Published in final edited form as:
*Ergonomics*. 2007 May ; 50(5): 660. doi:10.1080/00140130601164516.

# Multi-digit maximum voluntary torque production on a circular object

**JAE KUN SHIM**[†,*], **JUNFENG HUANG**[†], **ALEXANDER W. HOOKE**[†], **MARK L. LATSH**[‡], and **VLADIMIR M. ZATSIORSKY**[‡]

[†] Department of Kinesiology, University of Maryland, MD 20742, USA

[‡] Department of Kinesiology, Penn State University, PA 16802, USA

## Abstract

Individual digit-tip forces and moments during torque production on a mechanically fixed circular object were studied. During the experiments, subjects positioned each digit on a 6-dimensional force/moment sensor attached to a circular handle and produced a maximum voluntary torque on the handle. The torque direction and the orientation of the torque axis were varied. From this study, it is concluded that: (1) the maximum torque in the closing (clockwise) direction was larger than in the opening (counter clockwise) direction; (2) the thumb and little finger had the largest and the smallest share of both total normal force and total moment, respectively; (3) the sharing of total moment between individual digits was not affected by the orientation of the torque axis or by the torque direction, while the sharing of total normal force between the individual digit varied with torque direction; (4) the normal force safety margins were largest and smallest in the thumb and little finger, respectively.

### Keywords

Finger; Torque; Circular object; Safety margin

## 1. Introduction

Manipulation of circular objects, such as opening a jar lid, twisting a valve or rotating a door knob is a part of everyday activities. These activities usually involve torque production (a twisting action) on a grasped object and are commonly taken for granted. However, they may present serious problems for elderly people, stroke patients and people operating hand prostheses and for control of robotic grippers. Repetitive and forceful performance of such tasks during labour movements increases the risk of injury and motor disorders, such as carpal tunnel syndrome (Kutluhan *et al*. 2001, Kao 2003, Wei *et al*. 2003).

As in any multi-finger manipulation, the 'lid opening' task is mechanically redundant. In five-digit grasps, the digits exert 30 force and moment components on the grasped object while the object, if rigid, has maximally 6 degrees of freedom (Shim *et al.* 2005a,b) and the same object

*Corresponding author. jkshim@umd.edu.

manipulation can be performed in many different ways. In particular, due to the grasp redundancy, the sharing of the total force among the individual digits cannot be predicted from purely mechanical considerations. The torque production on mechanically constrained objects differs from manipulation of the objects in the air. When a hand-held object is mechanically free, the performer is allowed to exert only those forces and moments that satisfy the equilibrium requirements, for example, the vertical forces should equal the object weight. In contrast, when an object is fixed to an external support, the forces exerted on the object can be of any value. The only mechanical constraint is that the normal digit forces should be sufficiently large to prevent slipping at digit contact.

In the literature, studies of multi-digit prehension—in particular, the studies on the total force sharing among individual fingers—have been mainly limited to a prismatic precision grip (i.e. the grip by the tips of the digits in which the thumb and the fingers oppose each other (reviewed in Zatsiorsky and Latash 2004)). In such an action, the fingers act in parallel and the forces acting on the object are easier to measure and quantify (Kinoshita *et al.* 1995, 1996a, Santello and Soechting 2000, Rearick and Santello 2002, Zatsiorsky *et al.* 2002, Shim *et al.* 2003, 2004a,b, 2005a,b). While several previous studies have addressed the manipulation of circular objects (Amis 1987, Lee and Rim 1991, Radhakrishnan and Nagaravindra 1993, Kinoshita *et al.* 1996b, Shih and Wang 1997, Fowler and Nicol 1999), they mainly focused on the resultant force/moment (Fowler and Nicol 1999, Voorbij and Steenbekkers 2002), single-digit force exerted on the object (Fowler and Nicol 1999) or the force production without a twisting action (Kinoshita *et al.* 1996b).

This study focuses on the individual digit-tip forces and moments during torque/moment production on a mechanically fixed circular object. Two independent variables, the torque direction and the orientation of the axis of rotation with regard to the subject's body, have been systematically varied. The goal of the study was to investigate: (a) the magnitudes of total force and moment under different torque directions and axes; (b) the relative contributions of individual digit force/moment to the total force/moment; and (c) the relationships between normal and tangential forces at individual digit contacts.

## 2. Methods

### 2.1. Subjects

Ten right-handed males participated in this study as subjects (table 1). The hand lengths were measured as the shortest distance between the distal crease of the wrist and 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 being 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. The preferred angular positions of digit tips were measured during an all-digit natural prehension of a wooden circular object of 4.5 cm radius. The relative angular positions of fingers measured with regard to the thumb position (0°) were averaged across all subjects for later equipment settings (of the digit contacts as illustrated in figure 1A). All subjects gave informed consent according to the protocol approved by the Internal Review Board of the University of Maryland.

### 2.2. Equipment

Five, six-component sensors (Nano-17; ATI Industrial Automation, Garner, NC, USA) were attached to a circular aluminium handle whose centres were positioned at the relative angular positions of fingers averaged across subjects (figure 1A). An aluminium cap was attached to the surface of each sensor. The bottom of the cap was flat and mounted on the surface of the sensor while the top part was round (with curvature $k$ = 0.222/cm) to accommodate the curvature of the dotted circle in figure 1A. Sandpaper (100-grit, giving a static friction coefficient between the digit tip and the contact surface of 1.5, as measured previously (Zatsiorsky *et al*. 2002)) was placed on the round contact surface of each cap to increase the friction between the digit and the cap. The radius from the centre of the circular handle ($O_G$) to the contact surface ( $r_o^j$) 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 (figure 1B). The whole circular handle with the sensors was mechanically fixed to the head of a heavy tripod (Husky; Quick Set Inc., Skokie, IL, USA). The position of the handle could be adjusted by adjusting the tripod head while three 15 kg barbells were loaded on each leg of the tripod to prevent tripod movement during force/torque exertion at the circular handle. The sensors were aligned in the x-y plane. The plane spanned by the *x*- and *y*-axes will be referred to as the grasp plane (Shim *et al*. 2005a,b).

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, USA) and processed and saved in a customized LabVIEW program (LabVIEW 7.1; National Instrument) on a desktop computer (Dell Dimension E510; Dell, Round Rock, TX, USA). The sampling frequency was set at 100 Hz.

### 2.3. Procedure

Subjects washed their hands with soap and warm water to normalize the skin condition of the hands. The subject sat on a chair and placed their right upper arm in a forearm brace that was fixed on a table (figure 2). The forearm was secured in a customized plastic wrist-forearm brace with two sets of Velcro straps. The upper arm was abducted ~45° in the frontal plane and flexed ~45° in the sagittal plane. The forearm was aligned parallel to the sagittal axis of the subject. Two moment axes and two moment directions were used for four task conditions (2×2). The two moment axes were respectively parallel to the anterior – posterior (AP) axis and to the medio-lateral (ML) axis (as shown in figure 2), and the two directions were opening (OP, counter clockwise) and closing (CL, clockwise). The subjects grasped the handle with each digit positioned on the round part of the cap of the designated sensor. Subjects were required to turn the handle ‘as hard as possible’ for a few seconds in each of the task conditions, AP-OP (i.e. moment production about the AP axis in OP direction), AP-CL, ML-OP and ML-CL. Subjects had a 5-min rest between conditions and the order of conditions was balanced across subjects. The whole experiment was completed in less than 1 h for all subjects.

### 2.4. Data processing

Since planar tasks in the grasp plane were employed in this experiment, the focus was on individual digit forces in the plane and moments of these forces orthogonal to the plane. Since sticking a digit tip to the contact surface was not allowed in this experiment (so-called ‘soft contact model’ (Mason and Salisbury 1985, Shimoga and Goldenberg 1996, Arimoto *et al*. 2001, Nguyen and Arimoto 2002)), a free moment (Zatsiorsky 2002, Shim *et al*. 2005a,b) about the direction of a normal force was possible only due to the friction between the digit tip and the contact surface. However, this component will not be considered because the magnitude of this component recorded could be ignored and it did not contribute to the task moment about the Z-axis. 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 the LRS of coordinates ( $F_y^j$; directly recorded from the sensor) and the moment about the z-axis at the centre of the sensor surface ( $m_z^j$) (equation 1). In the present experiment, the digit was not in direct contact with the sensor, but rather in contact with the sensor cap. The moment $m_z^j$ is due to the distance from the LRS origin ($O_L$), 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 ($O_L$) were converted into the components in the global reference system (GRS) of coordinates using the direction cosines (equation 2). These components and the moment about the Z-axis in the GRS ( $M_Z^j$) values computed from equation 1 were then used to compute the tangential force components ( $F_t^j$) at the digit contact on the cap (equation 3). The normal force component was calculated from equation 3. It should be noted that the force measured at the LRS origin is equivalent to the force produced by the digit in terms of its magnitude and direction.

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

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

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

The safety margin of the normal force ( $F_s^l$) was calculated as the magnitude of the difference between the normal force ( $F_n^j$) calculated from equation 3 and the minimal normal force ( $F_{\mu,n}^l$) required to avoid the slipping of a digit tip on the contact surface with the given friction coefficient $\mu$ (equation 4) (Westling and Johansson 1984, Kinoshita *et al*. 1996b, Pataky *et al*. 2004c). The relative safety margin was expressed as the ratio of $F_s^l$ to $F_n^l$. The safety margin of the force angle ( $\alpha_s^l$) was calculated as the difference between the recorded force angle ($\alpha^l$) and the minimum angle of force ( $\alpha_\mu^l$) required to avoid the slipping of the digit tip given the tangential force (equation 5). It should be noted that the safety margins occur because the normal force produced by a digit is greater than the minimal normal force required to prevent slipping of the digit on the contact surface with a given $\mu$ and tangential force.

$$F_s^l = F_n^l - F_{\mu,n}^l, \quad j=\{thumb, index, middle, ring, little\} \tag{4}$$

$$\alpha_s^l = \alpha^l - \alpha_\mu^l, \quad j=\{thumb, index, middle, ring, little\} \tag{5}$$

The resultant force ($F^{re}$) is the force that would have caused a translational effect of the handle if the handle had not been mechanically fixed to the tripod. This force is also known in the literature as the manipulation force (Gao *et al*. 2005b). The internal force ($F^{in}$) is a set of forces that cancel out due to oppositions of digit forces. Thus, it does not cause a translational effect, even on a free handle. $F^{re}$ and $F^{in}$ were calculated along the

$$\begin{bmatrix} F_X^{re} \\ F_Y^{re} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{5} F_X^{j} \\ \sum_{j=1}^{5} F_Y^{j} \end{bmatrix}, \quad j=\{thumb, index, middle, ring, little\} \tag{6}$$

$$\begin{bmatrix} F_X^{in} \\ F_Y^{in} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{5} |F_X^{j}| - |F_X^{re}| \\ \sum_{j=1}^{5} |F_Y^{j}| - |F_Y^{re}| \end{bmatrix}, \quad j=\{thumb, index, middle, ring, little\} \tag{7}$$

Equation 7 yields the total internal force, i.e. the sum of magnitudes of force components acting in the X and Y directions that cancel each other. This value is different from the usually determined grip or pinch force. The difference can be explained with an example: suppose that a grip force recorded at rest equals 10 N. This means that both the thumb and the opposing finger each exert a 10 N force. Equation 7 in such a case would yield an internal force of 20 N. This method of internal force computation was used rather than determining an average internal force per digit (i.e. dividing the total force by 5) because, in circular grasps, the individual normal digit forces act in different, but not necessarily opposite, directions. An internal moment (i.e. a set of local moments in opposite directions that cancel each other (Gao *et al*. 2005b)) is not addressed because, in the present experiment, the moments produced by each digit were always in the direction of the task moment.

### 2.5. Statistical analysis

Standard descriptive statistics and repeated-measures ANOVA were performed with the within-subject factors of DIGIT (five levels: thumb (T); index (I); middle (M); ring (R); and little (L)), AXIS (two levels: AP and ML axes), DIRECTION (two levels: OP and CL directions) and COORDINATE (two levels: x-axis and y-axis). The level of significance was set at $p = 0.05$. Although the safety margin of angle ($\alpha_s^l$) has a circular nature (Rao and Sengupta 2001), it was treated as a linear variable because $\alpha_s^l$ values formed a data cluster in the same quadrant. The Kolmogorov-Smirnov test and Shapiro-Wilks test were used to test violation of the normal distribution assumption, and Levene's homogeneity test was used to test the assumption of variance homogeneity. The data in figures are presented as group means and standard errors.

## 3. Results

### 3.1. Individual digit normal forces

At the time of maximum resultant moment production, subjects produced the largest normal force with the thumb and the smallest with the little finger (T > R = M = I > L and R = I, where the symbol > represents a significant difference shown by a Bonferroni post-hoc test at the level of significance $p = 0.05$), as shown in figure 3A. This finding was supported by three-way ANOVA with the factors DIGIT, AXIS and DIRECTION, which showed significant effects of DIGIT ($F(4,36) = 162.5$, $p < 0.001$) and AXIS ($F(1,9) = 63.5$, $p < 0.001$), with significant interactions DIGIT × AXIS ($F(4,36) = 5.8$, $p < 0.005$), DIGIT × DIRECTION ($F(4,36) = 38.6$, $p < 0.001$) and DIGIT × AXIS × DIRECTION ($F(4,36) = 4.8$, $p < 0.005$). On average, the sharing of the total normal force by individual digits was in the order of T = 40.8%, R = 18.8%, M = 18.0%, I = 15.5% and L = 6.9%, as shown in figure 3B.

### 3.2. Individual digit tangential forces and their moments

Due to the perfect linear relationship between the individual digit tangential forces and individual digit moments ( $F_t^j = M_Z^j / r_o^j; r_o^j$ is a constant), only the individual digit moments will be discussed. Subjects produced the largest moment by the thumb and the smallest moment by the little finger and moments were in the order of anatomical digit alignments from the thumb to the little finger (T > I > M = R > L, shown by a Bonferroni post-hoc test at $p = 0.05$) (figure 4A). The subjects produced a larger total moment in the CL direction than in the OP direction. These findings were supported by significant effects of DIGIT (F(4,36) = 76.2, $p < 0.001$) and DIRECTION (F(1,9) = 10.2, $p < 0.05$), with significant interactions DIGIT × AXIS (F(4,36) = 4.0, $p < 0.01$) and DIGIT × DIRECTION (F(4,36) = 33.3, $p < 0.001$). The sharing of the total moment by the digits was T = 38.8%, I = 21.8%, M = 15.6%, R = 15.2% and L = 8.6%.

### 3.3. Internal and resultant forces

Subjects produced about twice as large an internal force along the x-axis than along the y-axis (x-axis > y-axis; F(1,9) = 279.0, $p < 0.001$) (figure 5). This reflects the fact that the internal force was larger in the direction of the thumb normal force than in the direction orthogonal to it. The internal force was 14% larger for the ML axis than for the AP axis (ML > AP; F(1,9) = 11.39, $p < 0.01$) and 20% larger in closing than in opening (CL > OP; F(1,9) = 17.44, $p < 0.01$).

The resultant forces along the x-axis during moment production in the closing direction were negative for all subjects, while the resultant forces for the other conditions were all positive. In other words, the thumb force along the x-axis was smaller than the resultant force of the fingers along the x-axis for the CL direction, but larger for the OP direction. However, when a three-way ANOVA was run on the magnitudes of resultant forces, it did not show any effects of AXIS, DIRECTION or COORDINATE. There were significant AXIS × DIRECTION (F (1,9) = 13.2, $p < 0.01$) and AXIS × DIRECTION × COORDINATE (F(1,9) = 7.2, $p < 0.05$) interactions.

### 3.4. Safety margins of normal forces and force angles

The thumb and little fingers showed the largest and smallest safety margins of the normal forces, respectively. On average, the safety margins were in the order of T = 41.8 N, R = 20.2 N, M = 19.4 N, I = 14.3 N and L = 6.8 N (with T > R = M = I > L and R > I; F(4,36) = 91.9, $p < 0.001$) (figure 6). The safety margin for the ML axis was larger than the AP axis (ML > AP; F(1,9) = 56.4, $p < 0.001$). No significant DIRECTION effect was found while a significant DIGIT × DIRECTION (F(1,9) = 42.2, $p < 0.001$) interaction was observed. The relative values of the safety margin (% of the exerted normal forces) showed the largest and smallest values for the thumb and index finger, respectively (T (72.2%) > R (79.1%) > M (73.2%) > L (67.9%) > I (61.6%); F(4,36) = 9.5, $p < 0.001$). There were significant effects of AXIS (ML > AP; F (1,9) = 24.0, $p < 0.005$) and all factor interactions, but no significant effect of DIRECTION (F (1,9) = 3.9, $p = 0.078$).

Compared to the force safety margins, the safety margins of the individual digit force angles showed somewhat different results: the largest was in the ring finger (R (38.8°) > M (35.2°) = T (34.7°) = L (31.5°) > I (28.6°), M = L, M > I, and T = I; F(4,36) = 9.93, $p < 0.001$). The safety margins of force angles were larger for the ML axis than for the AP axis (ML > AP; F (1,9) = 20.76, $p < 0.01$). A significant DIRECTION effect was not found while there were significant effects of all factor interactions.

# 4. Discussion

## 4.1. Sharing of normal forces and moments of tangential forces between digits

During the moment production on a circular object in this study, individual digit normal and tangential forces were not evenly distributed. Their sharing pattern was similar to that of previously reported individual maximum voluntary contraction forces during digit-tip pressing (Olafsdottir *et al*. 2005), that is, among all five digits, the thumb contributed the largest share while the little finger had the smallest share. In a study on forceful grasping of a circular object, Kinoshita *et al*. (1996b) showed that the sharing pattern of the individual digit normal forces was consistent regardless of the weight of the object. Although the present study differed from Kinoshita *et al*.'s in terms of the task (moment production vs. force production), the present study also showed that the sharing pattern of normal forces during moment production was not affected by such task conditions as the wrist position or the direction of the moment.

It has been known that the finger forces during grasping force production or grasping moment production are affected by the wrist positions (Hazelton *et al*. 1975, Fong and Ng 2001, Jung and Hallbeck 2002, Li 2002). In particular, (Dumont *et al*. 2006) recently made a study of repetitive dynamic movements of wrist flexion – extension with a cylindrical handle and reported that sharing of digit-tip forces at contacts with the handle varied throughout the wrist movements. However, in the present study, the sharing of the moments of individual digit tangential forces did not depend on whether the torque was generated by the pronation – supination efforts (AP axis) or by the abduction/adduction efforts (ML axis). The sharing of individual finger normal forces showed changes due to the moment directions (such as opening and closing actions). Besides the intrinsic and extrinsic muscles used for grasping, the moment production tasks require pronator and supinator muscles during moment production about the AP axis and muscles controlling radio-ulnar deviations during the twisting actions about the ML axis. Thus, this finding suggests that the moment sharing patterns among individual digits are preserved regardless of the muscle groups utilized for moment productions, although the muscle group involvement affects the sharing of the normal force. In a recent study, Kong and Lowe (2005) reported normal force sharing among individual fingers at different phalanges of the hand in a cylindrical grip during maximum torque production tasks. The sharing pattern reported by Kong and Lowe (2005) was similar to the sharing pattern found in the present study.

The lack of statistically significant effects of the AXIS orientation on the sharing pattern of the tangential forces or moments of tangential forces contributes to the discussion on whether the tangential forces of individual fingers work as active force generators or as passive force transmitters, similar to the fingers of robot hands and grippers (Pataky *et al*. 2004a). In most robotic hands, all the finger joints are simple hinges and the tangential (lateral) forces are supported by the structure and transmitted passively to the hand-held object via the fingers. In humans, the metacarpophalangeal (MCP) joints have the freedom to move in the radial-ulnar direction and, hence, exerting a tangential force requires generation of the abduction/adduction moment at the MCP joints. However, the passive resistance at the joint may also contribute to the moments at the MCP joints. To answer the question of the relative contribution of the active moment generation vs. passive resistance to the total moment at the MCP joints, electromyographic recordings of the activity of the internal muscles of the hand would be necessary.

## 4.2. Total moments in opening and closing directions

The maximum torque (8.7 Nm) previously reported during opening actions of a 'jar' (Voorbij and Steenbekkers 2002) was four times larger than the maximum torque (2.1 Nm) found in the present study. The difference could be due to: (a) the difference between the diameters of the circular objects tested (6.6 cm in Voorbij and Steenbekkers (2002) vs. 4.5 cm in this study);

(b) the different grasping configurations (two-hand power grip vs. multi-digit precision grip); and (c) different friction coefficients of the contact surfaces (unknown coefficient of an aluminium surface vs. 1.5). A previous study of the effects of diameter of a circular object during a maximum torque production task showed increased maximum torque and decreased grasping force with increasing handle diameter (Kong and Lowe 2005). Although different sizes of circular handles could also have been investigated, one diameter of the circular handle was chosen as the first investigation of multi-digit moment production task. Similarly, although the handle size could be scaled for subjects' hand sizes, it was decided to use one size because the sizes of jar caps and circular valves in everyday life are not usually scaled for users' anthropometry.

The total moment was larger in the CL direction than in the OP direction. However, the maximum moment production capability was the same for the pronation-supination (AP) and radio-ulnar deviation (ML) actions. Thus, the currently popular design of circular valves and jar lids may cause difficulties in opening. In everyday activities, a jar lid or a circular valve closed with the maximum moment may be hard to open due to the smaller moment production capability in the opening direction. This difficulty may also be exacerbated by the difference between dynamic and static frictions during the closing and opening movements. The dynamic friction during closing is usually smaller than the static friction for initiation of opening (Blau 1996, Zatsiorsky 2002). Thus, a larger moment is required to open a circular valve than to close it at the same angular position. Based on the directional difference in the maximum moment production capability found in the present study and in a previous study (Shim *et al*. 2004a), one may suggest a modification of the current designs of circular jar caps and valves to a reversed design of opening and closing directions. However, the suggestion for switching the OP and CL directions would require follow-up studies of other variations of moment production conditions such as grasping types, and with different subject groups inclusion including female/elderly people, left-handed people, etc. In particular, only right-handed people were tested in the present study and the suggestion of switching OP and CL directions is valid only for them. For example, if their capability of maximum torque production is larger in the OP direction than in the CL direction, the current designs of jars and valves may be already optimal for left-handers. The experiment involved one-handed torque production tasks without considering bi-manual interactions in which the other hand participated in the tasks. In a bi-manual jar opening task, in particular, one hand holds a jar lid and the other hand is commonly used to hold the bottom or the middle of the jar.

It is not known whether using the other hand would assist the task or act as a constraint. For instance, for a static equilibrium during a bi-manual jar opening task, the right-hand torque acting to open the lid should be equal and opposite to the left-hand torque acting to hold the bottom of the jar. Thus, if the maximum torque capability of the left hand is smaller than that of the right hand, the addition of the left hand would limit the maximum production of the right hand. A study on bi-manual torque production by right-handers and left-handers holding the jar lid with a right hand and a left hand would answer these questions.

### 4.3. Internal force and safety margin

Larger internal forces were found for the radio-ulnar deviation action of the wrist than for the pronation-supination action. If a large internal force is considered as an index of inefficient use of force, it can be suggested that the normal forces are used more effectively for pronation-supination than radio-ulnar deviations.

Due to the geometry of the circular handle, only a tangential force, not a normal force, can produce a moment around an axis orthogonal to the grasp plane. Humans usually exert a larger normal force on an object than absolutely necessary to prevent the object from slipping (Gordon *et al*. 1993, Johansson and Cole 1994, Hager-Ross *et al*. 1996, Gao *et al*. 2005a). The present study also found significantly larger individual digit normal forces than the normal forces that are required mechanically. Although the order of normal force safety margins across the digits did not follow the anatomical order of digits, the largest and smallest safety margin values were found in the thumb and little finger, respectively.

Although the safety margin forces are considered to help avoid slipping at contact surfaces and to increase grasping stability (Cole and Johansson 1993, Goodwin *et al*. 1998, Pataky *et al*. 2004b), one can consider the safety margin as an index of normal force inefficiency because, in particular, moment production on a circular object does not require any safety margin forces. In this context, the thumb and the little finger had the smallest and largest efficiencies of normal force use since they showed the largest and smallest safety margins, respectively. The underlying mechanism, which determines different safety margins for different digits, is not yet clear and remains for further investigations.

## 5. Conclusion

From the present study of five-digit moment productions on a circular object, it is concluded that: (1) the maximum torque in the CL direction is larger than in the OP direction; (2) the thumb and little finger, respectively, have the largest and the smallest share for both total normal force and total moment; (3) the sharing pattern of moments of individual digit tangential forces is not affected by the orientation of the torque axis or the torque direction, while the sharing of normal force changes with torque direction; (4) the normal force safety margins are largest in the thumb and smallest in the little finger.

## References

Amis AA. Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. Journal of Biomedical Engineering 1987;9:313–320. [PubMed: 3682795]

Arimoto S, Tahara K, Yamaguchi M, Nguyen PTA, Han HY. Principles of superposition for controlling pinch motions by means of robot fingers with soft tips. Robotica 2001;19:21–28.

Blau, PJ. Friction Science and Technology. New York: Marcel Dekker, Inc; 1996.

Cole KJ, Johansson RS. Friction at the digit-object interface scales the sensorimotor transformation for grip responses to pulling loads. Experimental Brain Research 1993;95:523–532.

Dumont CE, Popovic MR, Keller T, Sheikh R. Dynamic force-sharing in multi-digit task. Clinical Biomechanics 2006;21:138–146. [PubMed: 16225972]

Fong PW, Ng GY. Effect of wrist positioning on the repeatability and strength of power grip. American Journal of Occupational Therapy 2001;55:212–216. [PubMed: 11761138]

Fowler NK, Nicol AC. Measurement of external three-dimensional interphalangeal loads applied during activities of daily living. Clinical Biomechanics (Bristol, Avon) 1999;14:646–652.

Gao F, Latash ML, Zatsiorsky VM. Control of finger force direction in the flexion-extension plane. Experimental Brain Research 2005a;161:307–315.

Gao F, Latash ML, Zatsiorsky VM. Internal forces during object manipulation. Experimental Brain Research 2005b;165:69–83.

Goodwin AW, Jenmalm P, Johansson RS. Control of grip force when tilting objects: effect of curvature of grasped surfaces and applied tangential torque. Journal of Neuroscience 1998;18:10724–10734. [PubMed: 9852607]

Gordon AM, Westling G, Cole KJ, Johansson RS. Memory representations underlying motor commands used during manipulation of common and novel objects. Journal of Neurophysiology 1993;69:1789–1796. [PubMed: 8350123]

Hager-Ross C, Cole KJ, Johansson RS. Grip-force responses to unanticipated object loading: load direction reveals body- and gravity-referenced intrinsic task variables. Experimental Brain Research 1996;110:142–150.

Hazelton FT, Smidt GL, Flatt AE, Stephens RI. The influence of wrist position on the force produced by the finger flexors. Journal of Biomechanics 1975;8:301–306. [PubMed: 1184601]

Johansson RS, Cole KJ. Grasp stability during manipulative actions. Canadian Journal of Physiology and Pharmacology 1994;72:511–524. [PubMed: 7954081]

Jung MC, Hallbeck MS. The effect of wrist position, angular velocity, and exertion direction on simultaneous maximal grip force and wrist torque under the isokinetic conditions. International Journal of Industrial Ergonomics 2002;29:133–143.

Kao SY. Carpal tunnel syndrome as an occupational disease. Journal of the American Board of Family Practice 2003;16:533–542. [PubMed: 14963080]

Kinoshita H, Kawai S, Ikuta K. Contributions and co-ordination of individual fingers in multiple finger prehension. Ergonomics 1995;38:1212–1230. [PubMed: 7758447]

Kinoshita H, Kawai S, Ikuta K, Teraoka T. Individual finger forces acting on a grasped object during shaking actions. Ergonomics 1996a;39:243–256. [PubMed: 8851529]

Kinoshita H, Murase T, Bandou T. Grip posture and forces during holding cylindrical objects with circular grips. Ergonomics 1996b;39:1163–1176. [PubMed: 8681936]

Kong YK, Lowe BD. Evaluation of handle diameters and orientations in a maximum torque task. International Journal of Industrial Ergonomics 2005;35:1073–1084.

Kutluhan S, Akhan G, Demirci S, Duru S, Koyuncuoglu HR, Ozturk M, Cirak B. Carpal tunnel syndrome in carpet workers. International Archives of Occupational and Environmental Health 2001;74:454–457. [PubMed: 11563610]

Lee JW, Rim K. Measurement of finger joint angles and maximum finger forces during cylinder grip activity. Journal of Biomedical Engineering 1991;13:152–162. [PubMed: 2033951]

Li ZM. The influence of wrist position on individual finger forces during forceful grip. Journal of Hand Surgery 2002;27:886–896. [PubMed: 12239681]

Mason, MT.; Salisbury, KJ. Robot Hands and the Mechanics of Manipulation (Artificial Intelligence). Cambridge, MA: MIT Press; 1985.

Nguyen PTA, Arimoto S. Dexterous manipulation of an object by means of multi-dof robotic fingers with soft tips. Journal of Robotic Systems 2002;19:349–362.

Olafsdottir H, Zatsiorsky VM, Latash ML. Is the thumb a fifth finger? A study of digit interaction during force production tasks. Experimental Brain Research 2005;160:203–213.

Pataky T, Latash M, Zatsiorsky V. Tangential load sharing among fingers during prehension. Ergonomics 2004a;47:876–889. [PubMed: 15204280]

Pataky TC, Latash ML, Zatsiorsky VM. Prehension synergies during nonvertical grasping, I: experimental observations. Biological Cybernetics 2004b;91:148–158. [PubMed: 15378373]

Pataky TC, Latash ML, Zatsiorsky VM. Prehension synergies during nonvertical grasping, II: Modeling and optimization. Biological Cybernetics 2004c;91:231–242. [PubMed: 15503126]

Radhakrishnan S, Nagaravindra M. Analysis of hand forces in health and disease during maximum isometric grasping of cylinders. Medical and Biological Engineering and Computing 1993;31:372–376. [PubMed: 8231299]

Rao, JS.; Sengupta, A. Topics in Circular Statistics. River Edge, NJ: World Scientific Publishers; 2001.

Rearick MP, Santello M. Force synergies for multifingered grasping: effect of predictability in object center of mass and handedness. Experimental Brain Research 2002;144:38–49.

Santello M, Soechting JF. Force synergies for multifingered grasping. Experimental Brain Research 2000;133:457–467.

Shih YC, Wang MJ. The influence of gloves during maximum volitional torque exertion of supination. Ergonomics 1997;40:465–475. [PubMed: 9140206]

Shim JK, Latash ML, Zatsiorsky VM. Prehension synergies: trial-to-trial variability and hierarchical organization of stable performance. Experimental Brain Research 2003;152:173–184.

Shim JK, Latash ML, Zatsiorsky VM. Finger coordination during moment production on a mechanically fixed object. Experimental Brain Research 2004a;157:457–467.

Shim JK, Latash ML, Zatsiorsky VM. Prehension synergies in three dimensions. Journal of Neurophysiology 2005a;93:766–776. [PubMed: 15456799]

Shim JK, Latash ML, Zatsiorsky VM. Prehension synergies: trial-to-trial variability and principle of superposition during static prehension in three dimensions. Journal of Neurophysiology 2005b; 93:3649–3658. [PubMed: 15728759]

Shim JK, Lay BS, Zatsiorsky VM, Latash ML. Age-related changes in finger coordination in static prehension tasks. Journal of Applied Physiology 2004b;97:213–224. [PubMed: 15003998]

Shimoga KB, Goldenberg AA. Soft robotic fingertips. 2. Modeling and impedance regulation. International Journal of Robotics Research 1996;15:335–350.

Voorbij AI, Steenbekkers LP. The twisting force of aged consumers when opening a jar. Applied Ergonomics 2002;33:105–109. [PubMed: 11831209]

Wei SH, Huang S, Jiang CJ, Chiu JC. Wrist kinematic characterization of wheelchair propulsion in various seating positions: implication to wrist pain. Clinical Biomechanics (Bristol, Avon) 2003;18:S46–S52.

Westling G, Johansson RS. Factors influencing the force control during precision grip. Experimental Brain Research 1984;53:277–284.

Zatsiorsky, V. Kinetics of Human Motion. Champaign, IL: Human Kinetics; 2002.

Zatsiorsky VM, Gregory RW, Latash ML. Force and torque production in static multifinger prehension: biomechanics and control. I. Biomechanics. Biological Cybernetics 2002;87:50–57. [PubMed: 12111268]

Zatsiorsky VM, Latash ML. Prehension synergies. Exercise and Sport Sciences Review 2004;32:75–80.

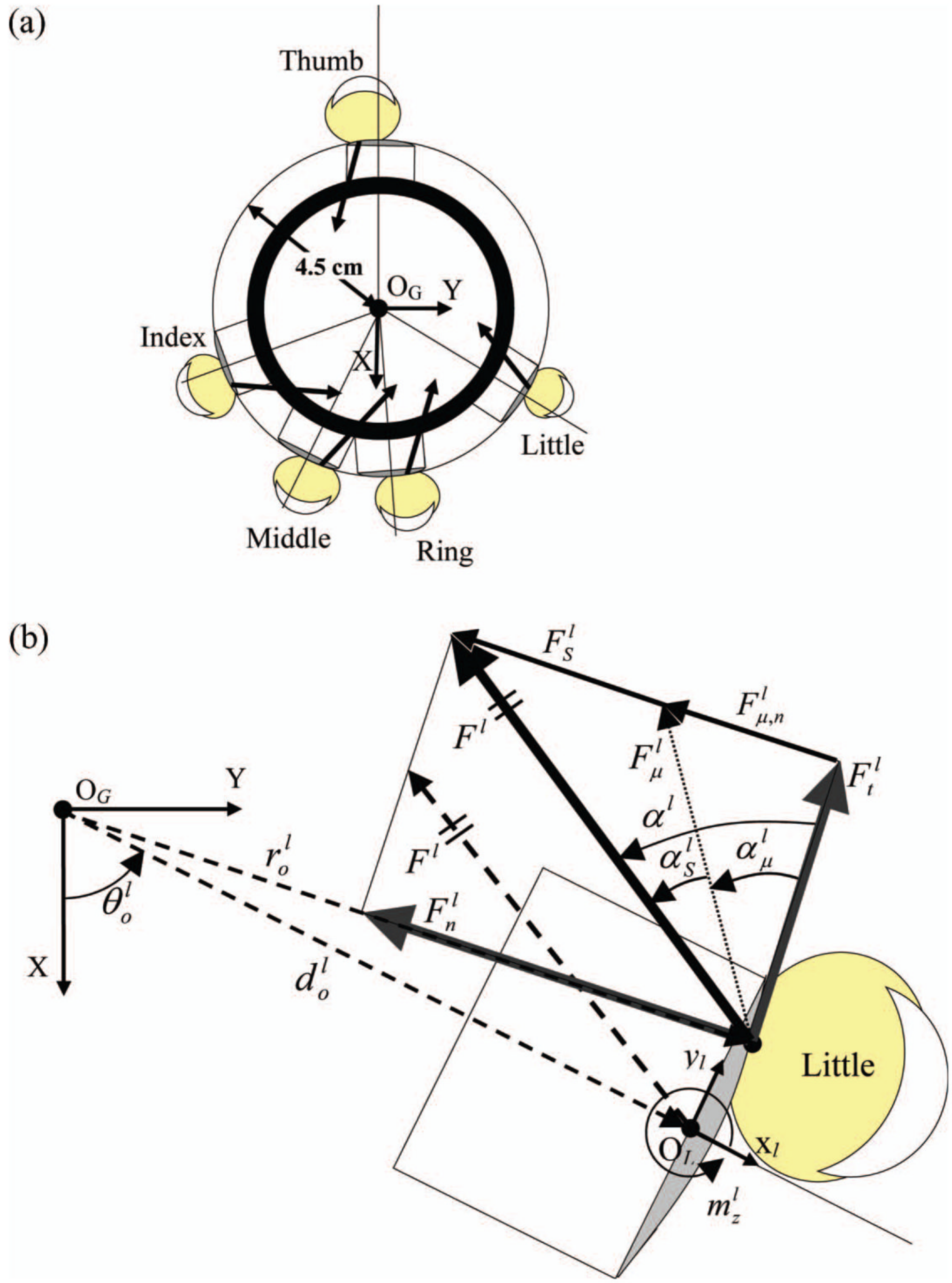


**Figure 1.**

(a) Schematic illustration of an aluminium handle (black 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 (GRS) of coordinates; X = x-axis in GRS; Y = y-axis in GRS (z-axis is not shown in the figures, but its positive direction follows the right-handed coordinate system and is from the paper to the reader); $O_L$ = origin of local reference system (LRS) of coordinates 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; $F_{\mu,n}^l$ = required normal force to avoid slipping of little finger with $F_t^l$ and friction coefficient ($\mu$ = 1.5) of the contact surface; $F_s^l$ = safety margin of normal force( $F_n^l - F_{\mu,n}^l$); $d_o^l$ = position of LRS origin in GRS; $r_o^l$ = position of little finger centre of pressure in GRS; $\theta_o^l$ = angular position of $d_o^l$ in GRS; $\alpha^l$ = angle between $F_t^l$ and $F^l$; $\alpha_\mu^l$ = angle between $F_t^l$ and $F_\mu^l$; $\alpha_s^l$ = safety margin of angle ( $\alpha^l - \alpha_\mu^l$) for little finger force. $O_L$ was fixed to the centre of the contact surface of the sensor and a cap (shown grey) was fixed on the sensor surface. The distance between the apex of the cap and $O_L$ was ~0.81 mm.

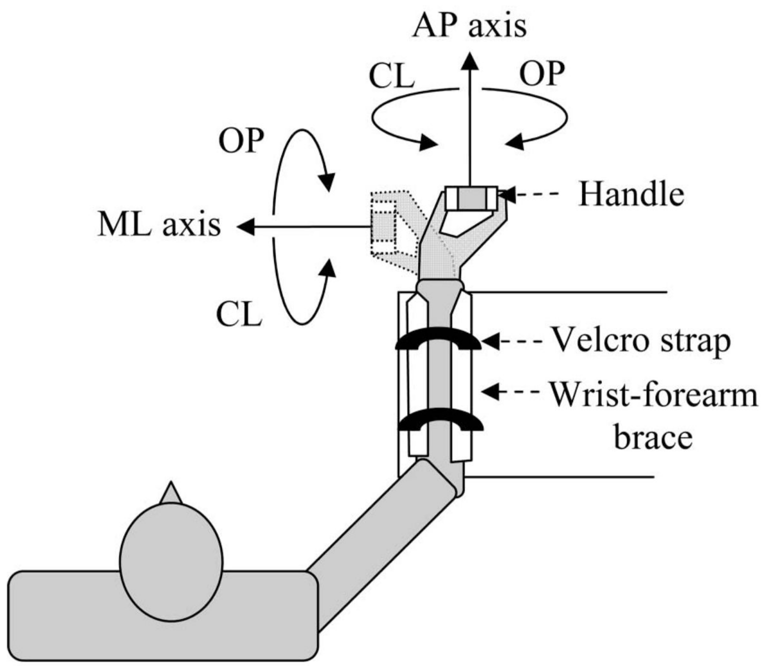


**Figure 2.**
Schematic top view of a subject posture during maximum moment production about anterior – posterior (AP) or medio-lateral (ML) axes in opening (OP) and closing (CL) directions.

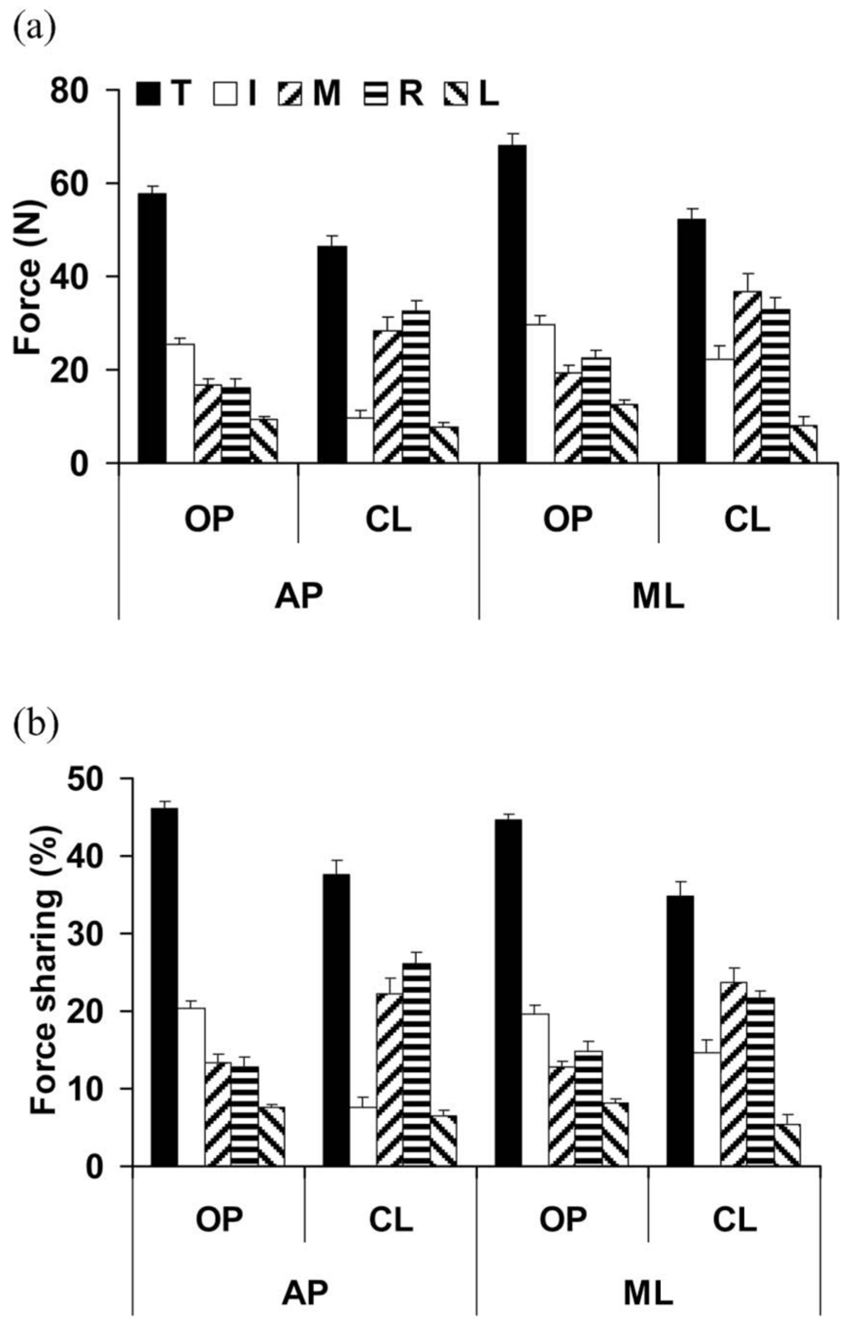


**Figure 3.**

Individual digit normal forces at the time of maximum resultant moment about anterior – posterior (AP) and medio-lateral (ML) axes in opening (OP) and closing (CL) directions. T, I, M, R and L, respectively, represent thumb, index, middle, ring, and little fingers. (a) Mean (± standard error) normal forces across subjects; (b) sharing of total normal force by individual digits (mean ± standard error).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

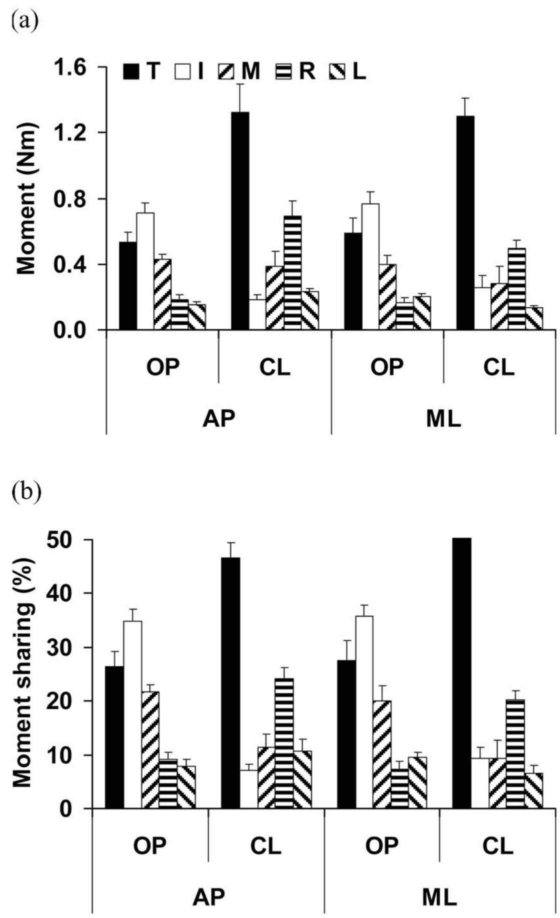


**Figure 4.**

Moments of individual digit tangential forces at the time of maximum resultant moment about anterior – posterior (AP) and medio-lateral (ML) axes in opening (OP) and closing (CL) directions. T, I, M, R and L, respectively, represent thumb, index, middle, ring, and little fingers. (a) Mean (± standard error) moments across subjects; (b) sharing of total moment by individual digits (mean ± standard error).

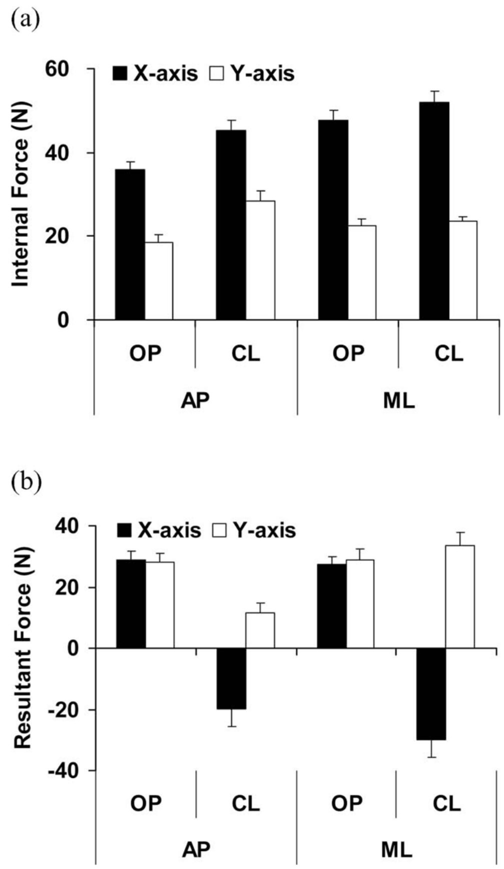


**Figure 5.**
(a) Internal force and (b) resultant force at the maximum moment production in opening (OP) and closing (CL) tasks about the anterior – posterior (AP) and medio-lateral (ML) axes. Mean ± standard errors across subjects are reported for each task condition.

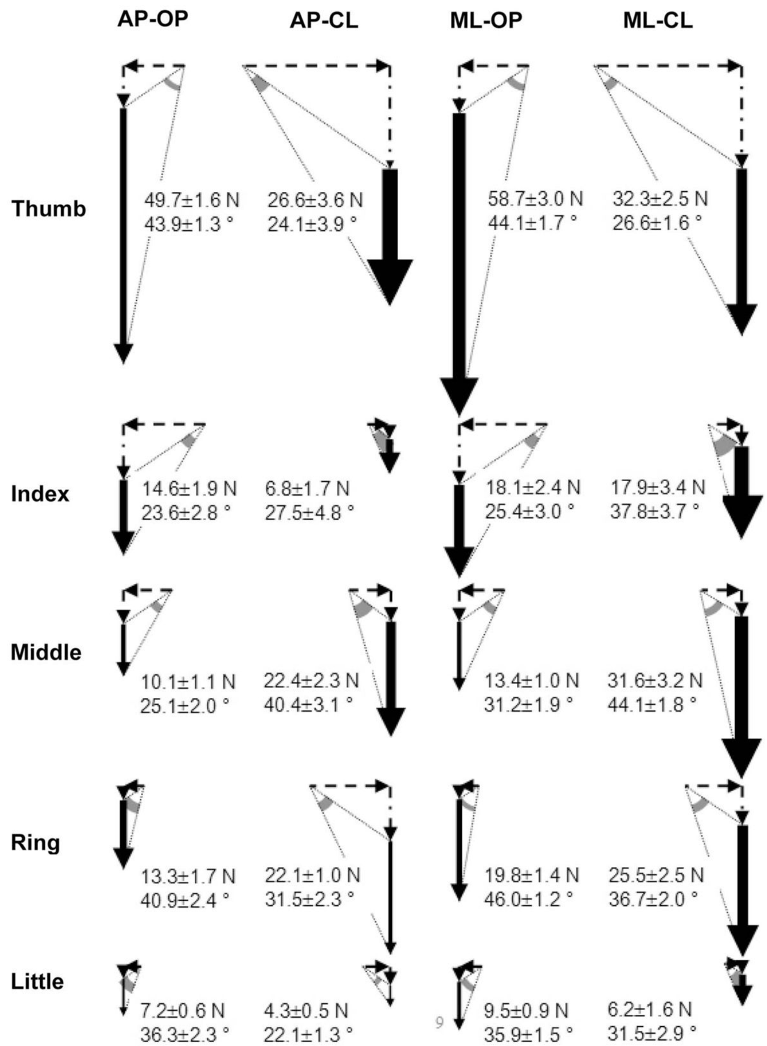


**Figure 6.**

Safety margins of individual finger normal forces and force angles about the anterior – posterior (AP) and medio-lateral (ML) axes in opening (OP) and closing (CL) tasks. The normal and tangential forces are shown as horizontal and vertical arrows, respectively. The mean values and standard errors of the safety margin of normal force and force angle across all subjects are shown next to each force vector diagram for each digit in each task condition. The mean values and standard errors of the safety margin of normal force are respectively shown as the length and thickness of a solid arrow while the mean values and standard errors of safety margins of force angle are respectively shown as the angles and their thickness.

**Table 1**

Age and anthropometric data of subjects (n = 10).

| | | |
|---|---|---|
| Age (years) | | 26.2 ±3.7 |
| Weight (kg) | | 70.1 ±2.1 |
| Height (cm) | | 176.3 ±4.7 |
| Hand length (cm) | | 19.9 ±1.9 |
| Hand width (cm) | | 9.1 ±0.9 |
| Digit position (°) relative to thumb as 0° | Index | 109.0 ±12.6 |
| | Middle | 156.3 ±11.2 |
| | Ring | 187.0 ±8.2 |
| | Little | 240.8 ±15.4 |

Mean values and standard deviations across subjects are reported.