-finger pressing task, the negative co-variation between two finger forces provides a constant resultant force, while a negative co-variation is necessary in order to maintain a constant moment of force about an axis located midway between the fingers. According to the results of the current study, the CNS seems to solve the conflict problem with redundancy by stabilizing only M_n in IF level (the lower level) and stabilizing both M_n and F_n in thumb-VF level (the upper level). This is supported by the hypothesis, which claimed that stabilization of rotational equilibrium action may be a default control strategy rather than actions made compulsory by the required tasks (Latash et al., 2001; Scholz, Danion, Latash, & Schoner, 2002; Zhang, Zatsiorsky, & Latash, 2006). The hierarchical organization of finger force might be valid in rotational equilibrium control only. This claim is supported by the synergy indices on the resultant moment of forces, which showed all positive values (i.e., dominant negative co-variances among IF moments) throughout all the experimental conditions. Because one of the main tasks during both free and fixed object conditions was the stabilization of task moments, a negative co-variance among IF moments was expected.

Also, the synergy indices on IF tangential forces, which were in the subset of rotational equilibrium control, were positive when the relation of thumb-VF tangential force was constrained (i.e., free object condition). Hence, we can infer that the hierarchical organization of finger forces in a static prehension is valid only in the rotational equilibrium control. This finding partially coincides with the principle of superposition, which explains the decoupled control of the grasping stability and rotational equilibrium. In other words, the hierarchies of synergies on the grasping action and the rotational action behave differently. It seems that the CNS utilizes the hierarchical organization of finger actions for controlling the stability of the total moment, not for grasping stability. Lastly, the linear translation affects synergy strength during static torque production tasks. In the results, the delta variance of *M* under the free object condition was larger than that under the fixed object implying that the synergy strength of moment production was stronger in the free object condition in which the linear translations were constrained. Thus, it seems that the CNS uses this strategy to generate larger error compensations between IF moments for the tasks in which the subject had to control linear translations. However, the effect of each of the linear translations (i.e., horizontal and vertical translations) on the synergy strength during a static prehension has yet to be examined.

5.5.4. Active control of tangential force

It has been reported that tangential forces was passively coupled during grasping task (Flanagan & Wing, 1995) by various mechanical factors such as the magnitude of normal force (Nagashima, Seki, & Takano, 1997), hand diameter (Adams & Peterson, 1988), contact surface condition (Amis, 1987b; Hall, 1997; Johansson, 1998; Kinoshita & Francis, 1996), and inertia force (Zatsiorsky, Gao, & Latash, 2005). Especially, it was reported that the tangential force rate changed systematically with the grasping force in a linear fashion during dynamic grasping tasks (Johansson, Backlin, & Burstedt, 1999; Johansson & Westling, 1988). Conversely, the issue of active control of tangential force was claimed in a circular object static prehension in which the geometry of handle was different from a rectangular object (i.e., the moment of normal forces was zero due to zero moment arms). The fact that the tangential forces were the only force components contributing moment production and their synergic actions for the stabilization of performance variable (i.e., moment of force) suggested the active control of digits' tangential force in a circular object static prehension against external torques (Shim & Park, 2007). However, these two contradictory opinions cannot be juxtaposed with each other because the task in a circular object prehension was a static prehension and the passively coupled tangential forces were observed in dynamics situations. The CNS control strategies on digits' tangential forces might be task dependent.

In the current study, the assigned task was a static prehension. Hence, the following discussion will focus on the issue of active control of tangential force regarding the effect of constraints of linear translations. Unlike coupling between the normal forces of thumb and VF regardless of prehension types in the current study, a high correlation between two tangential forces was only shown during the free object prehension. This result implies that a coupling of thumb and VF tangential forces only happened when a constraint of tangential forces was applied to the task. In contrast to the free object condition, two tangential forces can presumably be controlled independently during the fixed object condition. Indeed, the positive synergy indices, indicative of dominant negative correlations among IFs resulting in error compensation among IF, were only observed during the free object condition (Fig. 5.12c). Hence, the thumb and VF tangential forces might not always act together in order to stabilize a constant level of resultant VF tangential force. In particular, the directional freedom (i.e., upward or downward) might be more effectively utilized in the fixed object condition. If the two tangential forces were produced in opposite directions, then the directions of moment of the thumb tangential force and VF tangential force can be the same because the moment arms of two tangential forces were equal in magnitudes and opposite in direction, resulting in the same directional moment of forces. Therefore, the directional freedom on the production of moment of tangential force gives more options in the production of task moments.

In the correlation analysis, the correlation coefficient between one of the tangential forces and the total tangential force was significantly high during the fixed object conditions. If the total tangential force was constant over the repetition, the correlation between one of tangential forces and total tangential forces should not be significant (i.e., the pattern of scatter plot of two values would be flat because one value is constant). This finding implies that the production of tangential forces relies largely on one of the tangential forces, not the synergic action of two tangential forces. Further, the total tangential forces varied over the repetitions. Therefore, we can say that the CNS utilizes given conditions (i.e., mechanical constraints in the task) actively in the production of tangential forces.

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Chapter 6: Prehension synergy: use of mechanical advantage during multi-finger torque production tasks

Chapter 6 will be submitted to a journal for publication

6.1. Abstract

The aim of this study was to test the mechanical advantage hypothesis (i.e., the effectors with longer moment arms show larger involvements) during multi-finger torque production tasks. The mechanical advantage hypothesis explains the specific control strategies used by central nervous system (CNS) regarding sharing patterns of grasping forces among individual fingers. In particular, we employed a free object and a mechanically fixed object static prehension task in order to investigate the effect of mechanical constraints during static prehension and how the CNS controls digits' forces and moments against static constraints. There were twelve experimental conditions: two task conditions (i.e., fixed and free object prehensions) with two torque directions (i.e., supination and pronation) and three torque magnitudes: (i.e., 0.70, 0.47, 0.24 Nm). The subjects were asked to produce assigned task moments during the fixed object prehension or to maintain constant position of the hand-held object against external torques during the free object prehension. We found that greater grasping force recruitment of fingers with greater mechanical advantages (i.e., moment arms) was observed only when the fingers' grasping forces produced moments in the required direction during both free and fixed object prehension, supporting the mechanical advantage hypothesis. In contrast, the mechanical advantage hypothesis was not supported when fingers' grasping force produced moments opposite to the required direction. The fingers with greater mechanical

advantages were utilized more evidently during the fixed object condition as compared to the free object condition. We infer that the central controller can regulate the finger forces in effective ways without taking task mechanics into consideration during fixed object prehension.

6.2. Introduction

The fact that effectors with greater mechanical advantages show a larger involvement has been shown in muscle activation (Biewener, Farley, Roberts, & Temaner, 2004; Buchanan, Rovai, & Rymer, 1989; Gielen & Zuylen, 1988) and multi-digit torque production (Shim, Latash, & Zatsiorsky, 2004; Zatsiorsky, Gregory, & Latash, 2002a, 2002b). The changes of effectors' actions with greater mechanical advantages are more effective in leading to changes in the whole system's status. The mechanical advantages of individual effectors in the system are mainly determined by their anatomical structures, such as the origin and insertion of individual muscles and parallel finger connections. Eventually, the use of effectors with greater mechanical advantages would be an effective way to perform the tasks, minimizing the total effort (e.g., force).

When it comes to the human hand system, the central nervous system (CNS) maintains stable static grasping of hand-held objects while utilizing infinite combinations of digit forces and moments (Li, Latash, & Zatsiorsky, 1998; Pataky, Latash, & Zatsiorsky, 2004; Shim, Latash, & Zatsiorsky, 2003). Previous studies suggest that the CNS uses the mechanical advantage of fingers during torque production tasks (Shim et al., 2004; Zatsiorsky et al., 2002a). According to the mechanical advantage hypothesis, the fingers positioned further away from the axis of rotation have greater mechanical advantage due to their longer moment arms. The term “mechanical advantage” refers to the moment arm of individual fingers’ grasping force. For example, if a grasped object’s axis of rotation lies between the middle and ring fingers, the moment arms of the index and little fingers’ grasping forces (i.e., normal forces) are longer than those of the middle and ring fingers’ grasping forces. This means that the index and littler finger possess greater mechanical advantages than the middle and ring fingers. Hence, the force production of lateral fingers (i.e., index and little fingers) would be a more effective way of producing moments as compared to the force production of the central fingers. The selections of individual finger forces/moments are partially governed by the controller’s specific principle. Thus, utilizing the mechanical advantages of various fingers in multi-finger torque production tasks can be the controller’s specific strategy to control the kinetically redundant hand system.

Recognizing such a pattern may be a way to minimize the total finger forces in torque production. However, this would be only true when the fingers act as the moment agonist, when the effectors produce the moment of force in the required directions. The CNS might produce smaller forces with a longer moment arm, where the fingers produce moments of force opposite to the required direction (i.e., antagonist moment). Therefore, the mechanical advantage of these fingers would be utilized only when the fingers’ actions would make a positive contribution to the required task.

If the summed actions of individual fingers are constrained by mechanics (e.g., the sum of individual fingers' grasping forces should be equal to the thumb grasping force during a static free object prehension task), it would affect the action of individual fingers (IF). The selection of IF forces/moments might be limited as compared to a situation where the selection of summed actions of individual fingers is not constrained. It is known that the actions of fingers are not independent due to their internal constraints (i.e., biomechanics and central constraints) (Hager-Ross & Schieber, 2000; Leijnse, Walbeehm, Sonneveld, Hovius, & Kauer, 1997; Olafsdottir, Zatsiorsky, & Latash, 2005; Schieber & Santello, 2004). When a central command for intended finger action is executed, the internal constraints induce unintended actions of other fingers. The force productions of peripheral fingers (i.e., index and little finger) under the free object condition were less independent than those under the fixed object condition (Park, Kim, & Shim, 2009) possibly due to the prescribed condition of fingers' summed action. If the actions of fingers are less independent, then utilizing fingers with greater mechanical advantage would be restricted to some extent because the force recruitment of lateral fingers (i.e., fingers with greater mechanical advantage) would induce the force production of the adjacent finger. This would be an inefficient way of producing the required moments.

Although previous studies documented that the mechanical advantage hypothesis applies to the torque production task during free object prehension (Zatsiorsky et al., 2002a) as well as fixed object prehension (Shim et al., 2004), it is unknown how sharing patterns among fingers' grasping forces during torque production tasks are affected by mechanical constraints imposed in the tasks. For a free object static prehension, three mechanical constraints should be satisfied in the grasping plane (i.e., 2-dimensional plane formed by the finger and thumb contacts): 1) the thumb grasping force and the sum of fingers' grasping forces should be equal in magnitude (horizontal translation constraint), 2) the sum of digit shear forces should be equal to the weight of the object (vertical translation constraint), and 3) the sum of moments of grasping and shear forces should be equal to zero (rotation constraint). However, fixed object prehension is considered a constraint-free task (Shim et al., 2004).

In this study we employed a free object and a mechanically fixed object in static prehension in order to investigate the effect of static constraints during static prehension and how the CNS controls digits' forces and moments against static constraints.

The following two hypotheses have been tested in this study: 1) The mechanical advantage hypothesis is only valid when the grasping forces of fingers produce the moment of force in required directions. 2) The larger recruitment of fingers' grasping forces with longer mechanical advantages, i.e., moment arms, is much more evident during fixed object prehension.

6.3. Method

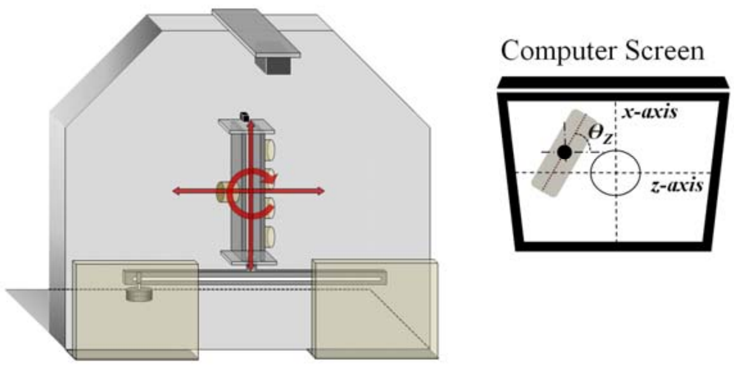
Seventeen right-handed male volunteers (age: 29 ± 3.1 years, weight: 67.1 ± 2.9 kg, height: 174.2 ± 5.3 cm, hand length: 18.7 ± 2.5 cm, and hand width: 8.7 ± 0.9) were recruited in the current experiment. No subject had a previous history of neuropathies or traumas to their hands. Before testing, the experimental procedures of the study were explained to the subjects and the subjects signed a consent form approved by the University of Maryland's Institutional Review Board (IRB).

Two types of sensors were used to measure digit forces/moments and to provide a real-time feedback to the subjects during trials. Five six-component (three force and three moment components) transducers (Nano-17s, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminum handle (Fig.6.1c) in order to measure each digit's forces and moments. Pieces of 100-grit sandpaper with a friction coefficient of about 1.5 were attached to the surface of each sensor in order to increase the friction between the digits and the transducers. The thumb sensor was positioned at the midpoint between the middle and ring finger sensors in the vertical direction where the center of rotation was positioned. One six-component (three position and three angle components) magnetic tracking sensor (Polhemus LIBERTY, Rockwell Collins Co., Colchester, VT, USA) was mounted to the top of the aluminum handle in order to provide feedback about the linear or angular positions of the handle during the free object prehension task (Fig. 6.1b). In addition, a horizontal aluminum beam (45cm in length) was attached to the bottom of the handle in order to hang a load (0.33kg) at different positions along the beam so as to provide different external torques for the free object condition. The analogue signals were routed to a 12-bit analogue-digital converter (a PCI-6031 and a PCI-6033, National Instrument, Austin, TX). Customized LabView programs (LabView 7.1, National Instrument, Austin, TX) were developed and the signals from sensors (i.e., force/moment sensor and magnetic sensor) were synchronized and recorded. The sampling frequency was set at 50 Hz. Sampled data were digitally low-pass filtered with a 2^{nd} order

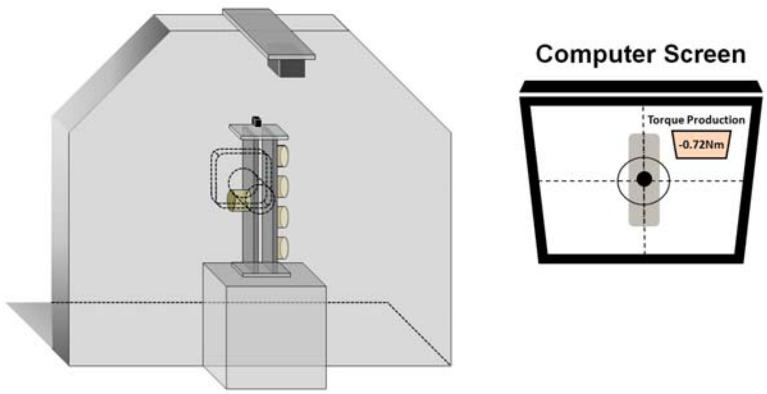
Butterworth filter. The low frequency cutoff was set at 5 Hz (Gao, Latash, & Zatsiorsky, 2005; Li et al., 1998; Park et al., 2009).

The subjects sat in the chair facing the computer screen and flexed the right elbow joint 90 degrees in the sagittal plane. The forearm was in a neutral position between pronation and supination. The height of chair was adjusted for each subject in order to keep the right-arm joint configuration of each subject constant. The subjects were instructed to place each digit on the designated sensor (i.e., Thumb, Index, Middle, Ring, and Little) and to keep all digits on the sensors during overall trials. The experiment consisted of two sessions. The first session involved a series of single-finger maximal voluntary force production tasks under both fixed and free object conditions. The second session involved a series of multi-finger torque production tasks under both fixed and free object conditions. In the first session, the subjects performed four single-finger maximal voluntary force (MVF) production tasks (i.e., index, middle, ring, and little fingers) under both fixed and free object conditions. The fingers' MVFs along the Z-axis (i.e., the direction of grasping force) were measured. The subjects were instructed to keep all digits on the sensors during each task, and were asked to pay attention to the task-finger maximal force production. Each subject performed a total of 8 trials (2 TYPEs × 4 MVFs tasks = 8) in the first session. In the second session, there were twelve experimental conditions: two prehension types (i.e., fixed and free object prehensions) with six torque conditions about *y*-axis (supination efforts: -0.70, -0.47, -0.24 Nm; pronation efforts: 0.24, 0.47, 0.70 Nm). For the fixed object condition, the handle was mechanically fixed to the table (Fig. 6.1b) so that the handle could not be translated or rotated by digits' forces. The subjects were instructed to produce six different moments of forces as accurately as possible for 3-s during the fixed object condition. In other words, for the fixed object condition the task was a constant moment production. Unlike a mechanically fixed object, the handle could be translated or rotated in any direction for the free object condition. The task for the subjects was to hold the handle while maintaining a pre-set constant linear and angular position of the handle against the given external torques. Real-time feedback of the linear and angular positions of the handle was provided on the computer screen during the free object prehension task. The subjects were instructed to minimize the angular and linear deviations of the handle. If the deviations exceeded the pre-defined criteria (rotation: $\sqrt{\theta_x^2 + \theta_y^2} < 1°$ or translation: $\sqrt{x^2 + y^2} < 1cm$) during each trial, the data collection automatically stopped, and the subject was asked to perform the trial again. For each condition, twenty five consecutive trials were performed. Thus, each subject performed a total of 300 trials (2 TASKs × 6 TORQUEs × 25 trials = 300) in the second session. Two-minute breaks were given at the end of each trial in order to avoid fatigue effects. The order of the twelve four experimental conditions was balanced and no subject reported fatigue.

(a)


Computer Screen
x-axis
θ_Z
z-axis

(b)


Computer Screen
Torque Production
-0.72Nm

(c)

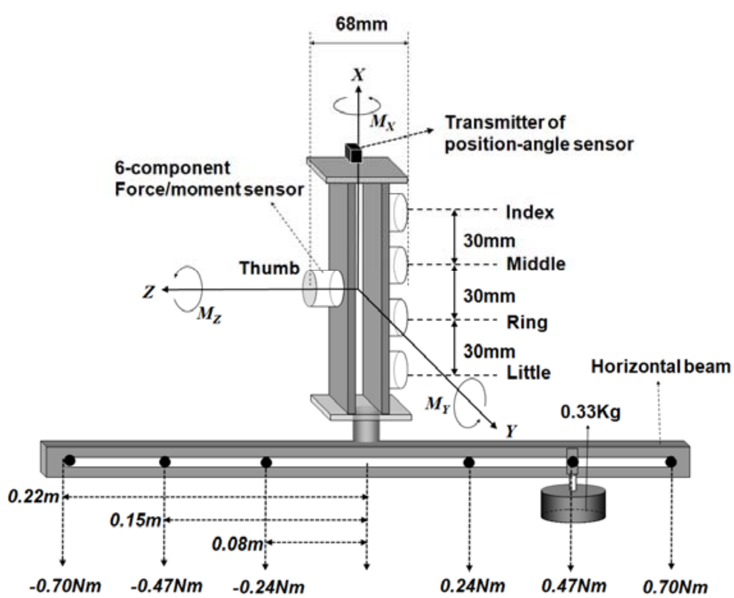

68mm
X
M_X
Transmitter of position-angle sensor
6-component Force/moment sensor
Index
30mm
Middle
Thumb
Z
M_Z
30mm
Ring
30mm
Little
Horizontal beam
M_Y
Y
0.33Kg
0.22m
0.15m
0.08m
-0.70Nm
-0.47Nm
-0.24Nm
0.24Nm
0.47Nm
0.70Nm

Figure 6.1. **(a)** Schematic illustration of experimental setup for the free object prehension (left) and position feedback (right). Arrows on the handle indicate that horizontal and vertical translations, and rotation about the axis orthogonal to the grasping plane are allowed during the free object prehension, but subjects have to maintain the static constraints. Real-time feedbacks of translation along *z*-axis (horizontal translation), translation along *x*-axis (vertical translation), and rotation about *y*-axis were provided using the magnetic position-angle sensor. **(b)** Schematic illustration of experimental setup for the fixed object prehension and torque feedback. The handle was mechanically fixed to the table so that translations and rotations were now allowed. Real-time feedback of the produced moment of force was provided. **(c)** Detailed illustration of the experimental 'inverted-T' handle/beam apparatus for the free object condition. The force-moment sensors, shown as white cylinders were attached to two vertical aluminum bars. The transmitter of a magnetic position-angle sensor, marked out as a small black cube, was attached to the plastic base affixed to the top of the handle. M_X, M_Y, and M_Z are moments produced by the digits about *X*-, *Y*-, and *Z*-axes, respectively.

In order to test the mechanical advantage hypothesis in multi-digit torque production tasks regarding positive or negative contributions of fingers' actions to the required task, individual fingers were classified into moment agonist (*ago*) and moment antagonist (*ant*) with respect to the task moments (Shim et al., 2004; Zatsiorsky et al., 2002a; Zhang, Zatsiorsky, & Latash, 2007). Agonist fingers produce the moment of grasping force in the required direction, while antagonist fingers produce the moment of grasping force in a direction opposite to the task moments. For example, the index and middle fingers are moment agonists during the pronation effort, while the ring and little fingers are moment antagonists in the grasping force production. Within the moment agonists (or moment antagonists), fingers were further classified into two types of moment agonists (or moment antagonists) based on the lengths of the moment arms of finger grasping forces. The grasping forces of fingers with a longer moment arm were described as F_2. Those with a shorter moment arm were described as F_1. For example, during the pronation effort, the index (little) finger force is F_2 and the middle (ring) finger force is F_1 in agonist (antagonist) fingers as they are producing opposite directional torques around the thumb. The same calculation was performed for fixed-object prehension although the thumb does not specify the axis of rotation. Then, we calculated the ratio of F_2 to F_1 within each group of moment agonists and moment antagonists to quantify the index of mechanical advantage (Eq. 1 & 2). In addition, F_2 and F_1 were normalized by corresponding fingers' maximal voluntary forces (MVF), and the ratio of normalized F_2 to F_1 was computed for both the moment agonist and antagonist (Eq. 3 & 4).

$$MA_{ago} = F_{ago2} / F_{ago1} \tag{1}$$

$$MA_{ant} = F_{ant2} / F_{ant1} \tag{2}$$

$$MA_{ago}^{norm} = (F_{ago2} / F_{ago2}^{\max}) / (F_{ago1} / F_{ago1}^{\max}) \tag{3}$$

$$MA_{ant}^{norm} = (F_{ant2} / F_{ant2}^{\max}) / (F_{ant1} / F_{ant1}^{\max}) \tag{4}$$

,where *ago* and *ant* stand for the agonist and antagonist, respectively.

Three-way repeated-measures ANOVAs were used with the following factors: TYPE (two levels: Fixed and Free), MAG (three levels: 0.70, 0.47, and 0.23Nm), and DIR (two levels: pronation and supination efforts). MA_{ago}, MA_{ago}^{norm}, MA_{ant}, and

MA_{ant}^{norm} were compared with 1 by the one-sample t-test in order to test if *MAs* values were significantly different from 1. All were performed at a significant level $\alpha = 0.05$.

6.4. Results

For both fixed and free object conditions, substantial grasping force differences were observed between the index and middle fingers (Fig. 6.2a). The grasping forces of the ring and little fingers were similar (Fig. 6.2b). The grasping forces of the middle finger were greater than that of the index finger during supination efforts, while the index finger grasping forces were greater than the middle finger grasping force during pronation efforts for both the fixed and free object condition.

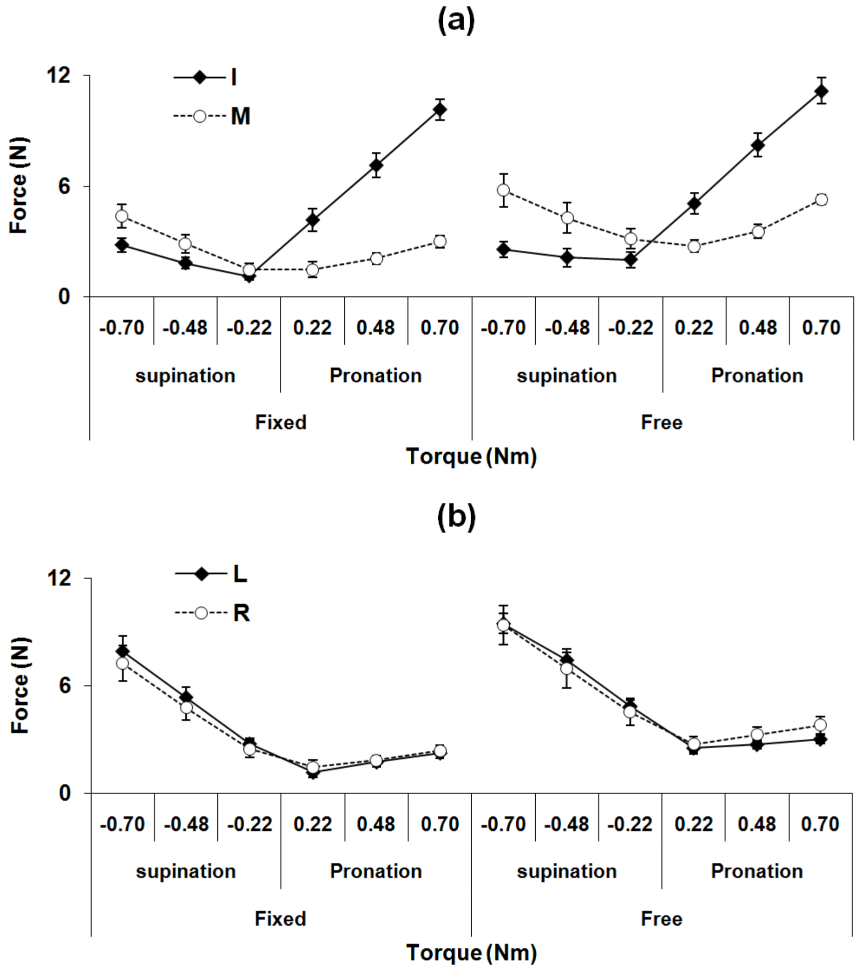


Figure 6.2. Individual finger grasping forces during torque productions. **(a)** Index and middle finger forces and **(b)** ring and little finger forces. Data averaged across subjects are shown with standard error bars.

For both the fixed and free object conditions, the MA_{ago} were not different from 1 during supination efforts and greater than 1 during pronation efforts, which was confirmed by one-sample t-test (Fig. 6.2a). This implies that the substantial grasping force difference between the index and middle fingers (i.e., moment agonist during pronation efforts) was significant, while the grasping forces of ring and little finger were not statistically different (i.e., moment agonists during supination efforts) when the fingers acted as moment agonist (Fig. 6.3a). The MA_{ago} under the fixed object condition was greater than those under the free object condition when pronation efforts were required (Fig. 6.3a). During the supination efforts, the difference of MA_{ago} between two prehension types (i.e., fixed and free object conditions) was not significant. In addition, there was no significant effect of MAG (three levels of torque magnitude: 0.24, 0.47, 0.70Nm) with significant interaction with DIR (i.e., pronation and supination). These finding was supported by three-way repeated measures ANOVA on the MA_{ago} with the factors of TYPE, MAG, and DIR, which showed significant effects of TYPE and DIR and significant interaction of TYPE × DIR and MAG × DIR [TYPE: F (1, 16) = 25.55, $p < .0001$; MAG: F (2, 32) = 4.91, $p > .04$; DIR: F (1, 16) = 54.30, $p < .0001$; TYPE × DIR: F (1, 16) = 17.07, $p < .0001$; TYPE × MAG: F (2, 32) = 3.99, $p > .05$; DIR × MAG: F (2, 32) = 14.86, $p < .0001$; TASK × MAG × DIR: F (2, 32) = 6.72, $p > .01$]. For the pronation efforts, all pair-wise comparisons on MA_{ago} between the fixed and free object conditions were statistically significant ($p<.01$). MA_{ago}^{norm} were statistically greater than from 1 throughout combinations of prehension types, torque directions, and torque magnitudes (Fig. 6.3c). In particular, MA_{ago} was statistically equal to 1, while MA_{ago}^{norm} was greater than 1 during supination efforts. The difference of MA_{ago}^{norm} between prehension types (i.e., free and fixed object conditions) was not significant, but MA_{ago}^{norm} during pronation efforts was greater than during pronation efforts for both the fixed and free object conditions [DIR: F (1, 16) = 27.78, p

<.0001]. For the pronation efforts, all pair-wise comparisons on MA_{ago}^{norm} between fixed and free object conditions were statistically significant (p<.01) except at 0.70Nm.

Both MA_{ant} and MA_{ant}^{norm} were less than 1 during supination efforts regardless of prehension types and torque magnitudes (Fig. 6.3b). During supination efforts, MA_{ant} was equal to 1 (or less than 1 at 0.24Nm for the free object condition) for both the fixed and free object condition, while MA_{ant}^{norm} was equal to 1 during the fixed object prehension and slightly greater than 1 during the free object prehension (Fig. 6.3c and 6.3d). These results mean that the index finger produced less grasping force than the middle fingers did when the fingers acted as moment antagonists, and that the grasping force of the ring and little fingers were similar when the fingers' grasping forces produced antagonist moments. There was no significant difference between the free and fixed object conditions for both MA_{ant} and MA_{ant}^{norm}. In addition, both MA_{ant} and MA_{ant}^{norm} were decreased with torque magnitudes especially during supination for both fixed and free object conditions [MAG: F (2, 32) = 17.20, p <.0001; DIR × MAG: F (2, 32) = 14.86, p <.0001 for MA_{ant}; MAG: F (2, 32) = 16.40, p <.0001; DIR × MAG: F (2, 32) = 4.244, p <.05 for MA_{ant}^{norm}].

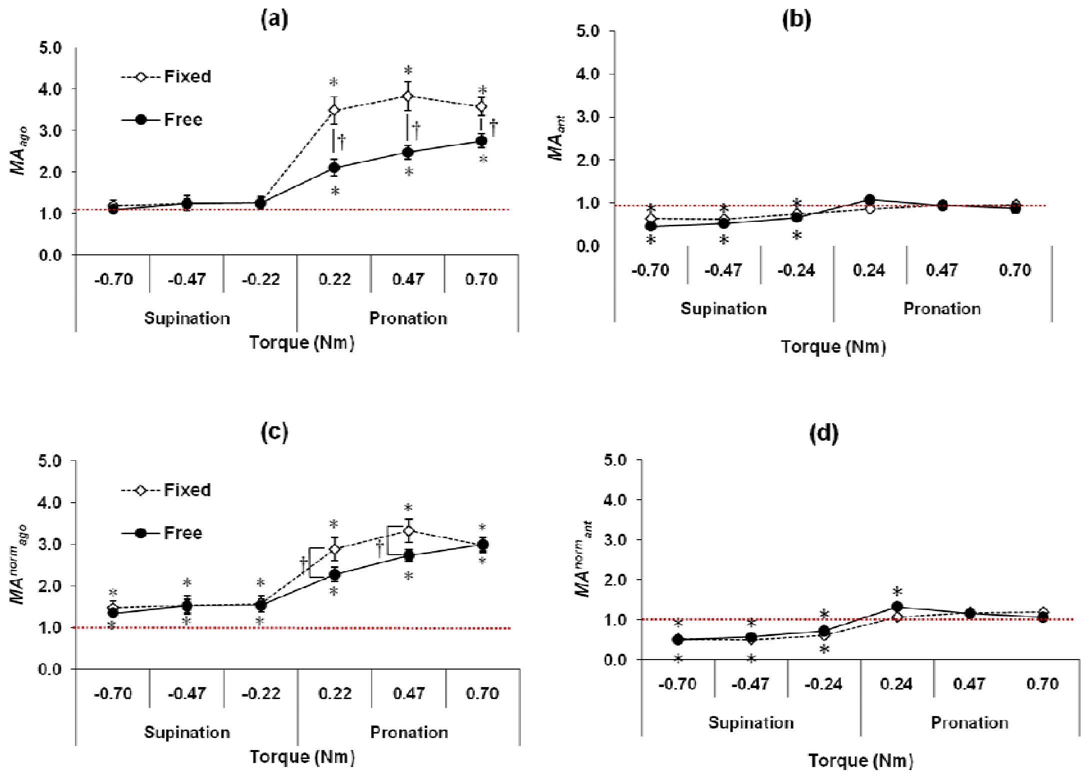


Figure 6.3. The ratio of the fingers' grasping force with a longer moment arm (F_2) to a shorter moment arm (F_1) when the fingers act as **(a)** moment agonist (MA_{ago}) and **(b)** moment antagonist (MA_{ant}). F_2 and F_1 were normalized by corresponding fingers' maximal voluntary forces (MVF). The ratio of normalized F_2 to F_1 was computed for **(c)** moment agonist MA^{norm}_{ago} and **(d)** antagonist MA^{norm}_{ant} . The averages across all subjects' data are shown with standard error bars. * represents statistical significance of sampled t-test ($p < .01$). † represents statistical significance of pair-wise comparison on *MAs* between fixed and free object conditions ($p <.01$)

6.5. Discussions

In the redundant human movement system, the selection of individual effectors' contributions to an output (i.e., performance variables) is governed by the controller's specific principle (Latash, Scholz, Danion, & Schoner, 2001; Li et al., 1998). At times, this principle considers the structure of the system, particularly parallel finger connections in a multi-finger prehension system. In this study, the tasks included the production of constant torques during the fixed object prehension and the constant maintenance of original positions against external torques during the free object prehension. Thus, the torque production was commonly instructed for both tasks (i.e., fixed and free object prehension). The mechanical advantages of individual fingers in grasping force production as determined by hand structure (e.g., parallel finger connection) is a crucial reference to the controller's strategy of selecting finger grasping forces. In this study, the term "mechanical advantage" refers to the moment arm of individual finger's grasping force which contributes to moment production.

It seems that the larger grasping force recruitment of fingers with greater mechanical advantages (i.e., moment arms) was more evident only when the fingers acted as moment agonist and the pronation efforts were required (Fig. 6.2a). Indeed, the lateral fingers (i.e., the fingers with longer moment arms) produced smaller (or equal to) grasping forces than the central fingers produced when the grasping forces of fingers produce moments in opposite to the required direction (Fig. 6.2a).

According to the force production profiles in this study, the mechanical advantage hypothesis seems to be valid only when index and middle fingers produced agonist moments (i.e., pronation efforts). During supination efforts, the lateral and central fingers which produce agonist moments were the little and ring fingers, respectively.

It has been reported that the action of the index finger is the most independent and is stronger than other fingers in normal force (i.e., grasping force) production. In contrast, the action of little finger is less independent and is weaker than others in force production (Li et al., 1998; Zatsiorsky, Li, & Latash, 2000). Therefore, the controller's effort to control finger forces might be different from the force production profiles due to the different interdependencies of finger actions as well as varied force production abilities among fingers. The ratios of normalized finger forces by MVFs of corresponding fingers (i.e., MA_{ago}^{norm} in Fig. 6.3c) were greater than 1 during both supination and pronation regardless of prehension types when fingers produced agonist moments (Fig. 6.3c). However, the ratios of normalized finger grasping forces (i.e., MA_{ant}^{norm} in Fig. 6.3d.) were still equal to or less than 1 when fingers produced antagonist moments (Fig. 6.3d). Thus, we can infer that the mechanical advantage hypothesis is valid during both supination and pronation efforts when fingers' grasping forces produce agonist moments taking the force production abilities of fingers into consideration.

In particular, when normalized values of fingers' grasping forces were used, the mechanical advantage indices (*MA*) were scaled up during supination effort for both fixed and free object conditions as compared to the *MA* before normalization (Fig. 6.3c), while the *MA* for the fixed object condition were scaled down during pronation efforts (Fig. 6.3d). These differences were possibly caused by the varied force production abilities among fingers as well as prehension types. In other words, the little finger, which is the moment agonist with a longer moment arm during supination efforts, produced less MVF than the ring finger did. Because of this, the normalized value of the little finger's force was greater than that of the ring finger, demonstrating that the ratio (i.e., MA^{norm}) can be greater than 1. In terms of the pronation effort, the MVF of the index finger was greater than the middle finger during the fixed object prehension, resulting in a scaling down of the mechanical advantage indices after the normalization. Nevertheless, MA_{ago}^{norm} were still greater during pronation efforts than during supination efforts. This might be caused by different independencies among fingers. It has been shown that the actions of index finger are more independent than the action of little finger (Li, Latash, & Zatsiorsky, 2003; Li et al., 1998; Park et al., 2009; Zatsiorsky et al., 2000). The force production of the little and index fingers induce substantial force productions of the ring and middle fingers (i.e., enslaving forces), respectively. However, the enslaving effect (in percentage of the maximal finger force) of the little finger was more evident than that of the index finger. Therefore, the ratio of the little and middle finger grasping forces can always be less than the ratio between the index and middle finger grasping forces.

Lastly, fingers with greater mechanical advantages were utilized more during the fixed object condition as compared to the free object condition, especially during pronation efforts (Fig. 6.2a: pronation). For the free object condition, the sum of the IF grasping forces should be close to the thumb grasping force as a horizontal translation constraint. For the fixed object condition, however, the selections of the IF grasping forces were perfectly free since there was no prescribed condition of summed value of IF grasping forces. It was reported that the force productions of peripheral fingers (i.e., index and little finger) under the free object condition were less independent than those under the fixed object condition (Park et al., 2009). This means that the internal constraint is the only factor which can cause the inter-dependency of finger forces during a fixed object prehension. The CNS can regulate the finger forces without taking the task mechanics into consideration. The greater grasping force production by the fingers with longer moment arm would minimize the total grasping force during torque production task. If the CNS should govern other constraints such as slip prevention and finger force relation with the thumb force, these constraints may affect the degree of the finger force involvement during torque production tasks. In addition, the grasping force involvement of the index finger (i.e., pronation effort) linearly increased with the torque magnitude during the free object prehension. Although it is evident that static constraints hamper the use of mechanical advantage of involved fingers during torque production tasks, it remains to be explored how each constraint (e.g., horizontal translation, vertical translation, and rotation) affects the sharing pattern of individual finger forces in static condition as well as dynamics condition.

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Chapter 7: Prehension control: separated effect of static constraints on a multi-finger torque production tasks

Chapter 7 will be submitted to a journal for publication

7.1. Abstract

In Chapter 5, it was revealed that the principle of superposition (i.e., decoupled control of grasping stability and rotational equilibrium) was valid during both fixed and free object prehension, suggesting the generalizability of the principle of superposition during human hand static prehension. However, the fixed object prehension was constraint free, meaning that both horizontal and vertical translations of the hand-held object were not constrained. Therefore, the separate investigations of the effects of horizontal and vertical translational constraints would be necessary in order to confirm the claim that the principle of superposition is valid regardless of linear translational constraints during static prehension tasks. There were eighteent experimental conditions: three types of prehension conditions (i.e., HR, VR, and HVR object prehensions) with two torque directions (i.e., supination and pronation) and three torque magnitudes: (i.e., -0.70, -0.47, -0.24 Nm). During the HR object prehension, the vertical translation of hand-held object was mechanically fixed so that coupling of the thumb tangential force and virtual finger (i.e., the vector sum of individual fingers forces/moments) tangential force was not necessitated. During the VR object prehension, the coupling of thumb normal force and virtual finger normal force was not mechanically constrained. The HVR condition contained horizontal translation, vertical translation, and rotation constraints (i.e., free object prehension)

The subjects performed 25 trials while holding object and maintaining constant position of the hand-held object against external torques during trials. The significant correlations between thumb normal force and virtual finger normal force were observed regardless of varied combinations of experimental condition, suggesting that invariant relations between thumb and virtual finger grasping forces in human hand static prehension. In spite of varied prehension conditions, the experimental variables at the virtual finger level were organized into two subsets, which were associated with two components of the prehension task: grasping force control and rotational equilibrium control. We concluded that the decoupling of grasping stability control and rotational equilibrium control was not affected under varied combinations of horizontal translation, vertical translation, and rotation constraints.

7.2. Introduction

This paper is a sequel to a previous study (Chapter 5) which investigated the validity of the principle of superposition (i.e., the decouple control of grasping stability and rotational equilibrium) during fixed and free object prehensions. It has been revealed that the grasping stability control and rotational equilibrium control were decoupled during free object prehension (Shim, Latash, et al., 2005b; Zatsiorsky et al., 2004), and it was questioned whether the decoupled controls of grasping stability and rotational equilibrium were affected by static constraints during human prehension tasks. The task in the previous study was to hold the handle while producing assigned moments during both fixed and free object prehension tasks. The results showed that the independent two sub sets of elemental variables at the virtual finger level (i.e., summed action of individual finger forces and moments), which explain the grasping stability and rotational equilibrium, were still maintained even during the fixed object prehension where both vertical and horizontal translation were not constrained.

Because the fixed object prehension was constraint free, which means that both horizontal and vertical translations were not constrained, separate investigations of the effects of horizontal and vertical translational constraints would be necessary in order to confirm the claim that the principle of superposition is valid regardless of linear translational constraints during static prehension tasks. Thus, we have decided to explore whether the decoupled control of grasping stability and rotational equilibrium is valid when horizontal translation and vertical translation are separately constrained.

The human hand system is a typical example of a redundant human movement system, meaning the number of elemental variables to be controlled is much greater than the number of mathematical equations which express the relation among elemental variables. Thus, an infinite combinations of digit forces and moments are possible for static prehension tasks (Pataky et al., 2004a; Shim et al., 2003b, 2005a; Zatsiorsky et al., 2002). Both theoretical analyses and experimental studies suggested that the hierarchical organization of prehension control was a solution of the redundant hand system. The idea is that individual fingers (IF) act together in order to stabilize the summed action of individual fingers (i.e., the virtual finger). In other words, the controller organizes two hierarchies: thumb-VF level (higher level) and individual finger (IF) level. Previous studies on multi-digit pressing (Li et al., 1998; Shinohara et al., 2003) and all-digit rectangular object prehension (Shim et al., 2004, 2005, 2006a) as well as circular object prehension used the indices of covariation (these variables, ΔVar and ΔVar_{norm} are similar to negated covariations between elemental variables; see Methods for computational details) between finger forces and moments of force, and showed that the CNS makes fine adjustments to IF forces/moments at the lower level to stabilize VF forces/moments at the higher level. Shim et al (2005) reported that the coefficient of correlation among individual finger forces were low and not always statistically significant (Shim et al., 2004a). However, the reported low correlations among individual fingers forces do not imply that the control of each finger forces was completely independent. Thus, we suspected that another hierarchy might exist in between the VF and IF levels. For example, if the task is to press the panel, which can rotate about an axis positioned midway between middle and ring finger, using all 4 fingers (index, middle, ring and little finger) while balancing the panel position, index-middle fingers (IM) and ring-little fingers (RL) can be grouped respectively because moment of IM force is opposite to that of RL force regarding moment directions. This idea can be similarly applied to prehension tasks in cases where the contact position of thumb in vertical is midway between the vertical positions of middle and ring fingers. If the correlations between pairs of the summed action of two fingers (i.e., IM-RL: upper finger-lower finger or IL-MR: lateral finger-central finger) is significantly correlated, the stabilization of VF level variables might arise at two finger level (TF) rather than the individual finger (IF) level. We expected to find significant negative correlations among TF level forces and moments, while the correlations among IF level force and moment are not significant.

7.3. Methods

7.3.1. Subjects

Seventeen right-handed male volunteers (age: 29 ± 3.1 years, weight: 67.1 ± 2.9 kg, height: 174.2 ± 5.3 cm, hand length: 18.7 ± 2.5 cm, and hand width: 8.7 ± 0.9; means ± SD are presented) participated in the current experiment. The handedness was determined by the Edinburgh Handedness Inventory (Oldfield, 1971). No subject had previous history of neuropathies or traumas on their upper extremities. The hand length was measured using the distal crease of the wrist to the middle fingertip when a subject positioned the palm side of the right hand and the lower arm on a table with all finger joints extended. The hand-width was measured from the radial side of the index finger metacarpal joint to the ulnar side of the little finger metacarpal joint. Before testing, the experimental procedures of the study were explained to the subjects and the subjects signed a consent form approved by the University of Maryland.

7.3.2. Equipments

Two types of sensors were used to measure digit force and moment and to provide a real-time position-angle feedback to the subjects during trials. Five six-component (three force and three moment components) transducers (Nano-17s, ATI Industrial Automation, Garner, NC, USA) were attached to an aluminum handle (Fig.

2) in order to measure each digit's forces and moments. Pieces of sandpaper with a friction coefficient of about 1.5 (100-grit) were attached to the surface of each sensor in order to increase the friction between the digits and the contact surface of transducers. The vertical distances between the center points of adjacent sensors for fingers were 30mm; the center point of the thumb sensor was positioned at the midpoint between the center point of middle and ring finger sensors in the vertical direction. The horizontal distance between the contact points of the thumb sensor and other sensors was 68 mm. One six-component (three position and three angle components) magnetic tracking sensor (Polhemus LIBERTY, Rockwell Collins Co., Colchester, VT, USA) was mounted to the top of the aluminum handle in order to monitor the linear and angular positions of the handle and to provide feedback according to the given conditions. A magnetic sensor was attached to the front edge of a Plexiglas base; this Plexiglas was affixed to the top of the handle. A horizontal aluminum beam (45cm in length) was affixed to the bottom of the handle in order to hang a load (0.33kg) at different positions along the beam (Fig. 7.2). A load at different positions along the beam generated different external torques due to different moment arms. The analogue signals were routed to a 12-bit analogue-digital converter (a PCI-6031 and a PCI-6033, National Instrument, Austin, TX). LabView programs (LabView 7.1, National Instrument, Austin, TX) were developed and used to synchronously record the signals from the force/moment sensors and magnetic sensor. The Labview program automatically initialized the values of sensor signals to zero at the beginning of each trial. The sampling frequency was set at 50 Hz. Sampled data were digitally low-pass filtered with a 2nd order Butterworth filter. The cutoff

low frequency was set at 5 Hz (Gao, Latash, & Zatsiorsky, 2005a; Li, Latash, & Zatsiorsky, 1998).

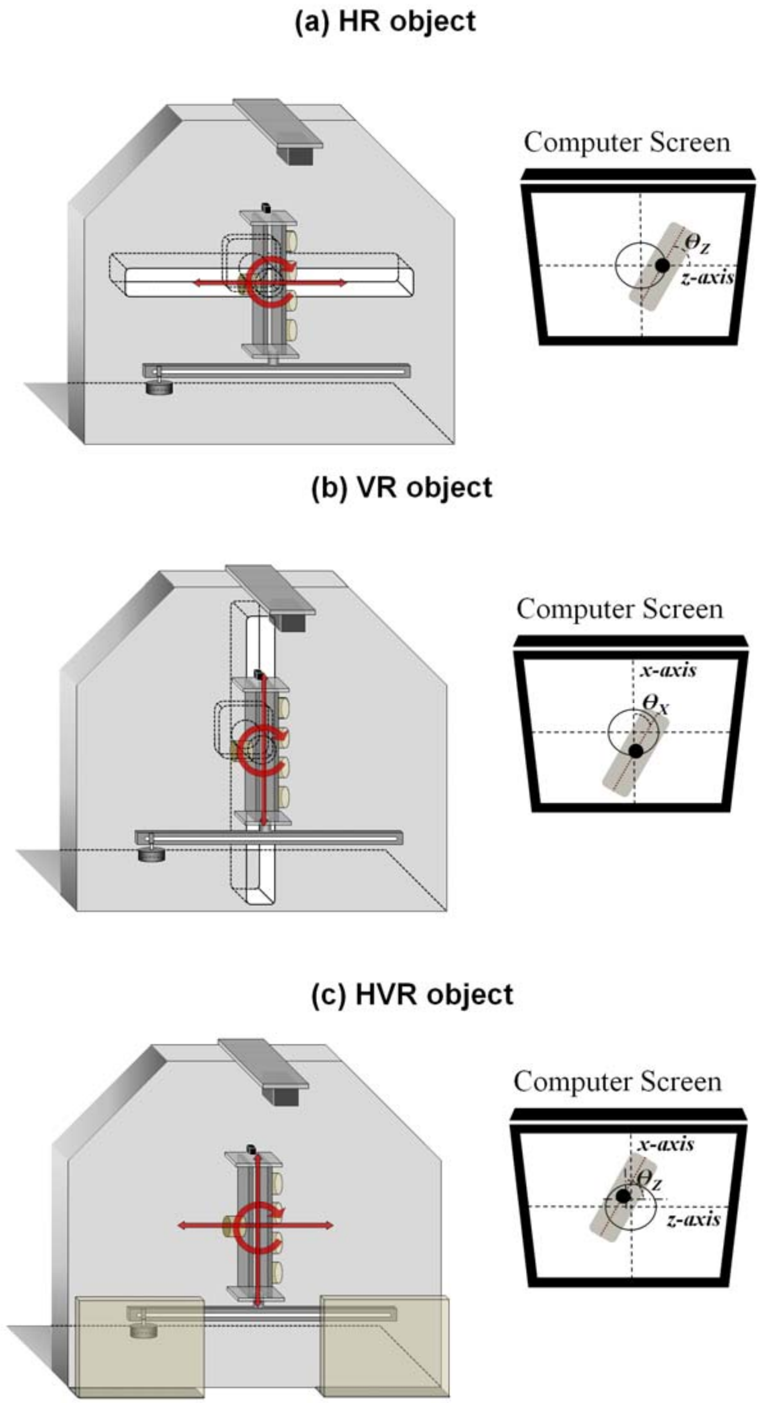

Figure 7. 1. **(a)** Schematic illustration of the experimental setup for the HR object prehension (left) and position feedback (right). Arrows on the handle indicate that horizontal translations and rotation about the axis orthogonal to the grasping plane are allowed during the HR object prehension, while subjects have to maintain the static constraints. Real-time horizontal translation feedbacks along *z*-axis, and rotation about *y*-axis were provided using the magnetic position-angle sensor. **(b)** Schematic illustration of the experimental setup for VR object condition (left) and position feedback (right). Arrows on the handle indicate that vertical translations and rotation about the axis orthogonal to the grasping plane are allowed during the VR object prehension. Real-time vertical translation feedbacks along *x*-axis, and rotation about *y*-axis were provided using the magnetic position-angle sensor. **(c)** Schematic illustration of the experimental setup for the HVR object (i.e., free object) condition (left) and position feedback (right). Arrows on the handle indicate that horizontal translation, vertical translations, and rotation about the axis orthogonal to the grasping plane are allowed during the free object prehension. Real-time feedbacks of translation along *z*-axis (horizontal translation), translation along *x*-axis (vertical translation), and rotation about *y*-axis were provided using the magnetic position-angle sensor.

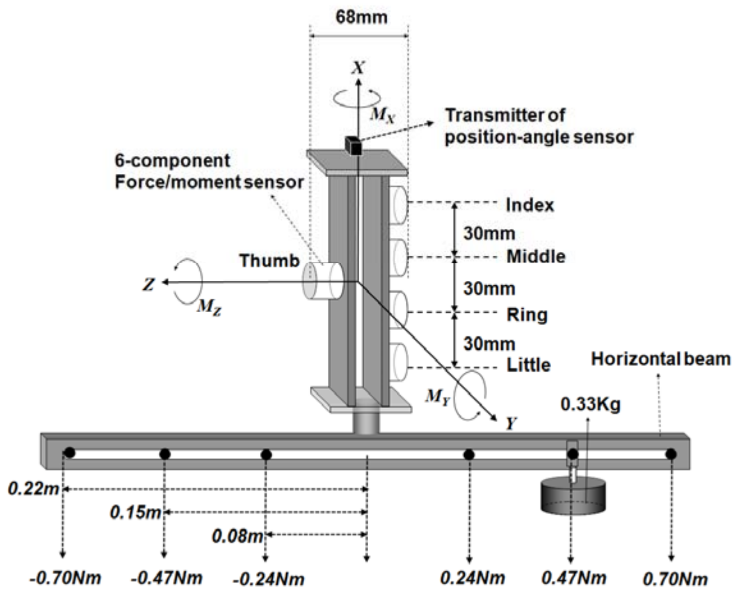

Figure 7.2. Detailed illustration of experimental 'inverted-T' handle/beam apparatus for the free object condition. The force-moment sensors shown as white cylinders were attached to two vertical aluminum bars. The transmitter of the magnetic position-angle sensor, marked out as a small black cube, was attached to the plastic base affixed to the top of the handle. M_X, M_Y, and M_Z are moments produced by the digits about *X*-, *Y*-, and *Z*-axes, respectively.

7.3.3. Experimental procedures

The subjects sat in the chair facing the computer screen and flexed the right elbow joint 90 degree in the sagittal plane. The forearm was in a neutral position between pronation and supination. A height-adjustable chair was used to keep the right-arm joint configuration of each subject constant throughout the experiments. Prior to the actual experiments, the subject had an orientation session to become familiar with the experimental devices and to ensure that the subjects were able to perform the experimental tasks. There are eighteen experimental conditions: three levels of prehension types (i.e., HR, VR, and HVR conditions); two levels of directions (i.e., supination and pronation); three levels of external torque magnitude (i.e., 0.24Nm, 0.47Nm, and 0.70Nm). Negative and positive torques about *y*-axis were generated through supination and pronation efforts, respectively. The three levels of prehension types included horizontal translation + rotation constraints (HR) (Fig. 7.1a), vertical translation + rotation constraints (VR) (Fig. 7.1b), and horizontal translation + vertical translation + rotation constraints (HVR) (Fig. 7.1c) in a two-dimensional grasping plane. Note that in this study, the term 'constraint' means that constrained actions were allowed during the trials, forcing the subject to control the constrained action in order to maintain the handle's static position. For example, the handle can be rotated and vertically translated under the VR condition (Fig. 7.1b), while the horizontal translation of the hand-held object was blocked. This means that the horizontal position of the handle was constant during the VR condition, implying that the handle was not translated horizontally by digits' normal forces. The subjects were instructed to place each digit on the designated sensor (i.e., Thumb, Index, Middle, Ring, and Little) and keep all digits on the sensors during overall trials. The instructed task was to hold the handle and to maintain the steady-state condition of the handle while satisfying given mechanical constraints. The subjects were instructed to maintain the handle in equilibrium (i.e., quasi-static grasping) against external torques for 5-s. Thus, the subject had to adjust the handle position intentionally against given constrained translations or rotation. Using the given mechanical constraints as referents, real-time feedback on the linear and angular position of the handle was provided on the computer screen. The subjects were instructed to avoid handle rotations or translations and were asked to minimize the angular and linear deviations of the handle. If the deviations exceeded the pre-defined criteria (rotation: $\sqrt{\theta_x^2 + \theta_y^2} < 1^\circ$ or translation: $\sqrt{\Delta x^2 + \Delta y^2}$ < 1cm) during each trial, the data collection automatically stopped with beep sound and the subject performed the trial over again. In addition, the subjects were instructed to grasp the handle by placing the tips of their digits on the corresponding sensors and to produce torques against external torques by using as little force from their digits as possible. Twenty five consecutive trials were performed for each condition. Thus, each subject performed a total of 450 trials (3 TYPEs × 2 DIRs × 3 TORs × 25 trials = 450). Prior to the actual experiments, the subjects had a familiarization session, which included an explanation of the experimental procedures and a few practice trials. Two-minute breaks were given at the end of each trial in order to avoid fatigue effects. The order of the eighteen experimental conditions was balanced and no subject reported fatigue.

7.3.4. Data analysis

The recorded force and moment data were averaged over the second half of the 5s, which supposedly reflects steady-state of the handle, for each trial for the following analysis.

<u>Task Constraints of static prehension in a 2D grasping plane</u>

The constraints model in this study was similar to that employed in previous studies (Zatsiorsky et al., 2004). Because the analysis was limited to a static grasping in a two-dimensional grasping plane (i.e., planar static task), the task constraints in each condition were also restricted to the grasping plane. The difference between the models employed in previous studies and the current study was that the subjects were asked to satisfy task constraints selectively according to the experimental conditions. During the HVR condition (i.e., free object prehension), all three task-constraints had to be satisfied simultaneously (Niu, Latash, & Zatsiorsky, 2007; Shim et al., 2005a; Zatsiorsky et al., 2004). In other words, task-constraints in this study were added or removed systematically in order to investigate the contributions of different combinations of task constraints during quasi-static prehension tasks. Hence, the following three task-constraints should be satisfied in order to maintain static equilibrium in the Y-Z grasping plane.

1) The sum of the normal force of all four fingers should be equal to the normal force of the thumb (i.e., horizontal translation constraint)

$$F_{th}^{n} = F_{i}^{n} + F_{m}^{n} + F_{r}^{n} + F_{l}^{n} = \sum_{j} F_{j}^{n},\ j = \{i, m, r, l\} \qquad (1)$$

2) The sum of the digit tangential forces should be equal to the weight of hand-held object (i.e., vertical translation constraint).

$$F_{th}^{t} + F_{i}^{t} + F_{m}^{t} + F_{r}^{t} + F_{l}^{t} = L \qquad (2)$$

3) The resultant moment created by the digit forces should be equal and opposite to given external torques on the object (e.g., the rotational constraint).

$$M_{TOT} = \underbrace{-F_{th}^{n} d_{th} + F_{i}^{n} d_{i} + F_{m}^{n} d_{m} + F_{r}^{n} d_{r} + F_{l}^{n} d_{l}}_{\text{Moment of normal force } (M_n)} + \underbrace{F_{th}^{t} r_{th} + F_{i}^{t} r_{i} + F_{m}^{t} r_{m} + F_{r}^{t} r_{r} + F_{l}^{t} r_{l}}_{\text{Moment of tangential force } (M_t)} = -Tq \qquad (3)$$

,where the subscripts *th, i, m, r*, and *l* stand for the thumb, index, middle, ring and little finger respectively. The superscript *n* and *t* indicate the normal and tangential force components. *d* and *r* are the moment arms, which are orthogonal to the each force component. Theoretically, *d* can be changed during the trials due to finger tip movement along the Y-axis, while *r* is constant, since it is always half of the grip width.

Equation 3 (i.e., rotational constraint) should be satisfied throughout all conditions while Eq.1 and 2 were selectively satisfied according to the conditions. For example, the subjects were asked to satisfy Eq.1 and 3 for HR condition (i.e., horizontal translation constraint + rotational constraint), Eq.2 and 3 for VR condition (i.e., vertical translation constraint + rotational constraint), Eq.1, 2 and 3 for HVR condition. In particular, the sum of digits' tangential forces were not necessarily equal to the weight of the object under the HR condition, and the equal and opposite normal forces of the thumb and VF was not necessitated under the VR condition. There were fifteen unknown variables (i.e., five normal, tangential forces, and the contact point of force application in the vertical direction) for all task conditions and the maximum number of constraints was three. An infinite number of digit force and moment combinations can be possible solutions for the given tasks. Thus, the system is undetermined. Because Eq. 3 was applied to all conditions, the system could have at least twelve degrees of freedom and at most fourteen degrees of freedom.

Virtual finger (VF) level analysis

The VF normal and tangential forces (F_n^{vf} and F_t^{vf}) can be obtained by the vector sum of fingers' normal and tangential forces, respectively. The moment of the VF tangential forces was obtained by the sum of the moment of the finger tangential forces. The moment arm of the finger tangential forces was constant (i.e., the half of the grip width) so that the moment arm of the VF tangential force was also constant. The moment arm of the normal VF was not constant, but can be computed from the Varignon theorem (Eq. 4).

$$D_{vf}^{n} = \sum F_{f}^{n} d_{f} / \sum F_{f}^{n} \qquad (4)$$

According to the Varignon theorem, the distributive property of vector products can be used to determine the moment of the resultant of several concurrent forces.

Correlations between experimental variables at VF level

For the 25 trials of each experimental condition, Pearson coefficient correlation between selected experimental variables (e.g., $F_{n}^{th}, F_{n}^{vf}, F_{t}^{th}, F_{t}^{vf}, F_{t}, M_{n}^{vf}, D_{n}^{vf}, and\, M_{t}$), which presumably construct simultaneous sequences of local cause-effect adjustment predicted by the task mechanics [so called "chain effect"], were computed (Fig. 7.3). The 1st local chain (i.e., correlation between normal forces of the thumb and VF, $F_{n}^{th} vs F_{n}^{vf}$) was necessitated by the task mechanics of the horizontal translation constraint, and the 9th local chain (i.e., correlation between normal forces of the thumb and VF, $F_{t}^{th} vs F_{t}^{vf}$) was predicted by the task mechanics of vertical translation constraint. Because these two constraints were selectively satisfied according to given prehension types, the whole chains might or might not be specified depending on selected task mechanics.

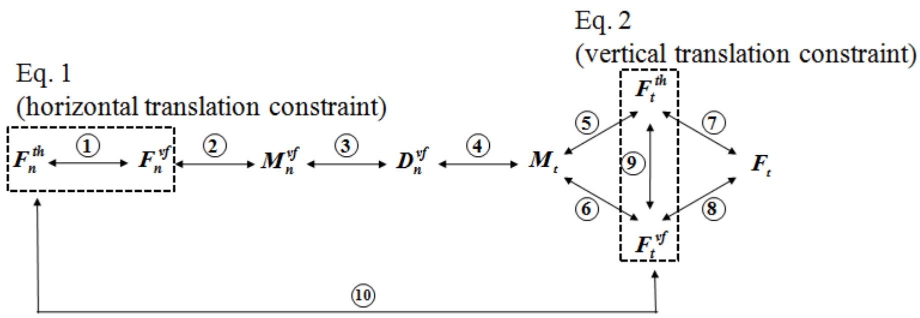

Figure 7.3. Schematic illustration of overall chains among VF level variables during multi-finger torque production tasks. 1st and 9th local chains represent the constraints of horizontal and vertical translation, respectively.

Principal Component Analysis (PCA)

The covariance matrix of sets of variables at the VF level (thumb and VF normal and tangential forces, and moment arm of VF normal force) was computed to perform a principle component analysis (PCA) with a variance maximizing (varimax) rotation. The Kaiser Criterion (i.e., extracted principal component should be the eigenvectors whose eigen-values are larger than 1) was employed to extract principal components (PCs). Then, the number of significant PCs with 0.4 of cutoff loading coefficient (Krishnamoorthy et al., 2003; Shim & Park, 2007) which accounted for more than 95% of total variance was counted.

The variances in thumb and VF forces spaces

The correlations of the 1st local chain ($F_n^{th} vs F_n^{vf}$) and the 9th local chain ($F_t^{th} vs F_t^{vf}$) should be significant when the horizontal and vertical translations were constrained in a static prehension, respectively. Particularly, the scatter plot formed by pairs of the two forces is an ellipse or a circle in a two-dimensional mapping of the thumb-VF normal or tangential forces coordinates in Newton (N). The data points could not be perfectly aligned in the null spaces imposed by the constraint of horizontal (*'*$F_n^{vf} = F_n^{th}$*'*) and vertical translations (*'*$F_t^{vf} + F_t^{th} = w$ *(weight of object)'*) due to error variances. Hence, we quantified the variances in (V_{null}) and orthogonal (V_{orth}) to the null space during three different types of prehension (Fig. 7.4) in order to examine and compare the scattered patterns of trial-to-trial changes of thumb and VF normal (Fig. 7.4.a) and tangential forces (Fig. 7.4b) between experimental conditions.

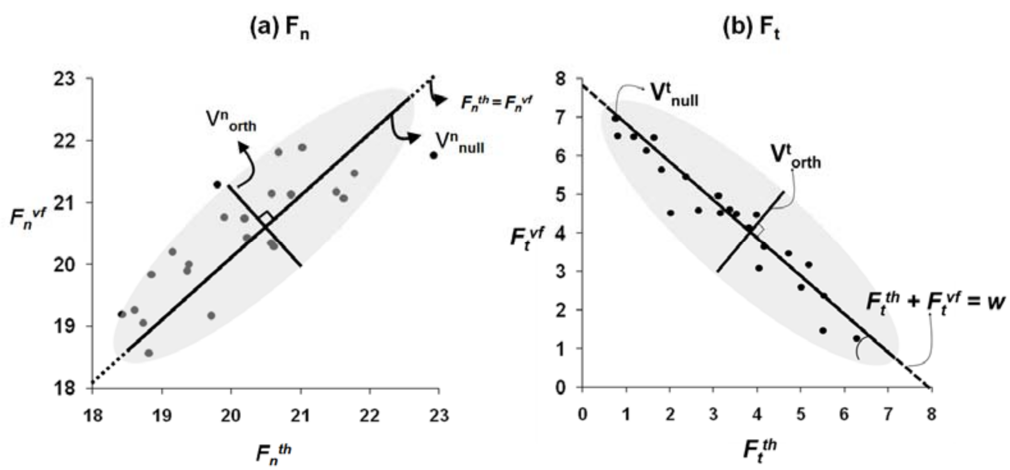

Figure 7.4. **(a)** The variance in the null space of *'*$F_n^{vf} = F_n^{th}$*'* (V_{null}^{n}) and orthogonal to the null space (V_{orth}^{n}) **(b)** The variance in the null space of *'*$F_t^{vf} + F_t^{th} = w$*'* (V_{null}^{t}) and orthogonal to the null space (V_{orth}^{t}).

<u>Individual finger (IF) level analysis</u>

Synergy index (delta variance)

ΔV was computed in order to examine the synergistic actions of individual fingers. Four components of ΔV were computed across 25 trials for each condition: 1) normal force (ΔV_{Fn}), 2) tangential force (ΔV_{Ft}), 3) moment of normal force (ΔV_{Mn}), and 4) resultant moment of force (ΔV_{M}). ΔV was obtained by subtracting the variance of the VF component (Var_{tot}) from the sum of variances of individual finger components $(\sum_{j=1}^{4} Var_j)$. These variables were normalized by the sum of variance of individual finger components (Eq. 5).

$$\Delta V_{Norm} = (\sum_{j=1}^{4} Var_j - Var_{tot}) / (\sum_{j=1}^{4} Var_j) \quad (5)$$

Correlation Analysis

Pearson coefficient correlation between selected pairs of individual finger normal forces, tangential force, and moment force were computed across 25 trials for each condition. The correlation analysis was performed for each group, not at inter-group stages. Pairs of individual fingers included I-M, R-L, I-L, M-R. In addition, the correlation coefficient between selected pairs of two-finger normal forces, tangential force, and moment force were computed over 25 repetitive trials for each condition. Pairs of two-finger cases included IM-RL (upper and lower fingers), and IL-MR (lateral and central fingers).

7.3.5. Statistics

ANOVAs were used with the following factors: TYPE (three levels: HR, VR, and HVR), DIR (two levels: supination and pronation efforts), and MAG (three levels: 0.23, 0.47, and 0.70Nm). The factors were chosen based on particular comparisons. The regression analysis between elemental variables was performed at the VF level and IF level and Pearson's coefficients of correlation (*r*) were computed in MATLAB. The *p*-value of statistical significance was set at p <.05 for both ANOVA and regression analysis. The *p*-value of statistical significance was set at p <.01 for both ANOVA and regression analysis. The sample size (*n*) of each regression analysis was 25 (i.e., 25 consecutive trials for each condition and subject). We assumed that the correlation coefficients are statistically significant as long as *r* is larger than 0.5, which gives a power=0.8 (α = .05) with a sample size of 25.

7.4. Results

In the virtual finger (VF) level analysis, the thumb and VF normal and tangential force, moment of each force component, and the moment arm of VF normal force were considered as elemental variables. The correlation of coefficients between pairs of elemental variables were calculated and the correlation matrix was constructed out of the thumb and VF normal and tangential forces, and moment arm of VF normal force in order to perform the principle component analysis (PCA). At the individual finger (IF) level analysis, the normal and tangential force of individual fingers (e.g., index, middle, ring and little), and moment of each force component were considered.

7.4.1. Correlations among virtual finger (VF) level forces and moments

The variance of the thumb normal force across the trials showed high correlations with that of VF normal force throughout all combinations of prehension types, torque directions and torque magnitudes ($r > .8$, F_n^{th} $vs F_n^{vf}$; $r = \{0.80, 1.00\}$:

range of correlation coefficient across all experimental conditions in table. 7.1). In contrast, the trial-to-trial changes of the VF normal force did not correlated with the trial-to-trial changes of the moment of VF normal force regardless of experimental conditions (r <.4, $F_n^{vf}\, vs\, M_n^{vf}$; r = {0.00, 0.40}: range of correlation coefficient across all experimental conditions in table 7.1). During the free object condition, the 1st $(F_n^{th}\, vs\, F_n^{vf})$ and 9th local chains $(F_t^{th}\, vs\, F_t^{vf})$ showed significant correlations as expected by the constraints of linear translations (i.e., the constraints of horizontal and vertical translation) (Fig. 8a). Respectively, the two normal and tangential forces showed high positive and negative correlations (Fig. 7.5a & Table 7.1). The correlations of the 3rd $(M_n^{th}\, vs\, D_n^{vf})$, 4th $(D_n^{th}\, vs\, M_t)$, 5th and 6th $(M_t\, vs\, F_t^{th}, M_t\, vs\, F_t^{vf})$ chains, which were serially linked, were all statically significant regardless of varied conditions of torque directions and magnitudes during free object prehension (Fig. 7.5a & Table 7.1). However, the 7th $(F_t^{th} vs F_t)$ and 8th $(F_t^{vf} vs F_t)$ chains were not significantly correlated due to the constant value of F_t as the task mechanics prescribed $(F_t^{th} + F_t^{vf} = F_t = w)$.

Effect of vertical translation constraint (VR condition)

When vertical translation of the hand-held object is constrained, the 9th chain $(F_t^{th}\, vs\, F_t^{vf})$ should show significant correlation as prescribed by task mechanics (i.e., the sum of tangential forces should be close to the weight of the object). It was obvious that the 9th chain ($F_t^{th}\, vs\, F_t^{vf}$: r = {-0.54, -0.95}) had significant negative correlation, while the 7th $(F_t^{th} vs F_t)$ and 8th chains $(F_t^{vf} vs F_t)$ did not significantly correlate due to constant resultant tangential force in the VR condition ($F_t^{th} vs\ F_t$: r = {0.22, 0.43}, $F_t^{vf} vs\ F_t$: r = {0.31, 0.43}) (Fig. 7.5c). However, the 1st chain $(F_n^{th} vs F_n^{vf})$ showed significant correlation over repetitions ($F_n^{th}\ vs\ F_n^{vf}$: r = {0.91, 0.95}), which did not mechanically necessitated in the VR condition. The correlations of the 3rd $(M_n^{th} vs\ D_n^{vf})$, 4th $(D_n^{th} vs\ M_t)$, 5th and 6th $(M_t\ vs\ F_t^{th}, M_t\ vs\ F_t^{vf})$ chains, which were serially linked and significant for the free object condition, were all statically significant regardless of varied conditions of torque directions and magnitudes. Therefore, the relationship between elemental variables expressed by correlation coefficients during the VR object prehension was similar to the relationship during the free object prehension with slightly varying levels of correlations.

Effect of horizontal translation constraint (HR condition)

When the horizontal translation is constrained, the 1st chain $(F_n^{th} vs\ F_n^{vf})$ should show significant positive correlation (i.e., the thumb normal force should be equal and opposite to the VF normal force). In the results, it was evident that the variation of normal forces of the thumb and VF over repetition showed significant positive correlations ($F_n^{th}\ vs\ F_n^{vf}$: r = {0.97, 1.00}). However, the correlations of the 9th chain were not significantly correlated ($F_t^{th} vs\ F_t^{vf}$: r = {-0.20, -0.36}) possibly due to the unconstrained condition of two tangential forces compensating for the weight of the object. Unlike the low correlations of the 7th and 8th chains under the

VR and HVR condition, these correlations were relatively high in the HR condition (F_t^{th} *vs* F_t : r = {0.57, 0.83}, F_t^{vf} *vs* F_t : r = {0.53, 0.68}).

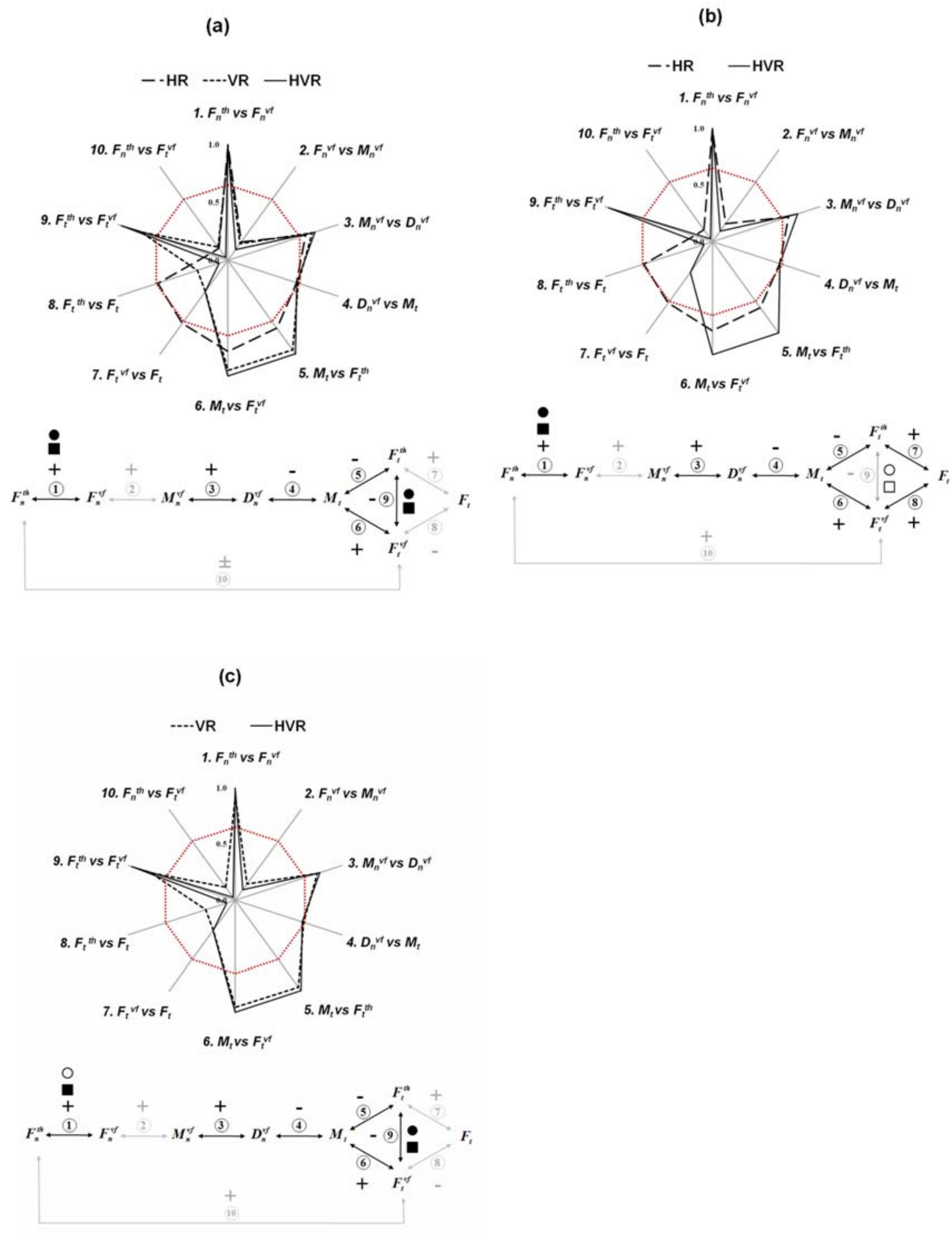

Figure 7.5. Capital *F, M* and *D* stand for the digit force, moment of force, and moment arm which is orthogonal to the each force component respectively. The subscripts *th* and *vf* stand for the thumb and virtual finger (VF) respectively. The superscript *n* and *t* indicate the normal and tangential force components.**(a)** (Top) The correlation coefficients between ten pairs of elemental variables at the VF level during all three types of prehensions (i.e., HR, VR and HVR object prehensions). Averaged data across subjects and experimental conditions in each prehension condition are presented. The red dotted line indicates the significant level of correlation coefficients (r = .5) with a sample size of 25. If the correlation coefficient is less than .5, the correlation coefficient is not statically significant; (Bottom) The cause-effect [so called 'chain effect'] relations among elemental variables at VF level under the HVR object (i.e., free object) condition. The bold arrows indicate that the correlation coefficients between linked variables by the arrow are statistically significant, while the blurred arrows indicate the correlation coefficient between variables are not significant ($r < .5$). The circles and squares placed on the 1st $(F_n^{th} vs F_n^{vf})$ and the 9th $(F_t^{th} vs\, F_t^{vf})$ local chains indicate 'task mechanics (circle)' and 'significance of correlation coefficient by experimental results (square)'. The closed and open circles indicate whether either of the 1st $(F_n^{th} vs F_n^{vf})$ or 9th $(F_t^{th} vs F_t^{vf})$ local chains are constrained by task mechanics within a task (closed circle) or not (open circle). The closed and open squares indicate the significance of the correlation coefficients of the 1st $(F_n^{th} vs F_n^{vf})$ or 9th $(F_t^{th} vs F_t^{vf})$ local chains from experimental results (i.e., open: not significant, closed: significant). The positive (+) and negative (-) signs represent positive and negative correlations, respectively. **(b)** (Top) The correlation coefficients between ten pairs of elemental variables at the VF level during HR and HVR object prehension; (Bottom) The cause-effect relations among elemental variables at VF level under the HR object condition. **(c)** (Top) The correlation coefficients between ten pairs of elemental variables at the VF level during VR and HVR object prehension; (Bottom) The cause-effect relations among elemental variables at VF level under the VR object condition.

Table 7.1. Correlation coefficients between ten pairs of elemental variables at the VF level during all three types of prehensions (i.e., HR, VR and HVR object prehensions)

TYPE	DIR	MAG (Nm)	1. F_n^{th} vs F_n^{vf}	2. F_n^{vf} vs M_n^{vf}	3. M_n^{vf} vs D_n^{vf}	4. D_n^{vf} vs M_t	5. M_t vs F_t^{th}	6. M_t vs F_t^{vh}	7. F_t^{vf} vs F_t	8. F_t^{vf} vs F_t	9. F_t^{th} vs F_t^{vf}	10. F_n^{th} vs F_t^{vf}
HR	Supination	**-0.70**	0.99 [100] (1.00, 0.99)	0.36 [23.53] (0.60, 0.03)	0.88 [100] (0.96, 0.77)	-0.76 [100] (-0.85,-0.59)	-0.78 [100] (-0.92,-0.65)	0.76 [88.24] (0.96, 0.39)	0.67 [88.24] (0.79, 0.45)	0.57 [58.82] (0.88, 0.12)	-0.32[23.53] (-0.78,-0.02)	0.36 [17.65] (0.73, 0.08)
		-0.47	0.99 [100] (1.00, 0.98)	0.33 [29.41] (0.68, 0.01)	0.88 [100] (0.99, 0.65)	-0.73[94.12] (-0.91,-0.47)	-0.79[88.24] (-0.91,-0.38)	0.81 [100] (0.94, 0.61)	0.57 [64.71] (0.89, 0.25)	0.55 [58.82] (0.80, 0.05)	-0.36[41.18] (-0.68, 0.02)	0.29 [11.76] (0.67, 0.02)
		-0.24	0.98 [100] (1.00, 0.90)	0.31 [17.65] (0.57, 0.02)	0.85 [94.12] (0.99, 0.47)	-0.62[70.59] (-0.88, 0.08)	-0.72[88.24] (-0.91,-0.46)	0.73 [88.24] (0.90, 0.43)	0.64 [76.47] (0.89, 0.36)	0.68 [82.35] (0.90, 0.48)	-0.31[23.53] (-0.63, 0.05)	0.38 [35.29] (0.65, 0.00)
	Pronation	**0.24**	0.99 [100] (1.00, 0.97)	0.30 [23.53] (0.71, 0.01)	0.50 [52.94] (0.80, 0.07)	-0.43[41.18] (-0.82, 0.03)	0.70 [100] (0.83, 0.51)	0.74 [100] (0.90, 0.52)	0.73 [100] (0.83, 0.52)	0.63 [76.47] (0.83, 0.29)	0.20 [0.00] (0.32, 0.01)	0.33 [23.53] (0.66, 0.06)
		0.47	0.99 [100] (1.00, 0.96)	0.30 [17.65] (0.78, 0.03)	0.62 [88.24] (0.85, 0.15)	-0.54[58.82] (-0.76, 0.10)	0.64 [82.35] (0.92, 0.20)	0.84 [100] (0.94, 0.76)	0.75 [100] (0.96, 0.51)	0.53 [58.82] (0.86, 0.19)	0.32 [23.53] (0.73, 0.02)	0.23 [11.76] (0.68, 0.02)
		0.70	0.99 [100] (1.00, 0.99)	0.24 [11.76] (0.57, 0.01)	0.52 [70.59] (0.73, 0.12)	0.50 [58.82] (0.79, 0.10)	0.74 [100] (0.90, 0.55)	0.81 [100] (0.91, 0.69)	883 [82.35] (0.84, 0.38)	0.57 [88.24] (0.73, 0.38)	0.23 [5.88] (0.64, 0.00)	0.17 [0.00] (0.49, 0.02)
VR	Supination	**-0.70**	0.91 [100] (0.98, 0.81)	0.28 [17.65] (0.66, 0.02)	0.84 [100] (0.97, 0.55)	0.72 [88.24] (0.92, 0.40)	0.96 [100] (0.98, 0.89)	0.96 [100] (0.98, 0.90)	0.34 [11.76] (0.66, 0.09)	0.22 [11.76] (0.59, 0.01)	0.85 [100] (0.93, 0.68)	0.25 [0.00] (0.46, 0.02)
		-0.47	0.92 [100] (0.98, 0.84)	0.28 [5.88] (0.78, 0.01)	0.85 [100] (0.98, 0.66)	0.69 [82.35] (0.94, 0.15)	0.95 [100] (0.99, 0.78)	0.92 [100] (0.99, 0.56)	0.31 [17.65] (0.73, 0.03)	0.43 [41.18] (0.94, 0.03)	0.78 [94.12] (0.95, 0.07)	0.34 [29.41] (0.88, 0.01)
		-0.24	0.95 [100] (0.99, 0.88)	0.40 [47.06] (0.84, 0.02)	0.88 [94.12] (0.99, 0.47)	0.69 [76.47] (0.96, 0.25)	0.95 [100] (0.98, 0.90)	0.94 [100] (0.98, 0.86)	0.32 [11.76] (0.59, 0.05)	0.35 [17.65] (0.59, 0.18)	0.78 [100] (0.94, 0.54)	0.40 [35.29] (0.78, 0.14)
	Pronation	**0.24**	0.91 [100] (0.98, 0.80)	0.20 [11.76] (0.63, 0.01)	0.80 [100] (0.93, 0.64)	0.68 [88.24] (0.88, 0.44)	0.90 [100] (0.98, 0.62)	0.92 [100] (0.98, 0.79)	0.43 [29.41] (0.79, 0.12)	0.36 [35.29] (0.62, 0.00)	0.67 [76.47] (0.93, 0.04)	0.19 [5.88] (0.76, 0.01)
		0.47	0.94 [100] (0.99, 0.85)	0.27 [23.53] (0.66, 0.01)	0.59 [76.47] (0.83, 0.02)	0.54 [64.71] (0.79, 0.02)	0.95 [100] (0.98, 0.88)	0.96 [100] (0.98, 0.92)	0.35 [29.41] (0.61, 0.09)	0.25 [5.88] (0.53, 0.03)	0.81 [100] (0.92, 0.64)	0.27 [11.76] (0.55, 0.01)
		0.70	0.92 [100] (0.97, 0.81)	0.19 [0.00] (0.44, 0.02)	0.64 [82.35] (0.81, 0.47)	0.51 [47.06] (0.70, 0.33)	0.94 [100] (0.99, 0.82)	0.95 [100] (0.98, 0.89)	0.36 [23.53] (0.81, 0.05)	0.24 [17.65] (0.61, 0.01)	0.79 [100] (0.94, 0.57)	0.21 [0.00] (0.40, 0.05)
HVR	Supination	**-0.70**	1.00 [100] (1.00, 0.99)	0.27 [0.00] (0.47, 0.03)	0.86 [100] (0.96, 0.56)	0.71 [88.24] (0.91, 0.33)	0.99 [100] (1.00, 0.93)	0.98 [100] (1.00, 0.85)	0.38 [35.29] (0.85, 0.09)	0.38 [29.41] (0.79, 0.08)	0.93 [100] (1.00, 0.59)	0.23 [17.65] (0.56, 0.03)
		-0.47	1.00 [100] (1.00, 0.98)	0.22 [11.76] (0.71, 0.00)	0.80 [88.24] (0.99, 0.29)	0.59 [82.35] (0.94, 0.05)	0.99 [100] (1.00, 0.98)	0.99 [100] (1.00, 0.97)	0.37 [35.29] (0.59, 0.11)	0.27 [5.88] (0.71, 0.01)	0.97 [100] (0.99, 0.91)	0.24 [17.65] (0.73, 0.00)
		-0.24	0.99 [100] (1.00, 0.96)	0.37 [41.18] (0.74, 0.01)	0.88 [100] (1.00, 0.66)	0.65 [76.47] (0.95, 0.08)	0.98 [100] (1.00, 0.88)	0.97 [100] (1.00, 0.72)	0.37 [29.41] (0.62, 0.05)	0.32 [17.65] (0.80, 0.04)	0.90 [88.24] (0.99, 0.33)	0.36 [41.18] (0.74, 0.01)
	Pronation	**0.24**	1.00 [100] (1.00, 0.99)	0.21 [11.76] (0.59, 0.00)	0.76 [88.24] (0.93, 0.35)	0.65 [64.71] (0.85, 0.38)	0.99 [100] (1.00, 0.97)	0.99 [100] (1.00, 0.98)	0.29 [11.76] (0.53, 0.05)	0.16 [0.00] (0.37, 0.01)	0.97 [100] (0.99, 0.90)	0.16 [11.76] (0.53, 0.01)
		0.47	1.00 [100] (1.00, 0.96)	0.28 [17.65] (0.69, 0.00)	0.73 [82.35] (0.91, 0.16)	0.62 [76.47] (0.85, 0.26)	0.99 [100] (1.00, 0.90)	0.99 [100] (1.00, 0.92)	0.35 [29.41] (0.71, 0.02)	0.22 [5.88] (0.51, 0.04)	0.95 [100] (0.99, 0.66)	0.26 [11.76] (0.61, 0.01)
		0.70	1.00 [100] (1.00, 0.98)	0.25 [5.88] (0.70, 0.00)	0.66 [70.59] (0.87, 0.24)	0.53 [58.82] (0.85, 0.00)	0.99 [100] (1.00, 0.93)	0.99 [100] (1.00, 0.95)	0.43 [47.06] (0.72, 0.05)	0.22 [5.88] (0.56, 0.01)	0.96 [100] (0.99, 0.76)	0.19 [0.00] (0.46, 0.00)

Averaged across subjects, the percent frequency of significant cases (in brackets), and minimal-maximal values (in parentheses) are shown. The subscripts *th, i, m, r*, and *l* stand for the thumb, index, middle, ring and little finger respectively. Capital *F, M* and *D* stand for the digit force, moment of force, and moment arm which is orthogonal to the each force component, respectively. The superscripts *th* and *vf* stand for the thumb and virtual finger (VF) respectively. The subscript *n* and *t* indicate the normal and tangential force components.

7.4.2. Variances in the thumb and VF forces spaces

It was shown that the correlation between the thumb and VF normal forces was significantly high (p >.8) regardless of prehension types, torque directions, and torque magnitudes, while the thumb and VF tangential force were only significantly correlated when the vertical translation was constrained (i.e., VR and HVR conditions) (Table 7.1 and Fig. 7.5). The variances of the trial-to-trial changes in the null space (V_{null}) ['$F_n^{vf} = F_n^{th}$' for F_n; '$F_t^{vf} + F_t^{t}$h= = w (weight of object)' for F_t] and orthogonal to the null space (V_{orth}) varied with the combinations of prehension type, torque directions, and torque magnitudes (Fig. 7.6).

Generally, V_{null} was relatively greater than V_{orth} in both normal and tangential force coordinates (Fig. 7.6). V_{null} of normal force (V^n_{null}) for HR condition was greater than that for other two prehension conditions (VR > HVR) except at ±0.47Nm conditions (Fig. 7.6a), while V_{orth} of normal force (V^n_{orth}) for VR condition was greater than other two prehension conditions throughout combinations of torque directions and magnitudes conditions [TYPE: $F(2, 32) = 8.35$, p <.01 for V^n_{null}; TYPE: $F(2, 32) = 66.83$, p <.0001 for V^n_{orth}] (Fig. 7.6b). There was no significant difference in the V_{null} of tangential force (V^t_{null}) between TYPE conditions, while the V_{orth} of tangential force (V^t_{orth}) of HR condition were relative greater than V^t_{orth} of other two conditions (V^t_{orth} of VR > HVR) [TYPE: $F(2, 32) = 70.64$, p <.0001 for V^t_{orth}] (Fig. 7.6c and 7.6d). Both V^t_{null} and V^t_{orth} increased with torque magnitudes, and V^t_{null} and V^t_{orth} during supination efforts were greater than those during pronation efforts [DIR: F (1,

16) = 9.00, p <.01]. There was no interaction between factors except significant interaction of TYPE × TOR on V^t_{orth} [TYPE × TOR: F (4, 64) = 28.99, p <.0001].

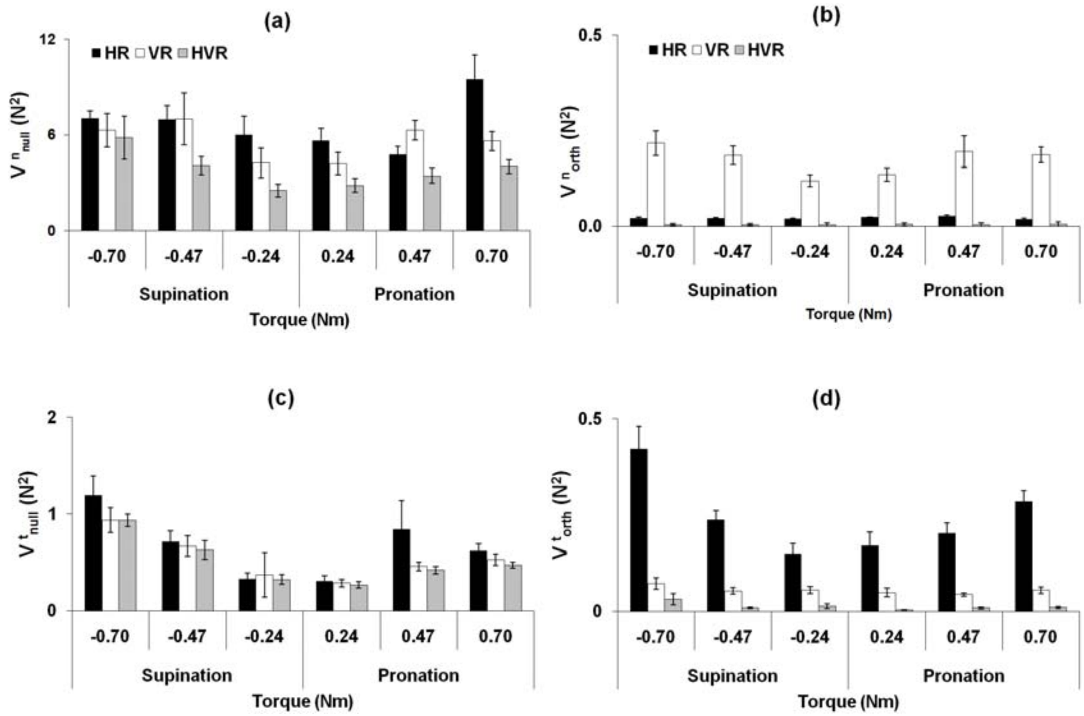

Figure 7.6. **(a)** The variance in the null space of the '$F_n^{vf} = F_n^{th}$' (V^n_{null}) and **(b)** orthogonal to the null space (V^n_{orth}) under varied combinations of prehension types, torque directions, and torque magnitudes. **(c)** The variance in the null space of 'F_t^{vf}+ F_t^{th}= w' (V^t_{null}) and **(b)** orthogonal to the null space (V^t_{orth}) under varied combinations of prehension types, torque directions, and torque magnitudes. The averages across subjects' data are presented with standard error bars.

7.4.3. Principal Component (PC) analysis on variables at the virtual finger (VF) level

PCA were performed at all VF level variables (i.e., the elemental variables: the thumb and VF normal and tangential forces, and the moment arm of VF normal force) which were associated with moment production during the tasks. The number of significant PCs which explains more than 95% of total variance was counted under total of 18 conditions (3 TYPESs × 2 DIRs × 3 MAGs). The number of significant PCs (SigPCs) of the HVR condition were less than other two conditions (SigPCs of HVR < VR < HR) regardless of torque directions and magnitude conditions (Fig. 7.7). In other words, the average number of significant PCs across subjects in the HVR condition was around 2, which was less than the numbers in the other two TYPE conditions (Table 7.2). These results were confirmed by a three-way repeated-measured ANOVA with the factors TASK, DIR, and TOR on the number of significant PCs, which showed that there was a significant effect of TYPE [$F(2, 32) = 65.47$, $p < .0001$]. There was no significant interaction between factors.

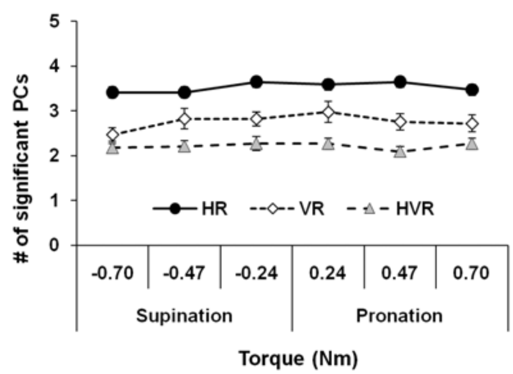

Figure 7.7. The number of significant principle components (PCs) explains more than 95% of total variance under the different TYPE (i.e., fixed and free objects), DIR (i.e., supination and pronation) and MAG (i.e., 0.24, 0.47, 0.70Nm) combinations. Subject's data was averaged, and presented with standard error bars (some of the standard error bars are very small).

The thumb and VF normal forces had large loadings (|loading| > 0.7) in the same PCs and small loadings in the other PCs regardless of experimental conditions

(Table 2). The large loadings in the same PCs for the rest of variables (e.g., thumb and VF tangential forces and the moment arm of VF normal forces) were only observed in the HVR condition. Two tangential forces had large loading in the same PCs for most cases in the VR condition, while the moment arm of VF normal force occasionally had large loading in the PCs in which two tangential forces had large loadings (Table 7.3). The number of significant PCs for the HR were greater than 3 (3 < # of sig PCs < 3.5 for the HR condition) (Table 7.2). Since two tangential forces had large loadings in the different PCs and two normal forces had large loading in the same PCs for most cases in the HR, the number of significant PCs was at least 3 (Table 7.2). The moment arm of VF normal force occasionally had large loadings in the same PC with either thumb tangential force or VF tangential force in the HR condition (Table 7.2).

Table 7.2. The number of significant PCs under varied combination of prehension types, torque directions, and torque magnitudes.

		TYPE		
		HR	VR	HVR
Supination	-0.70Nm	3.41 ± 0.12	2.47 ± 0.15	2.18 ± 0.10
	-0.47Nm	3.41 ± 0.11	2.82 ± 0.23	2.21 ± 0.12
	-0.24Nm	3.65 ± 0.12	2.82 ± 0.15	2.27 ± 0.15
Pronation	0.24Nm	3.59 ± 0.10	2.78 ± 0.23	2.27 ± 0.12
	0.47Nm	3.65 ± 0.13	2.76 ± 0.18	2.09 ± 0.11
	0.70Nm	3.47 ± 0.12	2.72 ± 0.19	2.27 ± 0.12

Table 7.3. Elemental variables in PCs from the principal component analysis(PCA) under HVR, VR, and HR conditions. Note that the table represents the general trend of the grouping of elemental variables from PCA across subjects and experimental

conditions. F_n^{th} thumb normal force, F_n^{vf} VF normal force, F_t^{th} thumb tangential force, F_t^{vf} VF tangential force, D_n^{vf} moment arm of VF normal force

	PC1	PC2	PC3	PC4
HVR	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, F_t^{vf}, D_n^{vf}\}$		
VR	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, F_t^{vf}, (D_n^{vf})\}$	$\{(D_n^{vf})\}$	
HR	$\{F_n^{th}, F_n^{vf}\}$	$\{F_t^{th}, D_n^{vf}\}$ or $\{F_t^{vf}, D_n^{vf}\}$	$\{F_t^{vf}\}$ or $\{F_t^{th}\}$	$\{D_n^{vf}\}$

7.4.4. Delta variance

To quantify individual fingers' forces and moments interactions and compare their strength, delta variance (ΔV) of each component (e.g., ΔV_{Fn}, ΔV_{Ft}, ΔV_{Mn}, and ΔV_{M}) was calculated (Eq.5). Note that the positive value of ΔV presumably indicates that the negative co-variation among elemental variables (i.e., individual finger forces or moments) prevails resulting in error compensations, while negative ΔV might indicate that the positive co-variation between elemental variables is accepted.

The ΔV_{Fn} were negative throughout all experimental conditions (i.e., dominant positive co-variances among IF normal forces), and systematically decreased with the torque magnitudes [MAG: $F(2, 32) = 37.50$, $p < .0001$] (Fig. 7.8a). ΔV_{Fn} values in general were smaller in the HVR condition than in the other two TYPE condition, especially during pronation efforts [TYPE: $F(2, 32) = 10.19$, $p < .001$; TYPE × DIR: $F(2, 32) = 8.17$, $p < .01$] (Fig. 7.8c). In addition, the main effect of DIR was not significant. Unlike the ΔV_{Fn}, ΔV_{Mn} were positive for all experimental conditions (i.e., dominant negative co-variances among IF moment of normal forces). However, there was no significant difference of ΔV_{Mn} between TYPE conditions (Fig. 7.8b). The ΔV_{Mn} during the supination efforts were generally smaller than those during pronation efforts [DIR: F (1, 16) = 53.44, p <.0001]. There was no significant interaction between factors on ΔV_{Mn}. ΔV_{Ft} were generally positive, but ΔV_{Ft} under the HR condition were occasionally negative and showed large standard errors (Fig. 7.8c). The ΔV_{Ft} under the VR and HVR condition, where the vertical translation was constrained, were greater than ΔV_{Ft} under the HR condition [TYPE: F (2, 32) = 22.46, p <.0001]. The ΔV_M were all positive regardless of experimental conditions. ΔV_M were in general smaller in the HR condition than in other two TYPE conditions for both DIRs (i.e., supination and pronation) [TYPE: F (2, 32) = 22.67, p <.0001] (Fig. 7.8d). The ΔV_M during pronation effort were greater than those during supination effort [DIR: F (1, 16) = 32.50, p <.0001], while the main effect of MAG was not statically significant.

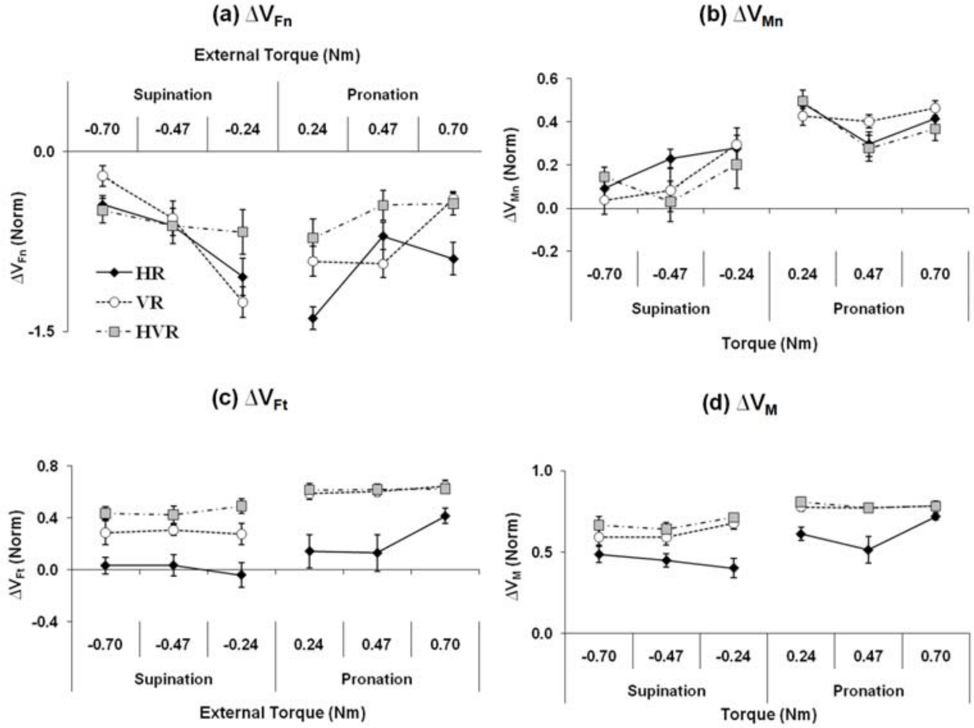

Figure 7.8. Normalized delta variances (ΔV) of **(a)** normal force (ΔV_{Fn}), **(b)** moment of normal force (ΔV_{Mn}), **(c)** tangential force (ΔV_{Ft}), and **(d)** moment of force (ΔV_M). The ΔV was computed over 25 repetitions for each condition and subject, and averaged data across subjects with standard error bars are presented. (Some of the error bars are very small to be seen)

7.4.4. Correlations among individual fingers forces and moments

The coefficient of correlation among the individual finger forces and moment of force with the combinations of prehension type (three levels) and torque direction (two levels) are presented in Fig . Three levels of torque magnitudes were grouped into each torque direction. Thus, the number of observations for each case of finger pair was 51 (17 subjects × 3 MAGs), and we decided the correlations of coefficient are generally significant if significant cases out of 51 were greater than 31 (> 60% of total cases). Generally, many of significant correlations among individual finger forces and moments were observed during the pronation efforts. Individual finger normal forces showed positive correlations over the repetitions although the significant levels varied with conditions (Fig. 7.9). Significant correlations (i.e., correlation coefficients > .5) among finger normal forces were shown at MR, and RL pairs during the pronation efforts [231 significant cases out of 306 (17subject×3MAGs×3TYPEs for MR and RL) cases in total observations] regardless of TYPEs (i.e., HR, VR and HVR conditions). In the correlations of two –finger pairs (i.e., IM-RL or IL-MR), significant positive correlations were observed at IM-RL pair for all three TYPE conditions [97 significant cases out of 153 (17subject×3MAGs×3TYPEs for IM-RL) observation in total]. In terms of individual finger tangential forces, significant negative correlations were shown at IM only in the VR and HVR conditions [VR: 31significant cases out of 51cases; HVR: 34 significant cases out of 51cases].

Similarly, significant correlations of two-finger pairs were observed at IL-MR pair in the VR and HVR conditions [VR: 41significant cases out of 51cases; HVR: 35 significant cases out of 51cases]. The negative coefficient of correlations prevailed between the moments of individual finger forces (Fig 7.9c). Significant negative correlations were also shown at IM regardless of TYPEs. For the HR condition, significant correlations were not shown between individual tangential forces, but the correlations of moment of individual finger forces were significant during the pronation efforts at IM (Fig 7.9b and 7.9c). For the correlations of IM-RL and IL-MR moments, all pairs showed significant negative correlations regardless of TYPE conditions [IM-RL: 235 significant cases out of 306 (17subject×3MAGs×3TYPEs×2DIRs); IL-MR: 221 significant cases out of 306]. The frequencies with six ranges of correlation coefficient of IM-RL and IL-MR moments were observed are presented in Fig 7.10.

The main point of these figures is that frequencies of significant correlation during the pronation efforts were greater than those during the supination efforts. In addition, the correlation coefficients with ranges greater than 0.9 (i.e., high correlations) were observed at IL-MR during pronation efforts (Fig. 7.10).

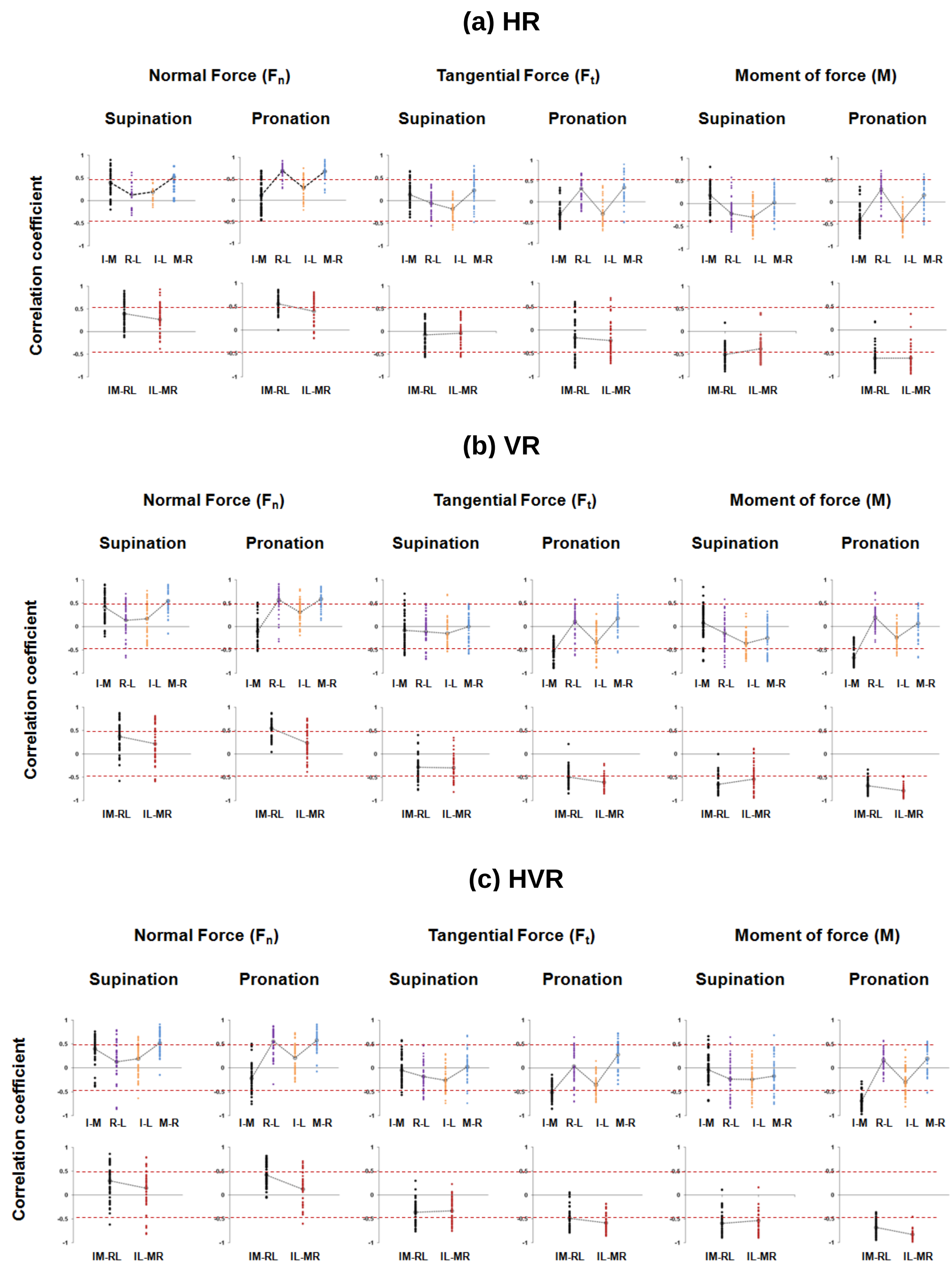
(a) HR
Normal Force (Fn)
Tangential Force (Ft)
Moment of force (M)
Supination
Pronation
Correlation coefficient
I-M R-L I-L M-R
IM-RL IL-MR
(b) VR
Normal Force (Fn)
Tangential Force (Ft)
Moment of force (M)
Supination
Pronation
Correlation coefficient
I-M R-L I-L M-R
IM-RL IL-MR
(c) HVR
Normal Force (Fn)
Tangential Force (Ft)
Moment of force (M)
Supination
Pronation
Correlation coefficient
I-M R-L I-L M-R
IM-RL IL-MR

Figure 7.9. Coefficient of correlation among individual fingers and summed of two fingers components including normal force, tangential force, and moment of force under varied combinations of prehension types and torque directions. Three levels of torque magnitudes, i.e., 0.70, 0.47, and 0.24Nm, were grouped into each torque direction. Pairs of individual fingers (IF) include I-M, R-L, I-L, and M-R, and pairs of summed of two fingers (TF) include IM-RL (i.e., upper fingers-lower fingers) and IL-MR (i.e., lateral fingers-central fingers).

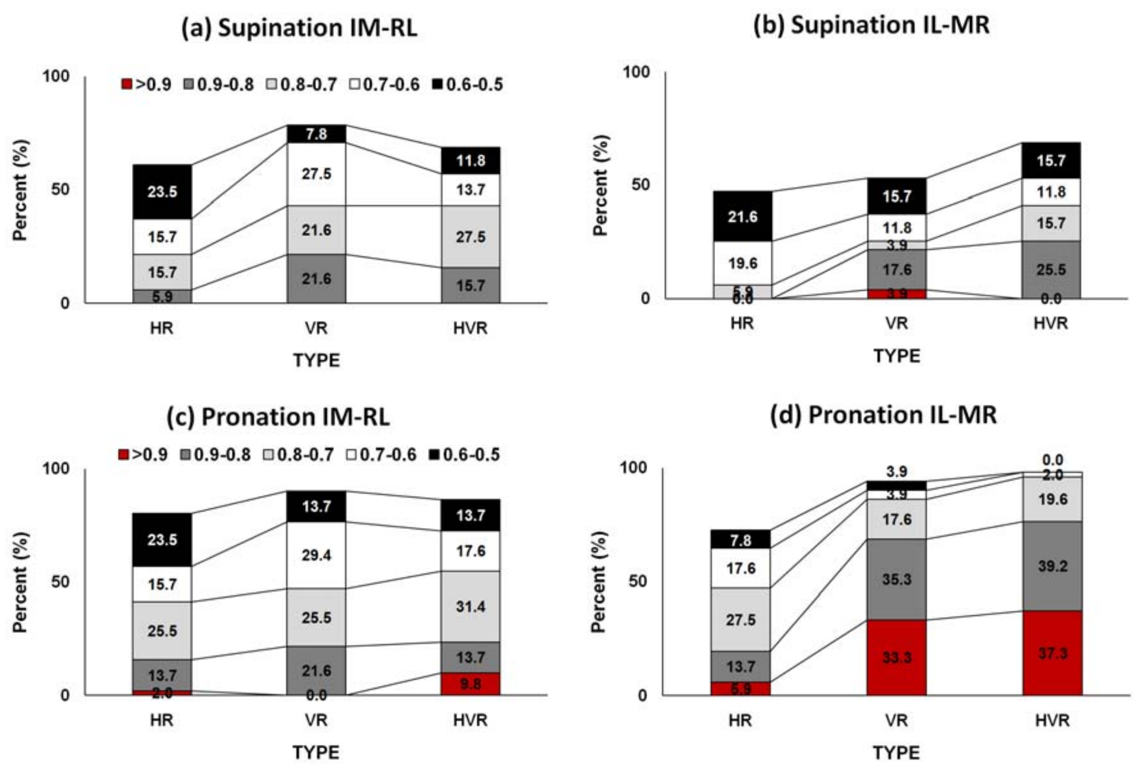

Figure 7.10. The percent frequency (i.e., frequency / total frequency) with six ranges of correlation coefficient of **(a)** IM-RL moments during supination efforts, **(b)** IL-MR moments during pronation efforts, **(c)** IM-RL moments during pronation effort, and **(d)** IL-MR moments during pronation efforts for the HR, VR, and HVR object conditions. Total observation for each bar is 51 (i.e., 17 subjects × 3 MAGs = 51).

7.5. Discussions

7.5.1. Independent control of grasping stability

Although there were a few extraordinary cases of connection between the flexor pollicis longus (FPL) and the tendon of the flexor digitorum profundus of the index finger (Stahl & Calif, 2005), the flexor pollicis longus (FPL) muscle, which is a flexor of the thumb, has been considered completely independent muscle meaning that the action of FPL does not affect the actions of any other muscles in general (Brand & Hollister, 1999). In other words, the action of the thumb is mechanically and anatomically independent. However, the recent studies have claimed the neural coupling of action of fingers and thumb (Yu et al., 2007). Further, Marc Schieber stated that the inter-dependency among digits was an evident phenomenon of the primate digits' actions. This suggests that an independent set of flexor and extensor muscles for each digit does not fully account for primate digit movement (Schieber, 2001). The result of this study is also in line with this claim regarding the coupled action of the thumb and fingers. Our previous study investigated this issue employing the free and fixed object (Chapter 5), which revealed that the coupling of two normal forces was still maintained during the fixed object condition in which the relation of two normal force (i.e., equal in magnitude) was not confined.

Free object prehension supposedly contains all static constraints, while the fixed object was considered a constraint-free condition, meaning that there was no prescribed condition among experimental variables such as digits' normal and tangential forces. However, both horizontal and vertical constraints were not constrained simultaneously during the fixed object prehension, and it might be possible that the two constraints interact with each other. Therefore, the effects of horizontal and vertical constraints need to be isolated in order to confirm the claim that grasping stability is always maintained in a static prehension task regardless of static constraints during prehension tasks.

The correlation analysis in this study clearly showed that that the correlation coefficients between the normal forces of thumb and VF were significant regardless of prehension types including the HR, VR, and HVR (i.e., free object prehension). Further, the PCA showed that high loadings of the two force components were always observed in the same PC throughout all experimental conditions. This implies that the coupling of the thumb and VF normal forces might not be affected by any combinations of static constraints imposed in tasks. In other words, the normal forces of the thumb were coupled with the VF normal force even when the relation of two normal forces was not constrained by task mechanics in static prehension. The scatter patterns of two normal forces over repetition were that most of data points lay on '$F_n^{vf} = F_n^{th}$' even during the VR condition. For the HR and HVR conditions, the data points of two normal forces over repetition should lie on the null space of '$F_n^{vf} = F_n^{th}$' while suppressing the variance orthogonal to the null space due to confined relation of two normal forces. For this reason, we can consider the variance orthogonal to the null space as an error variance during the HR and HVR prehensions. However, the variance orthogonal to the null space of '$F_n^{vf} = F_n^{th}$' under the VR condition was not error variance, but rather possible outcomes. Indeed, V_{orth} under the VR condition was larger than those under the HR and HVR conditions. Nevertheless, the variances in the null space were relatively larger than the variance orthogonal to the null space under the VR condition, meaning two normal forces are organized in null space of grasping stability. This implies that the CNS strategies to selects the normal forces of the thumb and VF in static prehensions was mainly a coupling of two normal forces rather than independent control of normal forces without taking the static constraints of horizontal translation into consideration. Therefore, the grasping stability control is not affected by the isolated effect of vertical translation constraint.

In the previous study, the coupling of two normal forces was evident during the fixed object in which both horizontal and vertical translations were not constrained (Chapter 5 & 6). In this study, two constraints of linear translations were isolated in order to investigate sole effect of each constraint, and the results clearly showed that any combination of static constraints did not affect coupling of the thumb and VF normal forces in static prehension tasks. Thus, we can conclude that the grasping stability is controlled independently and invariant in static human hand static prehensions.

7.5.2. Principle of superposition

It has been experimentally (Shim et al., 2005b; Zatsiorsky et al., 2004) and mathematically (Arimoto & Nguyen, 2001; Arimoto et al., 2001) suggested that the grasping force control and rotational equilibrium control are linearly superposed, and, therefore, independently controlled in a multi-digit static prehension. This decoupled controls of grasping stability and rotational equilibrium in human hand static prehension has been supported by the principle of superposition. There are two important aspects of the inter-relations among experimental variables in the virtual finger level regarding principle of superposition in the human hand static torque production tasks: The first is that the experimental variables are separated and grouped into two sub sets, and the second is that the correlations among variables in each sub-set are significantly high. This is also knows as a chain-effect (Zatsiorsky et al., 2004). The ‘chain effect’ explains coupled relations among elemental variables within each subset, and these significant correlations among variables, which forms “cause-effect” chain, where mechanically necessitated relations among elemental variables are prescribed by the given task mechanics. In the previous studies, two normal forces (i.e., the normal forces of thumb and VF) comprise the first sub set. The two tangential forces, the moment of VF normal force, moment of tangential force, and the moment arm of VF normal force are grouped into the second sub set (Shim et al., 2005b; Shim & Park, 2007; Zatsiorsky et al., 2004). The high correlation between two normal forces is indicative of the grasping stabilization (i.e., grasping force synergy), and high correlations among the experimental variables in the second sub set support the rotational equilibrium. It seems that the two normal forces were highly correlated regardless of static constraints within tasks, which has been confirmed by the experimental results in fixed object static prehension (Chapter 5) and in the VR condition (i.e., where the horizontal translation of the hand-held object is not constrained) in this study.

In contrast, the correlations between two tangential forces (i.e., the tangential forces of the thumb and VF) were significantly high where the relation of two tangential forces was prescribed by task mechanics (i.e., VR and HVR conditions). That increase (or decrease) in one tangential force is accompanied by decrease (or increase) in other tangential forces in order to maintain constant resultant tangential force as a task mechanics. The previous study also showed that the two tangential forces were not highly correlated under the fixed object static prehension in which both horizontal and vertical translations were not constrained (Chapter 5). Nevertheless, the correlations of 'F_n^{vf} *vs* M_n^{th}' and 'F_n^{th} *vs* F_t^{th}' were not significant throughout all the experimental conditions, and these two local chains are presumably points where one subset is separated from the other subset. In particular, the normal force of VF and the moment of VF normal force are seemingly highly correlated. However, it seems that statistically low correlations of 'F_n^{vf} *vs* M_n^{th}' were always observed in this study.

The separated two sub-sets of experimental variables and the same configuration of the chain as in the free object condition were shown in the VR condition, where the horizontal translation was not constrained. Varying levels of correlations were seen as compared to the correlations in the free object. Thus, we can infer that the grasping stability synergy is independent from the rotational equilibrium control, meaning the prescribed relation of digits' normal forces does not affect the relations among experimental variables regarding the rotational equilibrium control. When the horizontal translation was constrained (i.e., the HR condition), two normal forces were grouped into the first sub set with a high correlation due to their mechanically constrained relationship. However, the sum of the thumb and VF tangential forces can be of any magnitude when the vertical translation of the object is not constrained. Unlike a coupling of two normal forces regardless of the static constraints within tasks, the two tangential forces were not highly correlated during the HR condition. However, both the tangential force of the thumb and VF highly correlated with the moment of tangential force and the moment of normal force as well as moment arm of VF normal force. In other words, the CNS might alternate "cause-effect" relationships within a second sub-set under the HR condition possibly due to the unlimited selection of two tangential forces in terms of both magnitude and direction. In other words, the production of tangential forces did not need to compensate the weight of object so as to maintain a constant vertical orientation of the object. For this reason, the resultant tangential forces were not constant, and one of the tangential forces showed significantly high correlation with a resultant tangential force under the HR condition. We can conclude that the independent controls of grasping stability and rotational equilibrium are not affected by static constraints in human hand prehension, thus supporting the validity of the principle of superposition in human hand static grasping tasks.

7.5.3. Triple layers of control hierarchy

A virtual finger (VF) is an imaged finger which produces the same mechanical effects produced by individual fingers (Arbib et al., 1985; Cutkosky, 1989; Cutkosky & Howe, 1990; Iberall, 1987; Santello & Soechting, 1997; Shim et al, 2005; Yoshikawa, 1999; Zatsiorsky et al., 2003b). The central controller controls the actions of individual fingers at the lower level to produce desired outcome of the VF at the higher level, which forms the control hierarchy.

The hierarchical control of prehension has been supported by the experimental results which showed a large difference in the behavior of the virtual and individual finger forces. The idea is that the central nervous system (CNS) coordinates the actions of individual fingers in order to stabilize the actions of VF (i.e., higher level control), and the coordinated actions of thumb and VF directly affect the stabilization of performance variables.

In the virtual finger (VF) level analysis, it was obvious that the normal forces of thumb and VF showed high positive correlations regardless of mechanical constraints imposed in the tasks resulting in the stabilization of grasping force, while the two tangential forces were correlated significantly only when the relation of two tangential forces was constrained by task mechanics.

In the individual finger (IF) level, the delta variance is an indicative of a synergy index among the action of individual fingers (Li et al., 1998; Shim et al., 2005a, 2005; Shinohara et al., 2003, 2004). In particular, the actions of individual fingers (IF) normal forces did not employ an error compensation strategy by showing negative ΔV (i.e., dominant positive covariance among individual fingers) regardless of experimental conditions. Indeed, the correlation coefficients of selected pairs of individual fingers' normal forces were positive in most cases. This finding is in line with the reported data obtained in long duration prehension task, which showed positive correlations among the normal finger forces (Santello & Soechting, 2000) very small external torques. In fact, positive co-variances among IF normal forces can be a strategy to stabilize moment of normal force. Because the stabilization of resultant force and torque respectively require negative and positive co-variations among elemental variables (Latash et al., 2001; Zatsiorsky et al., 2002), these two sub-tasks apparently conflict with the other. Recent studies employing multi-finger pressing tasks reported a lack of force stabilization synergies. Therefore, we can say that the hierarchical organization was not applied in the grasping force control in static prehension tasks. Rather, the CNS seems to control the normal forces of the thumb and VF as a whole in order to stabilize grasping force, and normal forces at IF level stabilize moments rather than the VF level grasping (normal) force. This finding is more evident in the normal force production of the sum of two finger level. In the upper level (i.e., the sum of two fingers normal forces such IM-RL and IL-MR), it also showed a positive correlation for both IM-RL and IL-MR, while significant cases (i.e., in case that correlation coefficient > .5) of IM-RL were greater than those of IL-MR. The positive correlation between the normal forces of IM and RL would be a strategy to stabilize the moment of normal force control strategy. Thus, the CNS strategy of controlling the normal forces of individual fingers would be to stabilize the moment of normal force rather than the grasping force at VF level, and this strategy consists of three layers: I-M-R-L → IM-RL → VF.

In terms of tangential forces, the synergic actions among the tangential forces of individual fingers was evident only when vertical translation was constrained (i.e., VR and HVR conditions) by showing positive value of ΔV of IF tangential forces. We expected positive correlations between the tangential finger forces because the production of tangential forces depends on the passive resistance of finger structures (Pataky et al., 2004). This resistance is determined by the stiffness of the finger in the tangential direction. The apparent role of finger tangential forces during static prehension with a vertically oriented object was to compensate for the weight of object (i.e., load), so that the load might be disturbed proportionally to the fingers.

However, negative correlations among the tangential finger forces were discovered in this study, which suggest the active control of tangential forces (Rumann, 1991).

Because vertical translation was not constrained during the HR condition, the tangential force sharing among fingers was not affected by load magnitude at either VF and IF levels. It implies that the controller has more freedom to select the magnitude as well as directions of tangential forces as compared to when the relation of tangential force was prescribed. In addition, the apparent hierarchy (i.e., the sum of two tangential forces such IM-RL and IL-MR) in between IF and VF levels of tangential forces was shown in the VR and HVR conditions where vertical translation was constrained.

In this study, the moment production against external torques was commonly required during all three types of prehensions, and the result showed that the ΔV of resultant moment were positive throughout varied experimental conditions while varying their levels. This finding implies that the moments of individual fingers acted together in order to stabilize moment at VF level supporting the hierarchical organization of prehension. In addition, significant negative correlations of IM-RL and IL-MR moments were observed regardless of prehension types, while individual pairs of IF moments (i.e., I-M, R-L, I-L, and M-R pairs) did not always show significant correlation. The negative correlation of IM-RL and IL-MR can conspicuously be an error compensation strategy to stabilize VF moment. The stabilization of VF moment might arise from two finger (TF) level rather than directly from individual finger (IF) level. Thus, these results suggest that the CNS utilizes the three layers hierarchical organization of finger actions for controlling the stability of the total VF moment.

7.6. References

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Chapter 8: Summary of Conclusions

1. Force and moments produced by fingers during circular object prehension were decoupled into two groups: one group related to grasping stability control (normal force control) and the other group associated with rotational equilibrium control (tangential force control), which supports the principle of superposition. The synergy indices were always positive during the circular object prehension, suggesting error compensations between individual finger moments for the virtual finger moment stabilization, which confirms the hierarchical organization of multi-digit prehension.

2. During fixed object prehension, the closer the non-task fingers positioned to the task finger, the greater the forces produced by the non-task fingers, which supports the proximity hypothesis. During free object prehension, however, the non-task fingers with longer moment arms produced greater forces, which supports the mechanical advantage hypothesis. The different strategies used by the CNS for fix and free object prehension seems to be caused by different mechanical constraints imposed in these two types of prehension. Free object prehension possesses linear and rotational constraints to be satisfied by the CNS while fix object prehension does not have a mechanical constraint.

3. The grasping stability control and rotational equilibrium control were decoupled during fixed object prehension as well as free object prehension. During fixed object prehension, coupling of thumb and virtual finger forces was not mechanically necessitated/constrained in either normal direction (equal and opposite

grasping forces) or tangential direction (compensating the weight of the object). This result suggests that the principle of superposition is valid regardless of the mechanical constraints in human static prehension.

4. During torque production, the fingers with longer moment arms with respect to the moment axis produced greater magnitude of force only when finger force produces moments in required direction. Therefore, the mechanical advantage hypothesis was supported when fingers acted as moment agonists during multi-finger torque production tasks.

5. Coupling of thumb normal force and virtual finger normal force was not necessitated when horizontal translation of hand-held object was mechanically fixed. However, the coupling of two normal forces was always observed regardless of given translational constraints, and these two normal forces were independent to other mechanical variables such as tangential forces and moments. This result supports the principle of superposition hypothesis in static prehension under varied combinations of translational constraints.

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