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Prehension Synergy: Use of Mechanical Advantage During Multifinger Torque Production on Mechanically Fixed and Free Objects

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The aim of this study was to test the mechanical advantage (MA) hypothesis in multifinger torque production tasks in humans: fingers with longer moment arms produce greater force magnitudes during torque production tasks. There were eight experimental conditions: two prehension types determined by different mechanical constraints (i.e., fixed- and free-object prehension) with two torque directions (supination and pronation) and two torque magnitudes (0.24 and 0.48 N·m). The subjects were asked to produce prescribed torques during the fixed-object prehension or to maintain constant position of the free hand-held object against external torques. The index of MA was calculated for agonist and antagonist fingers, which produce torques in the same and opposite directions to the target torques, respectively. Within agonist fingers, the fingers with longer moment arms produced greater grasping forces while within antagonist fingers, the fingers with shorter moment arms produced greater forces. The MA index was greater in the fixed-object condition as compared with the free-object condition. The MA index was greater in the pronation condition than in the supination condition. This study supports the idea that the CNS utilizes the MA of agonist fingers, but not of antagonist fingers, during torque production in both fixed- and free-object conditions.

Keywords: moment agonist, moment antagonist, force sharing pattern

When the human motor system involves redundant motor effectors for a specific motor task, the central nervous system (CNS) needs to provide a solution for the motor task by determining the involvements of multiple effectors. Specifically, when the motor task involves a production of a torque using multiple fingers that are aligned parallel and contributing to the torque (Latash et al., 2001; Shim et al., 2005; Zhang et al., 2007), the CNS may consider the mechanical advantage (MA) of fingers in the redundant motor system. According to the MA hypothesis, effectors (fingers) positioned further away from an axis of rotation have greater MAs owing to their longer moment arms. Previous studies showed that effectors with greater MA are associated with greater muscle activations (Biewener et al., 2004; Buchanan et al., 1989; Gielen et al., 1988; Prilutsky, 2000; Smutz et al., 1998) and greater finger forces (Shim et al., 2004a; Zatsiorsky et al., 2002a, 2002b). The MAs of individual fingers in the multidigit grasping system are primarily determined by their anatomical structures, such as the origin and insertion of individual muscles and parallel finger connections. The use of fingers with greater MA would be an effective way to perform the tasks, reducing the total "effort" (e.g., total force produced for the task).

In the human hand system, the CNS maintains stable static grasping despite having infinite possibilities of digit force and moment combinations for the same motor outputs (Li et al., 1998; Pataky et al., 2004a; Shim et al., 2003). Previous studies suggested that the CNS (i.e., the controller) used the MA of fingers during torque production tasks (Shim et al., 2004a; Zatsiorsky et al., 2002a). The selections of individual finger forces/moments are partially governed by the controller's specific strategy. Thus, utilizing MA of various fingers in multifinger torque production tasks can be the controller's specific strategy to control the kinetically redundant hand-finger system during multifinger grasping tasks. Recognizing such a pattern may identify a way to reduce the total finger force in torque production. In other words, when

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the selection of finger forces is free but the value of total torque is prescribed, fingers with a longer moment arms (as compared with those with shorter moment arms) can generate greater torques with less force, thus reducing the total force generated by all fingers. However, this would only be true when the finger produces a moment of force in the required direction of rotation (i.e., agonist moment). In fingers that produce moments of force opposite to the required direction of rotation (i.e., antagonist moments), the finger with a longer moment arm might produce a smaller finger force to reduce antagonist moments. Antagonist moments need to be compensated with extra effort by agonist fingers, and the smaller antagonist moment would reduce the total force.

Although previous studies have documented that the MA is used by the CNS in torque production tasks during free-object prehension (Zatsiorsky et al., 2002a) as well as fixed-object prehension (the object is mechanically fixed to another immovable object) (Shim et al., 2004a), it is unknown how sharing patterns among fingers' grasping forces (i.e., normal forces) during torque production tasks are affected by mechanical constraints imposed in the tasks. For free-object (the object is held in the air and is free to move in any direction) static prehension, three mechanical constraints should be satisfied in the grasping plane (the 2-dimensional plane formed by the finger and thumb contacts) (Pataky et al., 2004a; Shim et al., 2003; Shim & Park, 2007). The thumb grasping force and the sum of fingers' grasping forces should be equal in magnitude to satisfy the horizontal translation constraint. The sum of digit shear forces should be equal to the weight of the object to satisfy the vertical translation constraint. Finally, the sum of moments of grasping and shear forces should be equal to zero to satisfy the rotation constraint. However, fixed-object prehension does not require any mechanical constraints, and one may consider it as a constraint-free task (Shim et al., 2004a).

To investigate the effect of static constraints during static prehension, we employed a free object and a mechanically fixed object in this study. Two hypotheses were tested. First, the MA of fingers is used by the CNS in both agonist fingers and antagonist fingers. Second, the utilization of MA of fingers will be different between the fixed-object prehension and free-object prehension.

Method

Seventeen right-handed male volunteers (age: 29.0 ± 3.1 years, body mass: 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 cm) were recruited in the current study. 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.

Two types of sensors were used to measure individual digit forces/moments and to provide a real-time feedback of the handle position 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 (Figure 1) to measure each digit's forces and moments. 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 to provide feedback of the linear or angular positions of the handle during the free-object prehension task. Pieces of 100-grit sandpaper (the static friction coefficient between the digit tip and the contact surface was about 1.5, measured previously [Zatsiorsky et al., 2002a]) was attached to the surface of each sensor 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. In addition, a horizontal aluminum beam (32 cm in length) was attached to the bottom of the handle to hang a load (0.31 kg) at different positions along the horizontal beam so as to provide different external torques for the free-object condition. The analog signals were routed to a 12-bit analog-to-digital converter (a PCI-6031 and a PCI-6033, National Instruments, Austin, TX, USA). Customized LabView programs (LabView 7.1, National Instruments, Austin, TX, USA) 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.

The subjects sat in a 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 chair height was adjusted for each subject to keep the right-arm joint configuration of each subject consistent. Before the testing session, subjects completed four single-finger maximal voluntary force (MVF) production tasks (i.e., index, middle, ring, and little fingers) for normalization purposes. These MVF tasks were performed in the fixed-object condition (mechanically constraint free) (Shim et al., 2004a) so subjects did not have to alter finger forces to satisfy mechanical equilibriums. 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 to pay attention to the task-finger maximal force production. Each subject performed two attempts for each finger MVF task, and the average data over two attempts were calculated for the analyses. The testing session involved a series of multifinger torque production tasks under both fixed- and free-object conditions. In this session there were eight experimental conditions: 2 prehension types (fixed and free object) × 4 prescribed torque conditions about the x-axis (supination efforts: –0.48, –0.24 N·m; pronation efforts: 0.24, 0.48 N·m). For the fixed-object condition, the handle was mechanically fixed to the vertical aluminum plate (Figure 1b) so that the handle could not be translated or rotated. Subjects were given 6 s after the start of each trial to reach the target torque as accurately

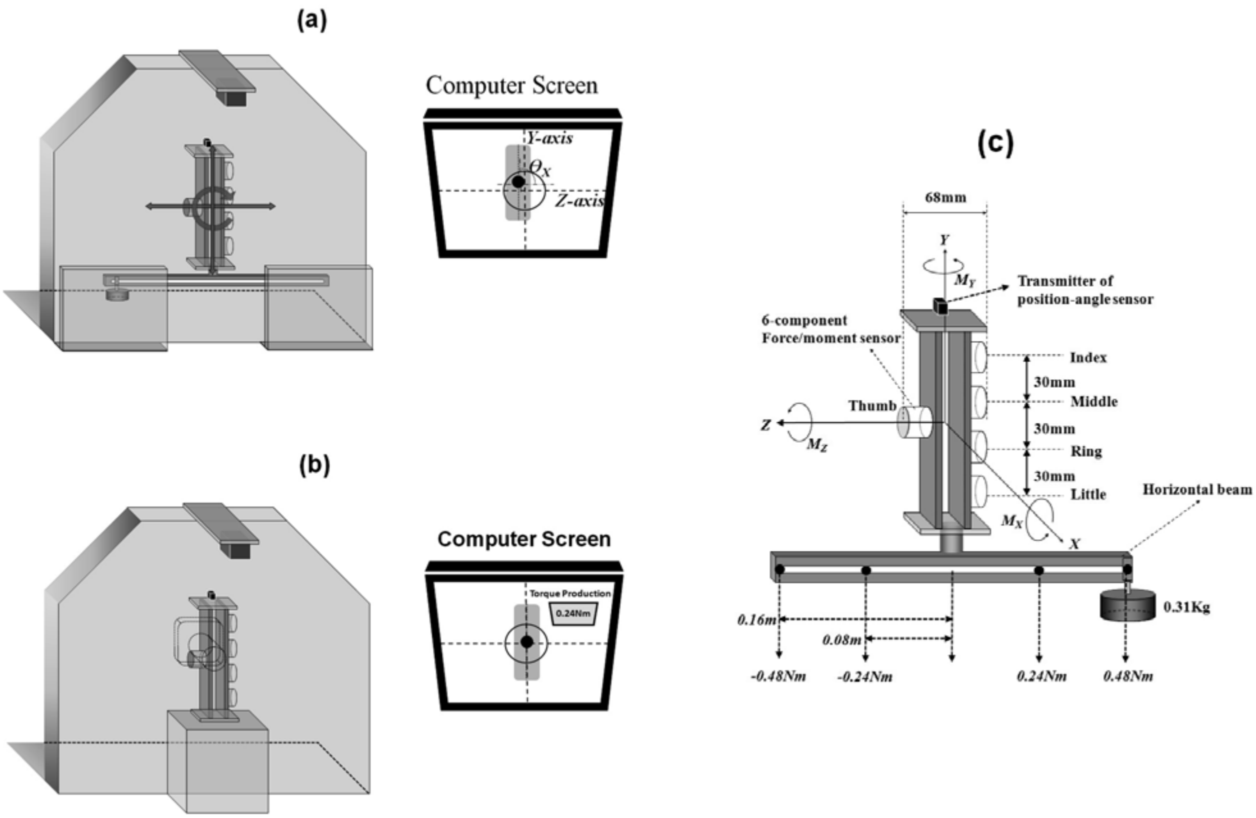

Figure 1 — (a) Schematic illustration of the experimental setup for free-object prehension (left) and position feedback (right). Arrows on the handle indicate that horizontal and vertical translations in addition to rotations were allowed during free-object prehension. Real-time feedback of translation along the *z*-axis (horizontal translation), translation along the *y*-axis (vertical translation), and rotation about the *x*-axis were provided using the magnetic position-angle sensor. (b) Schematic illustration of experimental setup for fixed-object prehension (left) and torque feedback (right). The handle was mechanically fixed to the table so that translations and rotations were not allowed. Real-time feedback of the produced moment of force calculated from the 6-component sensors was provided on a computer screen for subjects. (c) Detailed illustration of the experimental inverted-T handle/beam apparatus for the free-object condition. The 6-component 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.

as possible and maintain these values for 3–4 s while watching the feedback of the produced torque on a computer screen. For the free-object prehension task, subjects were instructed to produce moments to counteract the provided external torques, which were generated by placing a load at different positions along a horizontal beam (Figure 1c). In addition, the subjects were instructed to hold the handle vertically (i.e., perpendicular to the table) while maintaining the preset constant linear and angular handle position (Figure 1a). During the free-object prehension task, real-time feedback of the linear and angular handle positions was provided on the computer screen. The subjects were instructed to minimize the angular and linear deviations of the handle from the initial positions. If the deviations exceeded the predefined criteria,

$$\text{rotation, } \sqrt{\theta_x^2 + \theta_y^2} < 1°,$$

$$\text{or translation, } \sqrt{x^2 + y^2} < 1 \text{ cm}$$

during a 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 200 trials (2 prehension types × 4 torques × 25 trials = 200 trials) in the testing session. Twenty-second breaks were given at the end of each trial to minimize fatigue effects. The order of experimental conditions was balanced and no subject reported fatigue.

The measured data were digitally low-pass filtered with a 4th-order, zero-lag Butterworth filter at a cutoff of 5 Hz (Gao et al., 2005; Li et al., 1998; Park et al., 2010). Further, the data from each trial were averaged from the middle 3 s period of the 6 s period for each trial. Data from the 25 trials per condition were then averaged for each subject for the following analysis.

Individual fingers were classified into moment agonists and moment antagonists with respect to direction of the moment of finger force (Shim et al., 2004a; Zatsiorsky et al., 2002a; Zhang et al., 2007). Agonist fingers produce the moment of normal force in the required direction of torque, while antagonist fingers produce the moment of normal force in a direction opposite to the task torques. For example, the index and middle fingers are moment agonists during the pronation effort, while the ring and little fingers are moment antagonists. 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 from the thumb position. The normal forces of fingers with shorter moment arms were designated as F_s while those with longer moment arms were designated as F_l. For example, during the pronation effort, the middle finger force is F_s and the index finger force is F_l as agonist fingers since they are producing the same directional torques around the thumb. Likewise during this action, the ring finger force represents F_s and the little finger force represents F_l as antagonist fingers. The same calculation was performed for fixed-object prehension. Then, we calculated the ratio of F_l to F_s within each group of moment agonists and moment antagonists to quantify the index of mechanical advantage (Equations 1 and 2). In addition, F_l and F_s were normalized by corresponding fingers' maximal voluntary forces (MVF) measured earlier. The ratio of normalized F_l to F_s was computed for both the moment agonists and antagonists (Equation 3 and 4).

$$MA^{ago} = F_l^{ago} / F_s^{ago} \quad (1)$$

$$MA^{ant} = F_l^{ant} / F_s^{ant} \quad (2)$$

$$MA_{norm}^{ago} = \left(F_l^{ago} / F_{l,max}^{ago}\right) / \left(F_s^{ago} / F_{s,max}^{ago}\right) \quad (3)$$

$$MA_{norm}^{ant} = \left(F_l^{ant} / F_{l,max}^{ant}\right) / \left(F_s^{ant} / F_{s,max}^{ant}\right) \quad (4)$$

where *ago* and *ant* stand for the agonist and antagonist, respectively. $MA = 1$ indicates that normalized F_l and F_s force magnitudes (i.e., normalized efforts in individual finger actions by the CNS) are the same.

Three-way repeated-measures ANOVAs were used with the following factors: constraint (two levels of constraints provided by two prehension types: fixed- and free-object), MAG (two levels of torque magnitude: 0.24 and 0.48 Nm), and DIR (two levels of torque directions: pronation and supination efforts). MA^{ago} and MA^{ant} were compared with 1.0 by the one-sample *t* test to determine if *MA* values were significantly different from 1. All statistical analyses were performed at a significant level $\alpha = .05$.

Results

For both fixed- and free-object conditions, substantial grasping force differences were observed between the index and middle fingers (Figure 2a) while the grasping forces of the ring and little fingers were similar (Figure 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 conditions.

For both fixed- and free-object conditions, MA^{ago} values were significantly greater than 1 only for pronation torque tasks in agonist fingers ($p < .05$) (Figure 3a), whereas MA_{norm}^{ago} values were significantly greater than 1 for both supination and pronation torque tasks ($p < .05$) (Figure 3c). Both MA_{norm}^{ago} and MA^{ago} values were greater in fixed-object condition than free-object condition during pronation efforts, while MA_{norm}^{ago} and MA^{ago} values were not different between fixed- and free-object conditions during supination efforts (Figure 3a and c). These results were supported by the ANOVA with a significant main effect of DIR [$F_{[1,16]} = 19.93, p < .0001$ for MA_{norm}^{ago}; $F_{[1,16]} = 41.07, p < .0001$ for MA^{ago}] and significant interaction effects of Constraint × DIR [$F_{[1,16]} = 7.74, p < .01$ for MA_{norm}^{ago}; $F_{[1,16]} = 29.35, p < .0001$ for MA^{ago}] and DIR × MAG [$F_{[1,16]} = 10.66, p < .01$ for MA_{norm}^{ago}; $F_{[1,16]} = 35.28, p < .0001$ for MA^{ago}].

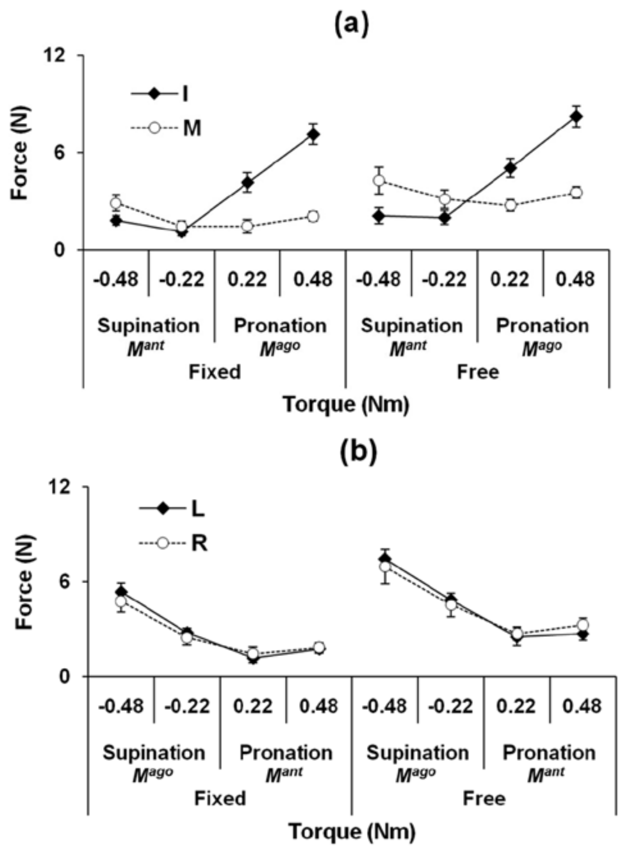

Figure 2 — Individual finger grasping forces during torque productions. (a) Index and middle finger forces and (b) ring and little finger forces. The MA^{ago}, MA^{ant} in the labels indicate the classifications of fingers' actions in torque production under given conditions. Data averaged across subjects are shown with standard error bars.

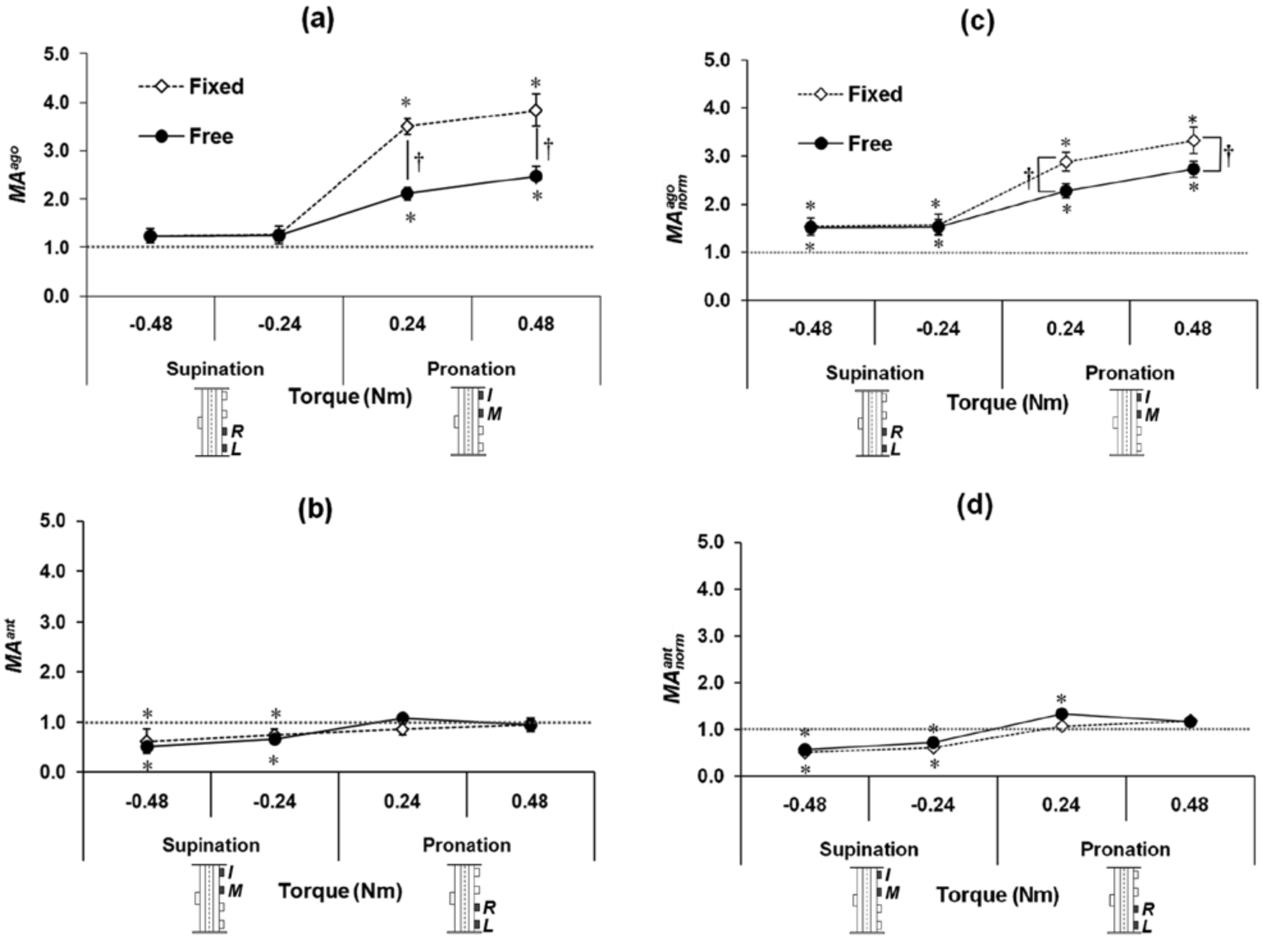

Figure 3 — The mechanical advantage index calculated from torque (a) agonist fingers (MA^{ago}) and torque (b) antagonist fingers (MA^{ant}) in original finger-force data. The mechanical advantage index calculated from torque (c) agonist fingers $\left(MA^{ago}_{norm}\right)$ and torque (d) antagonist fingers $\left(MA^{ant}_{norm}\right)$ in normalized data by corresponding fingers' maximal voluntary forces (MVF). The handles and marked finger initials (i.e., I, M, R, and L) under "Supination" and "Pronation" labels represent the fingers involved in the calculation of each index (e.g., MA^{ago}, MA^{ant}, MA^{ago}_{norm}, and MA^{ant}_{norm}). The averages across all subjects' data are shown with standard error bars. *Represents that the value is statistically different from 1.0 ($p < .01$). †Represents statistical significance of pairwise comparison on *MA* values between fixed- and free-object conditions ($p < .01$).

For supination efforts, both MA^{ant}_{norm} and MA^{ant} values were significantly smaller than 1 for both fixed- and free-object conditions ($p < .05$) (Figure 3b and d). During pronation efforts, however, only MA^{ant}_{norm} in the 0.24 N·m condition was significantly greater than 1 ($p < .05$) (Figure 3d). Both MA^{ant}_{norm} and MA^{ant} values were greater in the pronation condition than in the supination condition. This result was supported by the significant main effect of DIR [$F_{[1,16]} = 111.88$, $p < .0001$ for MA^{ant}_{norm}; $F_{[1,16]} = 43.47$, $p < .0001$ for MA^{ant}].

Discussion

In redundant human movement systems such as multifinger prehension tasks, the selection of individual effectors' contributions to a motor output is governed in part by the controller's specific strategies (Latash et al., 2001; Li et al., 1998). In this study, the tasks included torque production of different magnitudes and directions during fixed- and free-object prehension. The results from this study showed greater grasping force production by fingers with greater MA (i.e., longer moment arms) when the fingers acted as moment agonists for both fixed-object prehension and free-object prehension. In addition, the MA index was greater in the fixed-object condition as compared with the free-object condition. We hypothesized that (1) the MA of fingers is used in both agonist and antagonist fingers, and (2) the utilization of MA of fingers is different between the fixed- and free-object conditions. This contradicts our first hypothesis and partially supports the second hypothesis. This finding was more evident when the finger forces were normalized by their own MVF values. Thus, one can suggest that the MA of agonists is considered by the CNS regardless of the mechanical constraints imposed in the tasks (i.e., fixed-object prehension vs. free-object prehension). The MA^{ago} during pronation was greater in fixed-object prehension than free-object prehension. Therefore, the CNS appears to use the MA of agonist fingers during pronation to a greater extent in fixed-object prehension than it does during free-object pronation efforts. By combining all the results and two hypotheses in this study, we come to the conclusion that the CNS utilizes the MA of agonist fingers during pronation tasks, and it has a greater reliance on MA during fixed-object pronation tasks. In the rest of the discussion, we address the following two topics: (1) the MA of agonist and antagonists regarding "economy" of finger force production, and (2) effect of mechanical constraints on the use of MA during multifinger torque production tasks.

When fingers act as torque antagonists, greater indices of MA may not be the best strategy to improve the "economy" of the total finger force generated for torque production. During pronation efforts, for example, producing little finger normal force greater than the ring finger would result in a greater magnitude of antagonistic torque, which would need to be compensated for by increasing agonist finger torque (i.e., index and middle fingers). This would eventually result in the increased sum of finger force magnitudes. In this case, the thumb would also need to produce greater grasping force during free-object prehension to satisfy the static equilibrium. Eventually, this causes the CNS to produce greater grasping forces by all fingers and the thumb (Shim et al., 2004b). The results from our study showed that the normalized MA index was smaller than 1 in antagonistic fingers under most of the torque production conditions except for the 0.24 N·m torque condition in free-object prehension. Considering the "economy" of the total finger force production, one may suggest that this result demonstrates an "efficient" strategy by the CNS to reduce the total grasping force. However, this "efficient" force production strategy by the CNS is far from the ideal case because there were substantial force productions by agonist fingers with shorter moment arms as well as force production of antagonist fingers, which increase the total input force to produce the prescribed output torque. If total force minimization was used by the controller as the sole optimization criterion, this would result in zero force production by the agonist fingers with shorter moment arms as well as zero antagonist finger forces. However, considering that our experiments encouraged subjects to keep their fingers on the sensors and nonzero finger forces were inevitable, one may argue that it is reasonable to think that the CNS selects finger forces while considering total force minimization during torque production tasks.

Our study showed that the fingers with greater MA were used more during the fixed-object prehension as compared with the free-object prehension, especially during pronation efforts. For the free-object condition, the sum of the individual grasping forces should be equal to the thumb grasping force because of the horizontal translation constraint for static equilibrium. For the fixed-object condition, however, the selections of the individual finger grasping forces were not constrained since static equilibrium did not need to be satisfied. A recent study reported that the force productions of peripheral fingers with longer moment arms (i.e., index and little finger) were less independent under the free-object condition than those under the fixed-object condition (Park et al., 2010). This implies that the force ratio of agonist fingers with longer moment arms to those with shorter moment arms would be relatively larger in the fixed-object condition. Although consistent time-invariant force sharing patterns were observed in a previous study regardless of the task constraints during force production tasks (Rearick et al., 2003), the results from the this study support the idea that the CNS utilizes different finger force sharing patterns when different external constraints (e.g., fixed- vs. free-object prehensions) are given in motor tasks during torque production tasks. During the fixed- and free-object prehensions, the CNS needs to consider other constraints that are different from these two prehension types such as slip prevention (Flanagan et al., 1999; Johansson et al., 1999; Pataky et al., 2004b), and translational/rotational equilibrium constraints (Latash et al., 2004; Shim et al., 2005; Zatsiorsky et al., 2004).

It has been reported that the index finger action is the most independent and is stronger than other fingers in normal force production (i.e., grasping force). In contrast, the little finger action is more dependent on other finger actions and is weaker than others in force production (Li et al., 1998; Zatsiorsky et al., 2000). Therefore, the controller's efforts to produce specific finger forces might be different from the actual force production profiles due to the different levels of finger independence as well as varied finger strength. Normalized finger forces by MVFs of corresponding fingers were employed in our study to consider each finger's strength, but not the independent actions of the finger. To address the different levels of independent finger actions, one can use previously suggested mode analysis methods (Danion et al., 2003; Latash et al., 2002) and calculate the modes of fingers, which represent the CNS commands to each finger. However, in our study, we limited our analysis to the forces and normalized forces since the forces are the motor outcomes that are critical for torque production.

Our previous studies showed that the tangential forces are actively controlled by the CNS during prehension tasks (Park et al., 2010; Shim & Park, 2007), although other studies have suggested passive control of tangential forces (Flanagan & Wing, 1995; Pheasant & O'Neill, 1975). The tangential forces during a rectangular object prehension, as in our study design, have the same MA due to the same length of moment arms (i.e., the half of grip width). Because of this attribute, analyses of tangential forces were not included in the current study. It is currently unknown if the CNS would employ greater tangential finger force magnitudes with longer moment arms in torque production tasks.

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