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Internal Forces during Static Prehension: Effects of Age and Grasp Configuration

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Abstract

We studied effects of healthy aging on three components of the internal force vector during static prehensile tasks. Young and older subjects held an instrumented handle using a five-digit prismatic grasp under different digit configurations and external torques. Across digit configurations, older subjects showed larger internal normal (grip) and tangential (load-resisting) digit force components and larger internal moment of force. In contrast to earlier reports, safety margin values were not higher in the older subjects. The results show that the increased grip force in older persons is a specific example of a more general age-related problem reflected in the generation of large internal force vectors in prehensile tasks. It is possible that the higher internal forces increase the apparent stiffness of the “hand+handle” system and, hence, contribute to its stability. This strategy, however, may be maladaptive, energetically wasteful, and inefficient in ensuring safety of hand-held objects.

Keywords

Prehension; aging; internal forces; grasping; safety margin

Introduction

Many physiological changes occur within the neuromotor system with advanced age (Welford 1984; Grabiner and Enoka 1995). These include reduction of muscle mass (Doherty and Brown 1997), slowing down of muscle contractions (Cole 1991; Francis and Spirduso 2000), impairment of tactile sensitivity (Verillo 1979; Cole et al. 1999), and neuronal loss in a number of structures within the central nervous system (CNS) leading to plastic changes within the CNS (Booth et al. 1994; Brooks and Faulkner 1994; Eisen et al. 1996; Erim et al. 1999; Dinse 2006). All these changes can potentially contribute to impaired motor performance in older adults seen across a variety of everyday tasks including prehensile tasks (Rantanen et al. 1999; Francis and Spirduso 2000; Olafsdottir et al. 2008; Parikh and Cole 2012).

When older adults perform static prehensile tasks, such as holding an object, they show a number of differences from younger adults. One of the most consistent findings is the excessive grip force applied by older adults (Cole 1991; Cole et al. 1999; Gorniak et al. 2011). Interpretations of this observation included the drop in the friction coefficient between the fingertips and object surface (Cole et al. 1999) and an increase in the safety margin, defined as the proportion of grip force over the threshold for slippage (Johansson and Westling 1984). The latter phenomenon could be related to ensuring safety of the hand-held object given the increased motor variability in older adults (Vaillancourt et al. 2002; Newell et al. 2009; Christou 2011).

When a set of force vectors ($\mathbf{F}$) act on an object, they can produce a non-zero resultant force vector ($\mathbf{F}_{\text{RES}}$) and a non-zero internal force ($\mathbf{F}_{\text{INT}}$). $\mathbf{F}_{\text{INT}}$ is a set of contact forces, which act on an object without disturbing its equilibrium (Mason and Salisbury 1985; Murray et al. 1994). The $\mathbf{F}_{\text{RES}}$ and $\mathbf{F}_{\text{INT}}$ vectors are orthogonal (Kerr and Roth 1986; Yoshikawa and Nagai 1991). Grip force is arguably the most commonly studied example of $\mathbf{F}_{\text{INT}}$ in prehensile tasks. However, it is not the only component of $\mathbf{F}_{\text{INT}}$ acting during static prehension.

Consider a person holding a vertically oriented object using the prismatic grasp (the four fingers opposing the thumb) with all five digit tips in one plane and external torque acting in the same plane (the grasp plane). Some combinations of external load and torque result in tangential vertical forces, which can be generated by some fingers in the direction of gravity (downwards), while other fingers oppose the load force and act upwards (Zatsiorsky et al. 2002, 2003). As a result, a non-zero internal tangential force is being produced. If the external torque is not zero, some digits produce moments of force acting against the external torque (called “moment agonists”), while others produce moments of force acting in the same direction as the external torque (“moment antagonists”, Zatsiorsky et al. 2003; Park et al. 2011). As a result an internal moment of force is being generated ($\mathbf{M}_{\text{INT}}$, Zatsiorsky 2002).

The main purpose of this study has been to quantify the different components of $\mathbf{F}_{\text{INT}}$ in young and older adults. Based on the aforementioned increase in grip force (the normal force component of $\mathbf{F}_{\text{INT}}$) in older persons, we hypothesized that the tangential and moment components of $\mathbf{F}_{\text{INT}}$ will also be larger in older persons (Hypothesis-1). To test this hypothesis and explore its generality, we measured digit forces produced by young and older persons who held an instrumented handle with the external torque acting into pronation or into supination and using a basic grasp configuration or one of the five modified configurations selected to change the lever arms of the normal and tangential forces of some of the digits.

Our second goal was to explore the safety margin during a variety of grasp configurations and external torques. As mentioned, most earlier studies agree that the safety margin is increased in older persons. Note, however, that safety margin is a function of three variables, friction coefficient, tangential force, and normal force. Most of the cited studies used a standard, comfortable grip configuration and zero external torque. We computed the safety margin over a range of grip configurations and torques. Our Hypothesis-2 was that the safety

margin would be larger in older adults across external torques and configurations. To our surprise, Hypothesis-2 has been falsified in the experiment.

Methods

Participants

We recruited 8 young (4 male and 4 female, mean $\pm$ SD, age: 25.7 ± 5.1 years) and 8 older adults (4 male and 4 female, mean $\pm$ SD, age: 77.1 ± 5.2 years). All older adults were examined by a geriatrician and were free of any neurological or orthopedic condition that would interfere with the prehension task. All participants were right-handed according to their hand usage during writing. The hand length was measured from the distal wrist crease to the tip of the middle finger and, on average $\pm$ SD, was 18.3 ± 0.9 cm for young and 18.4 ± 1.0 cm for older adults. The hand width was measured on the metacarpal level and on average $\pm$ SD was 8.7 ± 0.6 cm for young and 8.9 ± 0.4 cm for older adults. All subjects gave written informed consent according to the procedures approved by the Pennsylvania State University Institutional Review Board.

Apparatus

Five 6-axis force/torque sensors (four Nano-17 for fingers and one Nano-25 for the thumb, ATI Industrial Automation, USA) attached to a custom-made aluminum handle were used to measure forces and moments of force produced by the tips of the index (I), middle (M), ring (R), little (L), and thumb (T) digits. To increase friction between digits and the force/torque sensors, 320-grit sandpaper (SandBlaster, 3M, USA) was placed on the contact surfaces of the sensors. The grip width, defined as the shortest distance between contact surfaces of the thumb and fingers sensors, was 6 cm. The total mass of the handle with attached force sensors was 229 g. A flat circular bull's eye level (15 g, radius = 1.5 cm, height = 1.7 cm) was mounted at the top of the handle. A horizontal aluminum beam (200 g, $2.5 \times 62 \times 0.5$ cm) was fixed at the bottom of the handle to which a movable load (308 g) was attached at different positions to provide different external torque conditions (Figure 1). The handle coordinate frame was affixed at the geometrical center of the handle, while sensors' coordinate frames were affixed at the centers of their contact surfaces.

A movable load suspended at two different positions (+100 mm or -100 mm along the Z-axis of the handle) generated two external torques τ_{EXT} ; positive forearm pronation torque ($\tau_{\text{EXT}} = [0 \ 294 \ 0]^T$ Nmm) and negative forearm supination torque ($\tau_{\text{EXT}} = [0 \ -309 \ 0]^T$ Nmm). Since the mass distribution of the handle was not perfectly symmetrical with respect to the X-axis of the handle, external pronation and supination torques had slightly different magnitudes. In order to maintain the handle in rotational equilibrium, the digits had to produce moments of force about the Y-axis of the handle, i.e. in the XZ plane, to resist τ_{EXT} .

We used six different grip configurations: one basic and five configurations with different sensor positions that modified moment arms for certain finger forces (Figure 2). For the basic grip configuration, the centers of the finger force sensors were evenly spaced at 25 mm along Y-axis of the handle, while the thumb sensor was placed opposite to the midpoint

between the M and R fingers. All sensors were aligned with the XZ plane of the handle. We also tested five different grip configurations that increased moment arms of normal (I and L fingers) and tangential forces (I, L, and T digits) when compared to the basic configuration. Grips with sensor configurations with increased moment arms are referred to as modified grip configurations. To increase the moment arm of normal forces we displaced the I finger sensor up by 10 mm (modified I^N configuration) or the L finger sensor down by 10 mm (modified L^N configuration), from their position in the basic grip configuration. To increase the moment arm of tangential forces, a 20-mm high spacer was attached to the top surface of the I (modified I^T configuration), L (modified L^T configuration), or T sensors (modified T^T configuration).

Experimental procedure

Before the experiment, for each subject we measured the coefficient of friction μ_i for each digit using the ‘imposed displacement’ technique (Savescu et al. 2008). This method uses passive displacement of a supporting surface with respect to a fingertip under controlled normal force conditions. The subject sat in front of the measuring device and placed a fingertip on the Nano-17 force sensor. The contact surface of the sensor was covered with the 320-grit sandpaper. The subject exerted a constant normal force at two levels: 15 N and 30 N, while a motor moved the sensor horizontally, away from the body with the constant speed (6 mm/s). The visual feedback on the applied normal force was displayed on the computer screen placed in front of the subject. The coefficient of friction was calculated as the ratio between the tangential force due to the sensor movement and the normal force applied by the subject. This procedure was repeated for all digits. The coefficient of friction did not depend on gender or force level. Consequently, coefficients of friction for male and female subjects and two force levels were pooled together for further analysis.

Every experimental trial started with the subject sitting on the chair relaxed. The experimenter gave the subject the handle to hold, asking him or her to place the tip of each digit on the corresponding sensor. When the subject held the handle, his or her upper arm was slightly abducted in the frontal plane with the elbow flexed at approximately 90° and the wrist in the neutral position. The subject was instructed to hold the handle naturally in the air for 3 s, with minimal force exertion. The subject was also asked to keep the handle vertical, with the horizontal bar parallel to the floor during the task. The circular level ($\pm 1^\circ$) placed on the top of the handle was used to ensure that this requirement was met throughout the trial. After each trial, the handle was returned to the experimenter, and the subject had a 30-s rest. All test conditions were presented in a randomized block design. Six grip configurations were presented in blocks in random order, and two torque conditions were randomized within each block. Each condition was repeated three times, which resulted in a total of 36 trials.

Data analysis

The output analog signals from sensors were digitized with the 16-bit data acquisition card (PCI-6225, National Instrument, Austin, TX, USA) at 100 Hz. A LabVIEW program (LabVIEW 2011, National Instrument, USA) was used to for data acquisition (Dell Inc., USA) while offline processing and analysis was done in Matlab (MathWorks, USA). The

force signals were low-pass filtered at 10 Hz using fourth-order, zero-lag Butterworth filter. For all measured forces and moments of force, mean value of each 3-s long trial was computed and further averaged across 3 trials per condition. In the following text, all forces and moments of force are expressed in the handle coordinate system. Force components along Z-direction are called normal forces, in the X-direction - tangential forces. Please see Appendix for detailed description of data computation.

For each location of the movable load, the position vector of center-of-gravity of the whole assembly ($\mathbf{l}_{\text{COG}}$) was calculated using Varignon's theorem. Then, the external torque was computed as a cross product:

$$\boldsymbol{\tau}_{\text{EXT}} = \mathbf{w} \times \mathbf{l}_{\text{COG}} \quad (1)$$

where $\mathbf{w} = [7.37 \ 0 \ 0]^T$ N stands for the total weight of the assembly.

The mass of individual sensors (9 g) and the additional spacer (10 g) were low compared to the mass of the whole assembly. Thus, the sensor displacement along X-axis of the handle or attaching a spacer on top of the sensor had minuscule effect on $\mathbf{l}_{\text{COG}}$ of the whole assembly (less than 0.6 mm and 0.9 mm along X- and Z-axes, respectively). Consequently, these effects were neglected.

Since the external torque due to additional load was about the Y-axis of the handle, free moment exerted on the sensor about Z-axis did not contribute to the task of resisting the external torque. The net moment of all digit forces $\boldsymbol{\tau}_{\text{DIGIT}}$ was calculated as

$$\boldsymbol{\tau}_{\text{DIGIT}} = \sum_i \boldsymbol{\tau}_i \quad (2)$$

where $\boldsymbol{\tau}_i$ is a moment of force of i -th digit ($i = \text{I, M, R, L, T}$).

For static equilibrium of the handle, the following constraints must be satisfied:

$$\mathbf{w} + \sum_i \mathbf{f}_i = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \quad (3)$$

$$\boldsymbol{\tau}^{\text{EXT}} + \boldsymbol{\tau}^{\text{DIGIT}} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \quad (4)$$

where $\mathbf{f}_i$ is a resultant force vector of i th digit.

To quantify different components of the internal force we computed the grip force (normal component of internal force, $F_{\text{INT,N}}$, see Equation 5), and tangential component of internal force ($F_{\text{INT,T}}$, see Equation 6).

$$F_{\text{INT},N} = \sum_i \frac{|f_i^Z|}{2} \quad (5)$$

$$F_{\text{INT},T} = \sum_i |f_i^X| - \sum_i f_i^X \quad (6)$$

where f_i^Z and f_i^X are components of the i th digit force in the Z and X -direction, respectively.

Internal moment of force about Y -axis was calculated using:

$$M_{\text{INT}} = \sum_i |\tau_i^Y| - \sum_i \tau_i^Y \quad (7)$$

where τ_i^Y is the component of moment of force of the i th digit force about the Y -axis.

Mean safety margin was computed by averaging safety margins computed for each digit, using:

$$SM = \frac{1}{n} \sum_{i=1}^n SM_i \quad (8)$$

where $n = 5$ is the number of digits and SM_i is safety margin computed for individual digits:

$$SM_i = \frac{\mu_i \cdot |f_i^Z| - f_i^X}{\mu_i \cdot |f_i^Z|} \quad (9)$$

Statistical analysis

All descriptive statistics are reported in the text and figures as means and standard errors unless stated otherwise. We pooled together the data over all grip configurations that involved modification of moment arms of the I and L fingers. This was done based on the lack of qualitative differences in conditions involving the manipulations with the I and L fingers. Pooling the data over those fingers was also a logical step following the idea of virtual finger (VF, Arbib et al. 1985): Both I and L fingers are components of the VF. As a result, in statistical analysis we contrasted three grip configurations: basic, finger-modified, and thumb-modified ones. We used mixed models ANOVA to test the effect of *digit* (five levels: I, M, R, L, and T) and *age* (between-subject factor, two levels: young and old) on μ_i . We also used four mixed models ANOVAs to test the effect of external *torque direction* (two levels: pronation or supination), *grip configuration* (three levels: basic, finger-modified, thumb-modified) and *age* (between-subjects factor, two levels: young and old) on $F_{\text{INT},N}$, $F_{\text{INT},T}$, M_{INT} , and SM .

To fulfill the assumption of normality and homogeneity of variances, dependent variables were log-transformed when needed. All figures represent non-transformed data. Multiple

pairwise comparisons and Fischer's LSD test with Bonferroni corrections were used to explore significant effects. Greenhouse-Geisser correction was used when the assumption of sphericity was violated.

The significance level was set at $p=0.05$ for all statistical tests, which were performed with SPSS 19.0 (IBM Corporation, USA).

Results

Friction coefficient and safety margin

All subjects, from both age groups were able to perform the task with relative comfort, and without reporting any signs of fatigue. Elderly subjects had approximately 29% lower coefficients of friction (μ) than young adults (0.57 ± 0.01 vs. 0.80 ± 0.03 , $F_{(1, 14)} = 17.35$, $p=0.001$). There were no differences among digits and no *digit* $\times$ *age* interaction effects.

The SM values were, on average, lower for the older group (0.55 ± 0.29) as compared to the younger group (0.61 ± 0.29); the group difference was, however, under the significance level ($p=0.19$). SM depended on the external *torque direction* and was about 20% smaller for supination τ_{EXT} (0.64 ± 0.15 vs. 0.51 ± 0.03 , $F_{(1, 14)} = 25.05$, $p=0.001$, for the pronation and supination τ_{EXT} respectively). SM did not vary across *grip configurations* (0.56 ± 0.32 vs. 0.59 ± 0.14 vs. 0.57 ± 0.22 for the basic, finger-modified, thumb-modified levels respectively, $p=0.25$). There were no interaction effects *age* $\times$ *grip configuration* ($p=0.35$), *age* $\times$ *torque direction* ($p=0.37$), *grip configuration* $\times$ *torque direction* ($p=0.62$), and *age* $\times$ *grip configuration* $\times$ *torque direction* ($p=0.36$). These data are illustrated in Figure 3.

Normal component of internal force

On average, across all conditions, older subjects showed 46.1% higher $F_{INT,N}$ compared to young subjects (22.2 ± 1.5 vs. 15.2 ± 1.5 N, respectively, see first row in Figure 4). $F_{INT,N}$ exerted on the handle with supination τ_{EXT} was 17.4% larger when compared to pronation τ_{EXT} (20.2 ± 1.2 vs. 17.2 ± 1.1 N, respectively). The largest $F_{INT,N}$ (24.5 ± 1.6 N) was produced by older subjects with supination τ_{EXT} . The smallest $F_{INT,N}$ (14.5 ± 1.5 N) was produced by young subjects with pronation τ_{EXT} . For older adults, the difference between $F_{INT,N}$ in conditions with supination and pronation τ_{EXT} was 4.6 N, while for young adults, this difference was only 1.5 N. These findings were supported by the significant main effects of *age* ($F_{(1,14)}=10.41$, $p<0.01$) and *torque direction* on $F_{INT,N}$ ($F_{(1,14)}=21.11$, $p<0.001$). There was also a significant *age* $\times$ *torque direction* interaction ($F_{(1,14)}=6.42$, $p<0.05$). Post-hoc analysis revealed that for both levels of *torque direction* there was significant *age* effect ($p<0.05$ and $p<0.01$ for pronation and supination directions, respectively), but the effect of *torque direction* was significant for older adults only ($p<0.001$). This supported the observation that *torque direction* affected $F_{INT,N}$ in older but not young adults.

$F_{INT,N}$ depended on *grip configuration*, with the largest value (19.2 ± 1.1 N) for the thumb-modified configuration and smallest value (17.9 ± 1.1 N) for the basic configuration. The overall *grip configuration* effect was significant ($F_{(2,28)}=3.72$, $p=0.037$). Fisher's LSD test showed the difference between the basic and thumb-modified configurations ($p=0.039$). However, after Bonferroni corrections ($\alpha=0.017$) this effect appeared to be non-significant.

Differences between the basic and finger–modified configurations as well as between the finger and thumb–modified configurations were also non-significant.

Tangential component of internal force

On average, across all conditions, older adults showed almost a five-fold higher $F_{INT,T}$ compared to young adults (2.8 ± 0.7 vs. 0.6 ± 0.7 N, respectively, see second row in Figure 4). Across both groups, $F_{INT,T}$ was 69.2% higher when τ_{EXT} acted in pronation as compared to supination (2.2 ± 0.5 vs. 1.3 ± 0.5 N, respectively). $F_{INT,T}$ did not vary across *grip configurations* (1.8 ± 0.7 vs. 1.6 ± 0.3 vs. 1.7 ± 0.5 N, for the basic, finger–modified, and thumb–modified levels respectively). These findings were confirmed by the significant effects of *age* ($F_{(1,14)}=6.58$, $p<0.05$) and *torque direction* ($F_{(1,14)}=44.62$, $p<0.001$). There was also a significant *grip configuration* $\times$ *torque direction* interaction ($F_{(1.7,24.8)}=3.58$, $p<0.05$). Post-hoc tests with Bonferroni corrections ($\alpha=0.017$) showed that for all *grip configurations* there was a significant effect of *torque direction*. Only for supination *torque direction*, there was a significant difference between thumb-modified and finger-modified *grip configurations*. This supported the observation that effect of thumb sensor position modification on $F_{INT,T}$ depended on τ_{EXT} .

Internal moment of force

On average across all conditions, older adults exerted 76% more of M_{INT} than young adults (473.5 ± 51.8 vs. 269.3 ± 51.8 Nmm, respectively, see third row in Figure 4). All subjects exerted 22.7% more of M_{INT} when τ_{EXT} acted in supination, in comparison to pronation τ_{EXT} (409.3 ± 38.9 vs. 333.6 ± 37.3 Nmm, respectively). Modifications of the *grip configuration* changed the amount of M_{INT} . Subjects exerted lowest M_{INT} for the basic configuration (316.6 ± 36.1 Nmm) while modification of finger and thumb sensor positions increased M_{INT} (361.1 ± 36.1 and 436.5 ± 44.1 Nmm, for finger–modified and thumb–modified configurations respectively). The increase in M_{INT} due to *grip configuration* modification was the largest for pronation τ_{EXT} : The difference in M_{INT} exerted in the basic and thumb–modified configurations was 164.2 Nmm for pronation τ_{EXT} , and 75.6 Nmm for supination τ_{EXT} .

Statistical analysis confirmed these findings and showed significant main effects of *age* ($F_{(1,14)}=7.74$, $p<0.05$), *torque direction* ($F_{(1,14)}=13.19$, $p<0.01$), and *grip configuration* ($F_{(2,28)}=17.96$, $p<0.001$). Pairwise tests with Bonferroni corrections ($\alpha=0.017$) showed that M_{INT} differed significantly across all levels of *grip configuration*. There was a significant *grip configuration* $\times$ *torque direction* interaction ($F_{(2,28)}=7.59$, $p<0.01$). Post-hoc analysis with Bonferroni corrections ($\alpha=0.017$) revealed that M_{INT} depended on *torque direction* only for the basic and finger–modified *grip configurations*. For the supination *torque direction*, M_{INT} did not differ between the finger–modified and thumb–modified *grip configurations*. This supported the observation that M_{INT} was more sensitive to modification of the grip when τ_{EXT} acted in pronation.

Discussion

Our results supported one of the Hypotheses formulated in the Introduction and falsified the other one. The three components of the internal force ($\mathbf{F}_{\text{INT}}$) were consistently larger in older adults as compared to younger adults in support of Hypothesis-1. We believe that this is the first observation of age effects on the internal tangential force and internal moment in prehensile tasks. It shows that the documented increased grip force in older persons (Cole 1991; Cole et al. 1999; Gorniak et al. 2011) may be a specific example of a more general age-related problem. The second Hypothesis was falsified: We observed no difference in the safety margin between the two groups. In fact, older persons tended to show lower safety margin values, although this difference was under the statistical significance level.

Internal forces: Their origin and control

As mentioned in the Introduction, $\mathbf{F}_{\text{INT}}$ are defined as sets of contact forces that do not disturb the equilibrium of the object. This is possible only if the number of contact forces exceeds the number of constraints on resultant force vector ($\mathbf{F}_{\text{RES}}$) imposed by the task. Most of natural prehensile tasks are indeed mechanically redundant (reviewed in Zatsiorsky and Latash 2008). The problem of control of such systems is a particular example of the problem of motor redundancy (Bernstein 1967). For any performance variable, two sub-spaces can be identified in the redundant space of elemental variables, the self-motion space and the range space (Murray et al. 1994). With respect to $\mathbf{F}_{\text{RES}}$ as a performance variable, $\mathbf{F}_{\text{INT}}$ acts in the self-motion space, which coincides with the uncontrolled manifold (UCM) (Scholz and Schöner 1999). The UCM is a space where no changes in a selected performance variable take place. So, changes in $\mathbf{F}_{\text{INT}}$ by definition lead to no changes in $\mathbf{F}_{\text{RES}}$. For example, when a person holds an object, changes in grip force may be applied without moving the object, which means that these changes lead to no changes in $\mathbf{F}_{\text{RES}}$.

In some tasks, components of $\mathbf{F}_{\text{INT}}$ may be necessary. For example, in the studied static prehension task, $\mathbf{F}_{\text{RES}}$ in the normal direction ($\mathbf{F}_{\text{RES},N}$) had to be zero. However, individual digit forces in that direction had to be non-zero to ensure sufficient friction for the production of load-resisting tangential forces. To satisfy the constraint $\mathbf{F}_{\text{RES},N} = 0$, $\mathbf{F}_{\text{INT},N}$ had to be non-zero, confined to the UCM for $\mathbf{F}_{\text{RES},N}$. The non-zero $\mathbf{F}_{\text{INT}}$ in the tangential direction is less obvious. Earlier studies have shown that some of the fingers can press downwards (with the load rather than opposing the load) in specific conditions with a non-zero external torque. However, non-zero $\mathbf{F}_{\text{INT},T}$ is not directly imposed by the task but represents a choice of the neural controller.

With respect to moment production, non-zero $\mathbf{M}_{\text{INT}}$ can have different origins. For example, when two fingers of the hand produce pressing force, other fingers also produce force because of the phenomenon of enslaving or limited finger independence (Kilbreath and Gandevia 1994; Li et al. 1998; Zatsiorsky et al. 2000; Schieber and Santello 2004). For example, for external torque acting in pronation, the ring and little finger normal forces produce moments of force opposing the torque. Enslaving leads, however, to unintentional normal force production by the middle and index finger that act in the direction of the external torque. As a result, non-zero $\mathbf{M}_{\text{INT}}$ is being generated. Another potential source of

$\mathbf{M}_{\text{INT}}$ is the fact that tangential forces always have a resultant acting upward while the resultant may not be shared equally between the thumb and the four fingers combined (“virtual finger”, VF, Arbib et al. 1985). This results in a force couple producing a non-zero moment of force. If the couple acts in the direction of external torque, its moment has to be counteracted by moments produced by the normal forces resulting in a non-zero $\mathbf{M}_{\text{INT}}$. Finally, $\mathbf{M}_{\text{INT}}$ may get contributions from sources reflecting specific neural strategies, for example with the purpose to stabilize the handle orientation against possible torque perturbations.

According to the referent configuration (RC) hypothesis (Feldman 2009), voluntary movements are produced by shifts of neural variables leading to changes in referent values for task-specific, salient variables within a certain external force field. A set of such referent values has been addressed as the referent body configuration. The differences between the actual and referent values of those variables result in muscle activation and motion of the actual body configuration towards the RC, assuming that the motion is not blocked. If the motion is blocked, for example by a rigid hand-held object, a new steady state is characterized by non-zero muscle activations and net forces applied to the object. Within this framework, $\mathbf{F}_{\text{RES}}$ during static prehension is a consequence of the difference between the actual and referent coordinates related to task variables such as the object geometry, weight, orientation, friction between the digit tips and the surface and, possibly, others. Further, RC at the task level leads to RCs for individual digits, and digit forces are produced as consequences of the differences between the actual and referent coordinates of the digit tips (Pilon et al. 2007; Latash et al. 2010).

For a static prehension task with a non-zero external moment, RC at the task level may be viewed as consisting of three components, the referent aperture, which defines $F_{\text{RES},N}$ and $F_{\text{INT},N}$, the referent vertical coordinate that defines $F_{\text{RES},T}$, and the referent angle that defines $\mathbf{M}_{\text{RES}}$ (Latash et al. 2010). Note that defining referent aperture centered at equal distances from the coordinates of the opposing digits ensures $F_{\text{RES},N} = 0$, while the size of the referent aperture defines $F_{\text{INT},N}$. The other two components of $\mathbf{F}_{\text{INT}}$ emerge as results of redundant $\text{RC}_{\text{TASK}} \Rightarrow \text{RC}_{\text{DIGIT}}$ transformations leading to variable combinations of RCs at the digit level compatible with the RC at the task level. Specific patterns of such transformations may have different origins as discussed earlier.

Factors that define safety margin

The definition of safety margin (SM, see Eq. 9) makes it dependent on three variables that can potentially vary across persons, digits, and populations. In fact, friction coefficient, μ , can also vary with normal force magnitude (Savescu et al. 2008); hence, using the same μ values across different normal force values can lead to errors in computed SM values. If one views SM as a measure of safety to avoid slippage, computing SM in prehensile tasks makes sense only for individual digits, not for combinations of normal and tangential force computed across sets of digits (for example, SM for VF is meaningless).

Advanced age affects all three variables in the right side of Eq. 9. There is a drop in μ in older persons (Cole et al. 1999 and the current study) and an increase in all three components of $\mathbf{F}_{\text{INT}}$. When subjects grasp an object of the same weight, the task defines

only $F_{RES,T}$, while $F_{RES,N}$, $F_{INT,N}$ and $F_{INT,T}$ can differ across subjects and groups. Note that individual digit force vectors reflect all four force components. In particular, the higher F_{INT} observed in our experiments for the older subjects may have different effects on SM depending on the relative magnitudes of its components, $F_{INT,N}$ and $F_{INT,T}$. On average, the older subjects produced higher normal forces per digit but they also produced higher tangential forces (due to higher $F_{INT,T}$). As a result, we did not observe the commonly reported increase in SM with age (Kinoshita and Francis 1996; Cole et al. 1999; Rantanen et al. 1999). In fact, SM had a tendency to be smaller in older persons reflecting the smaller μ and larger $F_{INT,T}$ magnitudes as compared to the younger group.

The relatively large $F_{INT,T}$ values observed in our older subjects may partly reflect the relatively large external torques, in particular pronation torques that required a supination effort. The normal forces of the relatively weak ring and little fingers (cf. Li et al. 1998) needed help from the tangential forces to produce the required moment of force. The tangential forces had to obey the constraint of statics: $F_{VF,T} + F_{TH,T} = -w$. They formed a couple that acted against the external torque ($F_{VF,T} < F_{TH,T}$). The couple could produce higher magnitudes of supination moment if some of the fingers produced tangential force downward leading to larger $F_{INT,T}$ magnitudes. Note that placing the thumb on a post increased the lever arm for its tangential force and, as a result, large $F_{INT,T}$ magnitudes could be avoided (Figures 2 and 4). Overall, our findings on SM values suggest that one needs to be cautious making inferences on a general change in SM with age (or in comparison with a special sub-population, e.g., persons with Down syndrome, Cole et al. 1988) unless a variety of conditions and grip configurations are explored.

Changes in multi-digit coordination with age

Performance of a task by a redundant system can be described with two characteristics, the average across trials sharing of performance variables among the elemental variables and the structure of variance across repetitive trials. The former characteristic has commonly been interpreted as a reflection of an optimization principle, while the latter one has been described as an index of a synergy within the redundant space of elemental variables stabilizing a particular performance variable (reviewed in Latash et al. 2007; Latash 2010).

Studies of the effects of aging reported changes in both characteristics. In particular, several studies reported lower indices of multi-digit synergies stabilizing such performance variables as components of F_{RES} , the resultant pressing force and the resultant moment of force in older persons compared to younger subjects (Shinohara et al. 2004, Shim et al. 2004, Olafsdottir et al. 2007). Within the framework on the UCM hypothesis (Scholz and Schöner 1999), older persons show relatively less variance within the UCM computed for a particular performance variable (this variance component has no effect on the performance variable) as compared to variance orthogonal to the UCM (this variance component changes the performance variable).

By definition, F_{INT} lies within the UCM for F_{RES} . The larger values of F_{INT} for the older group seem to contradict the findings in the cited studies of multi-digit synergies. There may be no contradiction, however. The larger magnitudes of F_{INT} may be compatible with both relatively higher and lower amounts of variance within the UCM for F_{RES} . While most

studies report an increase in force variability with force magnitude (reviewed in Newell and Carlton 1993), this rule can be violated in redundant multi-finger tasks (Shinohara et al. 2004; Shapkova et al. 2008). Besides, even if the increased magnitude of F_{INT} leads to higher variance within the UCM, there may be a larger increase in variance orthogonal to the UCM resulting in the combination of increased F_{INT} and lower synergy indices in older persons. This is a topic for further research.

What could be the reason for the increased F_{INT} in older persons? Higher grip force has commonly been interpreted as a reflection of a strategy to increase safety of the hand-held object (Cole et al. 1999; De Freitas et al. 2009; Gorniak and Alberts 2013). Earlier studies reporting M_{INT} , interpreted the findings as a reflection of a strategy stabilizing the orientation of the object against possible changes in the external torque and spontaneous changes in digit forces (Shim et al. 2003; Zatsiorsky et al. 2004). Along these lines, one can suggest that higher F_{INT} increases the apparent stiffness of the “hand+handle” system and, hence, contributes to its stability. There is a trade-off, however. First, producing high F_{INT} is obviously associated with overall higher levels of muscle activation and may be viewed as wasteful. Using increased F_{INT} may be compared to elevated levels of muscle co-contraction documented in older persons across tasks (Seidler-Dobrin et al. 1998; Tang and Woollacott 1998). Second, high F_{INT} can contribute to fatigue. Third, as shown in this study, higher $F_{INT,T}$ can lead to a drop in the safety margin, which is a dangerous strategy. Fourth, muscle co-contraction is an inefficient strategy to deal with sources of perturbations that originate within the body (Latash and Goodman 1994).

The observed phenomena may get contribution from a range of physiological changes associated with aging. In particular, older persons show progressive loss of cutaneous receptors (Matthewson and Nava 1985), which may require higher contact forces to induce the same subjective feeling of pressure at the digit tips. Another reason for higher forces may be the documented increase in motor variability in older persons (Cole et al. 1999; Enoka et al. 2003): The higher force variability may bring the grip force magnitude dangerously close to slippage. It is also possible that higher F_{INT} reflect the overall lower confidence in one’s motor abilities. The last points allows to view the higher F_{INT} in older persons as an example of a maladaptive strategy (Latash and Anson 1996, 2006), which is energetically wasteful and inefficient in ensuring safety of hand-held objects. The low efficacy of this strategy is reflected in the fact that older persons frequently drop and otherwise mishandle objects during everyday prehensile tasks. We did not explore effects of practice on internal forces. It is conceivable that with proper practice, older person would be able to reduce the level of internal forces, but this is a topic for another study.

While the study did not focus on differences in adjustments to finger-modified and thumb-modified configurations, effects of modifying the thumb position were consistently stronger than those induced by modifications of finger positions. This difference may be related to the special role of the thumb that acts in opposition to all four fingers during prismatic grasps. On the other hand, the thumb-modified configuration can be seen as a modification of the grip condition for all five digits, i.e., adding a spacer on top of the thumb sensor increased grip aperture, that affected all digits.

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Appendix

In the subsequent text, left superscripts S and H are used to represent description of the variable in the sensor or handle coordinate frame, respectively; right subscript i designates one of the digits ($i = I, M, R, L, T$); right superscript represent X -, Y -, or Z -components of the variable. Lowercase bold letters indicate a vector, uppercase bold letters indicate matrix, and non-bold lowercase letters indicate scalars. For example, $^S f_i^X$ indicates X -component of an i th digit force in the sensor coordinate frame.

We assumed that digits made a soft-finger contact with the sensors, and the only free moment exerted on the sensor was about Z -axis ($^S T_i^Z$). For each sensor, point of digit normal force application ($^S \mathbf{p}_i$) in the sensor coordinate frame was computed (Equation 10 – 13).

$${}^S\mathbf{p}_i = \begin{bmatrix} {}^Sp_i^X \\ {}^Sp_i^Y \\ {}^Sp_i^Z \end{bmatrix} \quad (10)$$

$${}^Sp_i^X = \frac{-{}^Sm_i^Y + {}^Sd^Z \cdot {}^Sf_i^X}{{}^Sf_i^Z} \quad (11)$$

$${}^Sp_i^Y = \frac{{}^Sm_i^X + {}^Sd^Z \cdot {}^Sf_i^Y}{{}^Sf_i^Z} \quad (12)$$

$${}^Sp_i^Z = {}^Sd^Z \quad (13)$$

where ${}^Sf_i^X$, ${}^Sf_i^Y$, ${}^Sf_i^Z$ and are X-, Y-, and Z- components of the i th digit force, ${}^Sm_i^X$ and ${}^Sm_i^Y$ are measured moments about X- and Y- axis. For basic grip configuration, ${}^Sd^Z = 0$, and for I^T, L^T, and T^T configurations ${}^Sd^Z = 20$. Sensors' coordinate frames were not initially aligned with the X and Y axes of the handle, therefore each digit force vector (${}^S\mathbf{f}_i$) was expressed in the handle coordinate frame using

$${}^H\mathbf{f}_i = {}^H\mathbf{R}_i {}^S\mathbf{f}_i \quad (14)$$

where ${}^H\mathbf{R}_i$ is a rotation matrix from the sensor to the handle coordinate frame. The point of application of each digit's normal force in the handle coordinate (${}^H\mathbf{p}_i$) frame was calculated as

$${}^H\mathbf{p}_i = {}^H\mathbf{r}_i + {}^H\mathbf{R}_i {}^S\mathbf{p}_i + \begin{bmatrix} {}^Hd^X \\ 0 \\ 0 \end{bmatrix} \quad (15)$$

where ${}^H\mathbf{r}_i$ is the position vector of the i th sensor coordinate frame expressed in the handle coordinate frame. For basic grip configuration, ${}^Hd^X = 0$, and for I^N, L^N configurations ${}^Hd^X = 10$. The moment of each digit force was calculated with respect to the origin of the handle coordinate frame using

$${}^H\boldsymbol{\tau}_i = {}^H\mathbf{p}_i \times {}^H\mathbf{f}_i + {}^H\mathbf{R}_i \begin{bmatrix} 0 \\ 0 \\ {}^ST_i^Z \end{bmatrix} \quad (16)$$

Figure 1.

A schematic drawing of the handle assembly. Five 6-axis force/torque sensors were attached to the custom-made aluminum handle, with the flat circular bull's eye leveler mounted on top of the handle. A horizontal aluminum beam fixed at the bottom of the handle with attached movable load. The handle and sensor coordinate systems are shown as (H_x, H_y, H_z) and (S_x, S_y, S_z) . In this example, the load generated positive (pronation) external torque.

Figure 2.

The six grip configurations used in the study. **Basic:** all finger sensors at the same height and their centers evenly spaced by 25 mm along vertical direction; **Modified I^N and L^N :** The finger sensor is displaced by 10 mm; and **Modified I^T , L^T , and Th^T :** A 20-mm high spacer is attached to the top surface of the sensor.

Figure 3.

Safety margin (SM) for the three grip configurations: *basic*, *finger-modified* (finger-mod), and *thumb-modified* (thumb-mod). The data are shown for the external torque acting in pronation (left column, A) and in supination (right column, B). Averaged across subjects values (with standard *error bars*) are shown for the *young* (open bars) and *older* (black bars) age groups.

Figure 4.

Internal forces and internal moment of force for the three grip configurations: *basic*, *finger-modified* (finger-mod), and *thumb-modified* (thumb-mod). Rows show results for normal component of internal force ($F_{INT,N}$), tangential component of internal force ($F_{INT,T}$), and internal moment of force (M_{INT}), respectively. The data are shown for the external torque acting in pronation (left column A) and in supination (right column B). Averaged across subjects values (with standard error bars) are shown for the *young* (open bars) and *older* (black bars) age groups.