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RESEARCH ARTICLE

Manipulation of a fragile object by elderly individuals

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Abstract We investigated strategies of healthy elderly participants (74–84 years old) during prehension and transport of an object with varying degrees of fragility. Fragility was specified as the maximal normal force that the object could withstand without collapsing. Specifically, kinetic and kinematic variables as well as and force covariation indices were quantified and compared to those shown by young healthy persons (19–28 years old). We tested three hypotheses related to age-related changes in two safety margins (slip safety margin and crush safety margin) and indices of force covariation. Compared to young controls, elderly individuals exhibited a decrease in object acceleration and an increase in movement time, an increase in grip force production, a decrease in the correlation between grip and load forces, an overall decrease in indices of multi-digit synergies, and lower safety margin indices computed with respect to both dropping and crushing the object. Elderly participants preferred to be at a relatively lower risk of crushing the object even if this led to a higher risk of dropping it. Both groups showed an increase in the index of synergy stabilizing total normal force produced by the four fingers with increased fragility of the object. Age-related changes are viewed as a direct result of physiological changes due to aging, not adaptation to object fragility. Such changes in overall characteristics of prehension likely reflect diminished synergic control by the central nervous system of finger forces with aging. The findings corroborate an earlier hypothesis on an age-related shift from synergic to element-based control.

Keywords Prehension · Fragile object · Hand · Biomechanics · Safety margin · Elderly

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Introduction

A variety of physiological changes occur with human neuromotor system as one moves into late adulthood (Grabiner and Enoka 1995; Levinson 1978; Welford 1984) including reduction of muscle mass (Doherty et al. 1993; Rodgers and Evans 1993), decrease in the coefficient of friction between skin and handheld objects (Comaish and Bottoms 1971; Kinoshita and Francis 1996), impairment of tactile sensitivity (Cole et al. 1999; Verillo 1979), slowing down of muscle contractions (Cole 1991; Francis and Spirduso 2000; Seidler–Dobrin et al. 1998), and neuronal loss in many CNS structures (Booth et al. 1994; Brooks and Faulkner 1994; Eisen et al. 1996; Erim et al. 1999; Dinse 2006). These physiological changes have been linked to the production of excessive grip forces when handling objects as well as impairment in the production and maintenance of low grip forces necessary for the completion of fine motor activities (Cole 1991; Cole and Beck 1994; Cole et al. 1999; Kinoshita and Francis 1996; Lindberg et al. 2009). Each of these changes may contribute to the overall decline in hand function associated with aging.

Given the wide variety of tasks presented to us each day, many of the objects we manipulate are fragile. The issue of manipulating fragile objects has been barely touched upon in studies of prehension. Recently, two studies have focused on the mechanics and digit interaction during manipulation of deformable objects (Winges et al. 2009;

Gorniak et al. 2010). The former study focused on grip and load force coupling during tripod grasp of a spring-like object. Gorniak and colleagues focused on changes in kinematic and kinetic indices during manipulation of an object that crushed when the grip force exceeded a specific threshold magnitude. In that study, quick lifting of the fragile object led to changes in grip force and reductions in both peak acceleration and movement smoothness indices. Additionally, the typically high correlation between grip force and object acceleration (Flanagan and Wing 1993, 1995; Flanagan and Tresilian 1994; Wing et al. 1997) was decreased during the handling of fragile objects.

Elderly persons are known to exert excessive caution when manipulating fragile objects, which may lead to failure at the task (e.g., dropping the object or spilling its contents). The purpose of this study was to investigate age-related changes in the characteristics of quick movements of a hand-held fragile object and in associated multi-digit synergies (defined later).

We hypothesize that the effects of fragility on kinematic indices will be more pronounced in the elderly because of the demonstrated preference of the elderly for safer motor patterns (Hypothesis 1; Cole 1991; Cole and Beck 1994; Gilles and Wing 2003). We also expect normalized jerk values to be larger in elderly individuals due to their excessive sub-movements documented for upper limb tasks (Cooke et al. 1989; Fradet et al. 2008; Walker et al. 1997).

Healthy aging is known to be associated with higher grip forces and safety margins (Cole 1991; Cole and Beck 1994; Gilles and Wing 2003). When dealing with a rigid object, this strategy provides for a higher safety margin defined as the normalized difference between actual and lowest possible grip forces (Burstedt et al. 1999; Johansson and Westling 1984; Pataky et al. 2004). During fragile object manipulation, however, there are constraints not only on the lowest permissible force (to avoid slippage) but also on the highest one (to avoid crushing the object). Given such constraints, high safety margins may be impossible to achieve when handling fragile objects. Based on the mentioned preference of safe motor patterns by the elderly, we hypothesize that the elderly persons will show both increased grip forces and safety margins for all objects independent of their fragility (Hypothesis 2).

Covariation patterns between individual finger forces and moments of force across repetitive trials have been addressed as prehension synergies (Zatsiorsky and Latash 2004, 2008; Latash et al. 2002b, 2007). As compared to young persons, elderly persons show lower indices of multi-digit synergies in multi-digit actions (Olafsdottir et al. 2007b; Shinohara et al. 2003a, b, 2004; Park et al. 2011). In this study, we analyzed indices of multi-digit synergies at two levels of a presumed control hierarchy. At the upper level of this hierarchy, the hand action is shared between the thumb and an opposing effector ("virtual finger", VF, an imaginary digit with the mechanical action equal to the combined action of the actual fingers; Arbib et al. 1985; Mackenzie and Iberall 1994). At the lower level, VF action is shared among the actual fingers. Recently, a trade-off between synergies at the two levels of the control hierarchy has been reported: strong synergies at the higher level have been associated with weak or absent synergies at the lower level (Gorniak et al. 2007b, 2009b; Zhang et al. 2009; Sun et al. 2011). Prehension of fragile objects has, however, been associated with emergence of synergies at the lower level (Gorniak et al. 2010). Based on these studies, we hypothesize that strong synergies, although not as strong as in young persons, will be seen at the upper level of the hierarchy in the elderly, while weak synergies at the lower level will emerge during manipulation of fragile objects (Hypothesis 3).

Methods

Participants

Fourteen young (23 ± 3 years old; 7 men and 7 women) and nine elderly (78 ± 3 years old; 3 men and 6 women) subjects volunteered to participate in this study (mean ± SD). The average height and weight were, respectively, 1.71 ± 0.09 m and 66.5 ± 9.0 kg for the young subjects, and 1.64 ± 0.12 m and 67.8 ± 15.7 kg for the elderly subjects. Handedness was assessed by the Edinburgh Inventory (Oldfield 1971), which ranges from a laterality quotient (LQ) of—100 (which indicates strong left-handedness) to +100 (which indicates strong right-handedness). All subjects were strongly right-handed (LQ average = +89) and had no previous history of neuropathies or traumas to the upper limbs. None of the subjects had a history of long-term involvement in hand or finger professional activities such as typing or playing musical instruments. The elderly subjects were recruited from local retirement communities and passed a screening process that involved a cognition test (mini-mental status exam ≥24 points), a quantitative sensory test (monofilaments ≤3.22), and a general neurological examination. All subjects gave informed consent according to the procedures approved by the Office of Regulatory Compliance of the Pennsylvania State University.

Experimental setup and procedure

Extensive details regarding the experimental setup, an illustration of the equipment, and general details of the testing procedure can be found in an earlier publication (Gorniak et al. 2010). Briefly, the subjects were required to move a vertically oriented handle instrumented with five six-component force/torque sensors (Nano-17 and Nano-25, ATI Inc.) upwards to a visual target. Sandpaper (320-grit) was attached to the contact surfaces of each sensor to increase the friction between the digits and the transducers. The finger pad-sandpaper coefficient of static friction was approximately 0.96 for young subjects (Savescu et al. 2008) and 0.8 for elderly subjects (Kinoshita and Francis 1996). Transducer signals were amplified, multiplexed, and sampled at 480 Hz. Handle kinematics were recorded using passive reflective markers (2 cm in diameter) and a four camera ProReflex system (Qualysis Inc.) at 240 Hz.

Subjects sat with an erect posture, arms unsupported, in a chair facing a small table. They were instructed to grasp the object using the right or left hand (in different series). For each of the three fragility settings (see later), the trials were presented in blocks to allow the subject to adjust better to different fragility settings. At the onset of the task, the upper arm(s) of the subjects were abducted at approximately 45° in the frontal plane, flexed 45° in the sagittal plane, and internally rotated approximately 30°. Each of the hands was in a neutral supination-pronation position. The wrists were flexed approximately 30° during each task. Once the object was grasped, subjects lifted the object to a height of 0.10 m above the surface of the table, indicated by a visual target. When subjects indicated that they were ready to start a trial, data collection began. Subjects were instructed to move the object quickly and accurately 0.30 m vertically to the second visual target and remain there until the end of the trial. Data were recorded for 5 s. Three successful practice trials were required prior to the onset of data collection for each condition. A minimum of 15 successful trials were recorded for each experimental condition.

Handle fragility

Handle fragility was manipulated by changing the current through the solenoid that maintained the object width by resisting the panel with the thumb force/torque sensor (for details see Gorniak et al. 2010). Fragility indices (FR-indices) were calculated as the quotient of the minimum grip force required to maintain the handle in static equilibrium (F^{GRIP} min = 7.5 N for young controls; F^{GRIP} min = 8.9 N for elderly subjects) divided by the grip force needed to collapse the handle. The difference in F^{GRIP} min is a direct result of the lower coefficient of friction in elderly individuals. As the grip force needed to collapse the handle increases, FR-index approaches zero. Data were collected from each subject using three different FR-indices (Low, Mid, and High). For control subjects, these indices correspond to FR-index values of 0.15, 0.37, and 0.45. Similar FR-indices were used to test the majority of conditions in elderly subjects; however, the value of FR-indices was different for elderly subjects due to the documented physiological drop in skin coefficient of friction (Kinoshita and Francis 1996). The tested FR-indices for elderly subjects were 0.18, 0.40, and 0.45 corresponding to Low, Mid, and High FR-indices, respectively.

Data analysis

Data analyses performed were consistent with measures and methods presented in Gorniak et al. (2010). No difference between the right and left hands was found in either the control or elderly populations, thus the averaged data across hand conditions have been considered for analysis in this manuscript. Basic kinematic measures such as movement time, object acceleration, and normalized mean squared jerk measures (movement smoothness) are briefly presented here. The location and orientation of the handle was calculated using standard 3D kinematic procedures, as described by Zatsiorsky (1998) and Hamill and Selbie (2004). The displacement of the handle along the *Z*-axis was also used to calculate the normalized mean squared jerk, a dimensionless index of movement smoothness that takes into account both movement time and handle displacement (Teulings et al. 1997):

$$\mathrm{NMSJ} = \sqrt{\frac{\mathrm{MT}^5}{L^2}\int_0^{\mathrm{MT}} \frac{J^2}{2}\,\mathrm{d}t} \quad (1)$$

where MT is the duration of the movement, J is the time derivative of the recorded acceleration, and L is the displacement of the handle.

Kinetic analysis

The slip safety margin ($\mathrm{SM_s}$, the amount of grip force exerted beyond what is required to prevent object slip) has been defined in literature (Johansson and Westling 1984; Burstedt et al. 1999; Pataky et al. 2004) as:

$$\mathrm{SM_s} = \frac{(F^{\mathrm{G}} - |F^{\mathrm{L}}|/\mu_{\mathrm{s}})}{F^{\mathrm{G}}} \quad (2)$$

where F^{G} is the grip force applied to the object, F^{L} is the load-bearing force applied to the object, and μ_{s} is the coefficient of static friction between the finger pad and sandpaper interface. Thus, the maximum value for $\mathrm{SM_s}$ is unity if no load-bearing force (F^{L}) is exerted on the object and the minimum value for $\mathrm{SM_s}$ is zero if just enough force is exerted on the object to prevent slipping.

Another type of safety margin index (crush safety margin, $\mathrm{SM_c}$) was calculated with respect to handle fragility (originally $\mathrm{SM_{FR}}$, introduced in Gorniak et al. 2010) defined as:

$$\mathrm{SM_c} = \frac{F^{\mathrm{G}}_{\max} - F^{\mathrm{G}}}{F^{\mathrm{G}}_{\max}} \quad (3)$$

where $F^{\mathrm{G}}_{\max}$ is the maximal grip force the handle can withstand prior to collapse and F^{G} is the total gripping force ($F^{\mathrm{G}}_{\max} = F_{\mathrm{TH}} + (-F_{\mathrm{VF}})$; $F_{\mathrm{TH}} = -F_{\mathrm{VF}}$) applied to the handle. If $\mathrm{SM_c} \sim 1$, then the handle is not likely to be crushed; if $\mathrm{SM_c} \sim 0$, then the handle is close to collapse.

During movement, the distance between the slip and crush thresholds varied with applied forces. The range of grip forces that may be applied to the handle between the crush and slip thresholds was computed via a new measure introduced here, termed drop–crush range (R_{DC}). The allowable grip force difference between the two thresholds is normalized by the crush threshold as a means to determine the relative size of the acceptable grip force range. It is computed as:

$$R_{\mathrm{DC}} = \frac{(F^{\mathrm{G}}_{\max} - |F^{\mathrm{L}}|/\mu_{\mathrm{s}})}{F^{\mathrm{G}}_{\max}} \quad (4)$$

where F^{L} is the load-bearing force applied to the handle, μ_{s} is the coefficient of static friction between the finger pad and sandpaper interface, and $F^{\mathrm{G}}_{\max}$ is the maximal grip force the handle can withstand prior to collapse. If $R_{\mathrm{DC}} \sim 1$, the two thresholds are far apart while $R_{\mathrm{DC}} \sim 0$ indicates that the two thresholds are close to each other.

An index comparing the range of applied forces above the slip threshold to the acceptable grip force range, introduced in Gorniak et al. (2010), was also computed. This index has been termed drop–crush index (I_{DC}) and defined as:

$$I_{\mathrm{DC}} = \frac{(F^{\mathrm{G}} - |F^{\mathrm{L}}|/\mu_{\mathrm{s}})}{(F^{\mathrm{G}}_{\max} - |F^{\mathrm{L}}|/\mu_{\mathrm{s}})} \quad (5)$$

where F^{G} is the grip force applied to the handle, and other symbols are the same as in Eq. 4. If $I_{\mathrm{DC}} \sim 1$, then the amount of grip force applied to the handle is near the crush threshold of the handle; if $I_{\mathrm{DC}} \sim 0$, then the amount of grip force applied to the handle is near the slip threshold of the handle. More detail can be found in Gorniak et al. (2010).

Analysis of multi-digit synergies and finger force variance

Analysis of grip force variability was performed at two levels of the assumed hierarchy, the VF-TH level and the individual finger (IF) level. At the VF-TH level, the outputs of the VF and the thumb are analyzed as elemental variables. At the IF level, the outputs of the fingers within the VF are analyzed. Indices of covariation of elemental variables (forces produced by individual digits) were computed reflecting the stabilization of combined effector output across trials (Kang et al. 2004; Shim et al. 2005; Gorniak et al. 2007a, b, 2009b). Positive ΔV values correspond to negative covariation, thus the presence of a grip stabilizing synergy (for analysis of normal digit forces). A result of $\Delta V = 0$ implies independent variation of digit forces, and correspondingly the absence of a synergy, while $\Delta V < 0$ may be interpreted as covariation of elemental variables destabilizing their combined output.

In addition, the total variance (across trials) of all the elemental variables at that level (V^{TOT}) was computed at both hierarchical levels. The value of V^{TOT} can be viewed as the sum of two components, only one of which has an effect on performance (variance of task performance, V^{P}). To disambiguate changes in the index of covariation (synergy index), we analyzed separately changes in V^{TOT} and V^{P} (Zhang et al. 2009; Gorniak et al. 2010; SKM et al. 2010).

Statistics

The data are presented in the text and figures as means and standard errors. Mixed model repeated-measures analysis of variance (ANOVAs) were performed on the kinematic and kinetic data with the within-subject factor of *FR-index* (three levels; High, Mid, and Low). The between-subjects factor was *Age* (two levels; Young and Elderly). Pair-wise comparisons were performed using Tukey's tests to explore significant effects. Bonferroni corrections were also used to analyze significant effects of ANOVAs with a controlled experiment-wise error rate for the *FR-index* multiple comparisons. The analyses for all kinematic measures were performed on the average data across the entire movement time duration for each condition. The kinetic and synergy index analyses (with the exception of the grip and load force correlation) were performed on the average data from the first 10% of movement time of each condition. The assumption of sphericity was checked using Mauchly's sphericity test. If sphericity was violated, the degrees of freedom were adjusted using Greenhouse–Geisser corrections.

The R^2 values from the regression analysis between grip and load forces and ΔV data were subjected to Fisher *z*-transformation to mitigate the ceiling effects inherent to these variables. Non-transformed data are presented in the figures to avoid confusion. Student's *t* tests with Bonferroni corrections were performed to compare ΔV indices with zero.

Results

This section is organized in the following manner: the results for kinematic data, such as object acceleration and movement time are presented in Part I; the results for kinetic data, grip force, safety margins, and the correlation between grip and load forces are presented in Part II; and analyses of the force variance and synergy indices for grip force, $\Delta V(F^{G})$, for the two hierarchical levels (VF-TH and IF levels) are presented in Part III.

Basic movement patterns

Typical movement trajectories were smooth, sigmoid, with bell-shaped velocity and double-peaked acceleration (positive and negative) across all conditions, for both young and elderly subjects. An example of typical acceleration profiles can be found in Fig. 1a and b for the most fragile (high FR-index) and least fragile (low FR-index) objects moved by both young and elderly subjects. Handle acceleration rapidly increased as the handle was lifted from the table (in the first 30% of movement time) then decreased halfway through the movement. Minimum acceleration values were achieved around 60–70% of total movement time. Similar features in the total applied grip force were also found across subjects and tested fragility indices. Examples of typical total grip force profiles for the most fragile and least fragile handles moved by young and elderly subjects can be found in Fig. 1c and d.

Part I: basic kinematics

The overall magnitude of both peak handle acceleration and peak deceleration were similarly affected by age and object fragility. Hence, average absolute values of object acceleration were considered for statistical analyses. The magnitude of object acceleration was larger in young subjects as compared to elderly subjects, on average by 48% (*Age*: $F_{1.0,24.0} = 46.5$, $P < 0.001$). The magnitude of object acceleration decreased as handle fragility increased; this effect was larger in young subjects (Fig. 2a). Statistical analysis confirmed a main effect of *FR-index* ($F_{2.0,24.0} = 21.6$, $P < 0.001$) and the *Age* × *FR-index* interaction ($F_{2.0,24.0} = 4.1$, $P < 0.05$). Pair-wise Tukey tests indicated that object acceleration magnitude ($|A_Z|$) was significantly different among *FR-indices* in the following manner: $|A_Z|$ (Low FR-index) > $|A_Z|$ (Mid FR-index) $\sim |A_Z|$ (High FR-index).

Movement time showed opposite yet complementary effects compared to $|A_Z|$ with respect to subject age and object fragility. Movement time (MT) was larger for elderly subjects as compared to young subjects, on average by 18% (*Age:* $F_{1.0,24.0} = 27.3$, $P < 0.001$). MT increased on average by 19% as FR-index increased from low to high ($F_{2.0,24.0} = 17.5$, $P < 0.001$). These main effects with no interaction are illustrated in Fig. 2b. Pair-wise Tukey tests indicated that MT was significantly different among

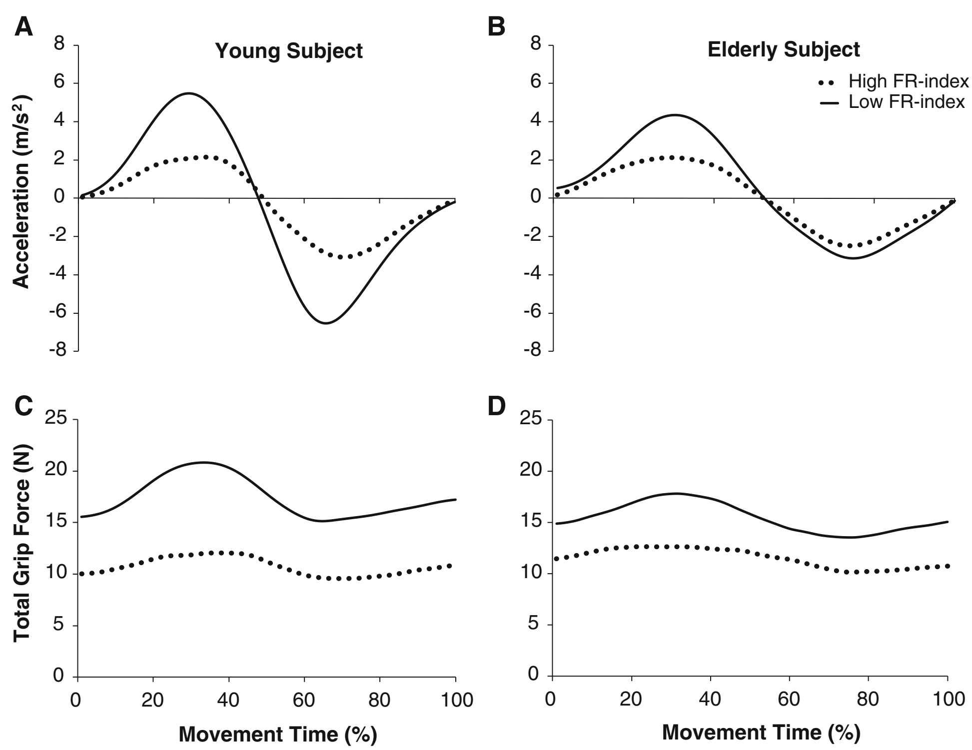

Fig. 1 Average object acceleration and total grip force profiles of a typical young and elderly subject in trials with the highest and lowest fragile settings. **a** Object acceleration for the young subject. **b** Object acceleration for the elderly subject. **c** Total grip force for the young subject. **d** Total grip force for the elderly subject

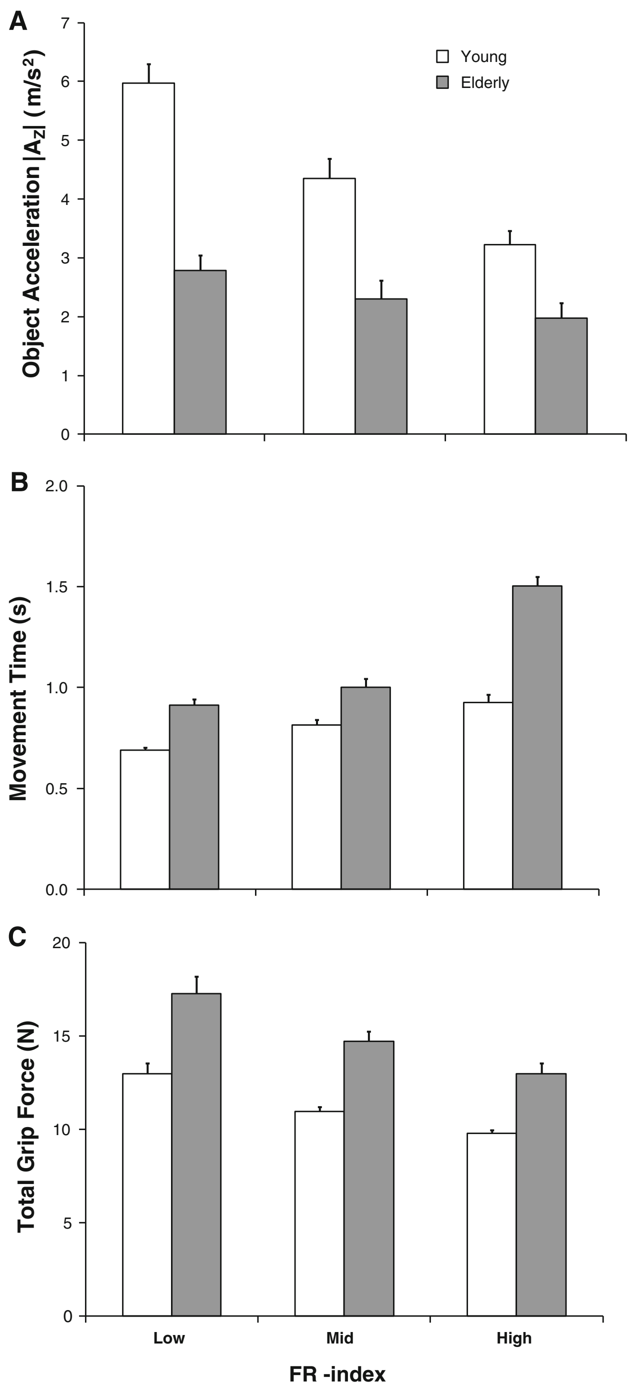

Fig. 2 Mean values (with standard errors) of the magnitude of object acceleration ($|A_Z|$), movement time (MT), and total grip force. Data are shown for the three different FR-indices for young and elderly subjects, respectively. **a** Average $|A_Z|$. **b** MT. **c** Total Grip Force

FR-indices in the following manner: MT (Low FR-index) < MT (Mid FR-index) ~MT (High FR-index).

Analysis of movement smoothness via normalized mean squared jerk (NMSJ) did not reveal age-related differences in movement smoothness; movement smoothness was also not affected by object fragility across the two age groups.

Part II: kinetics

Grip force

Overall, the average total grip force (F^G) was 13.1 ± 0.4 N across all the tested conditions and intervals. The grip forces produced by the VF and the thumb were nearly perfectly matched; on average, the VF force was 99.9% of the thumb force. Total grip force was higher in elderly subjects, on average by 33%, as compared to young subjects (*Age:* $F_{1.0,24.0} = 88.0$, $P < 0.001$); the grip force was lower when subjects handled the most fragile object (on average by 24%; *FR-index:* $F_{2.0,24.0} = 13.5$, $P < 0.001$). An illustration of these main effects can be found in Fig. 2c; no significant interactions were found. Pair-wise testing confirmed that grip forces significantly decreased as *FR-index* increased; F^G (Low FR-index) > F^G (Mid FR-index) $\sim F^G$ (High FR-index).

Slip safety margin

One of the major variables of interest, slip safety margin (SM_s), was found to be smaller in elderly subjects, on average by 21%, as compared to young subjects (*Age:* $F_{1.0,24.0} = 16.9$, $P < 0.001$). SM_s also decreased with increasing object fragility (*FR-index:* $F_{2.0,24.0} = 22.3$, $P < 0.001$). However, SM_s was lowest for the mid-fragility level in the elderly subjects, while being nearly the same for both elderly and young subjects for the most fragile object (*Age* × *FR-index:* $F_{2.0,24.0} = 6.5$, $P < 0.01$). These effects are illustrated in Fig. 3a. Pair-wise Tukey testing confirmed that on average, SM_s (Low FR-index) > SM_s (Mid FR-index) $\sim SM_s$ (High FR-index).

Crush safety margin

Crush safety margin (SM_c; the difference between the force required to crush the handle and the total grip force, normalized by the force required to crush the handle) was smaller in elderly subjects, on average by 38%, as compared to young subjects (*Age:* $F_{1.0,24.0} = 164.4$, $P < 0.001$). Additionally, average SM_c decreased by 33% as handle fragility increased (*FR-index:* $F_{2.0,24.0} = 40.9$, $P < 0.001$). The effect of handle fragility on SM_c was large in young subjects while this effect was muted in elderly subjects. Stronger modulation of grip forces (via SM_c analysis) across handle fragility settings was demonstrated by young subjects, see Fig. 3c. This interaction effect was confirmed by ANOVA, *Age* × *FR-index* ($F_{2.0,24.0} = 41.9$, $P < 0.001$). Pairwise Tukey testing indicated that SM_c (Low FR-index) > SM_c (Mid FR-index) $\sim SM_c$ (High FR-index).

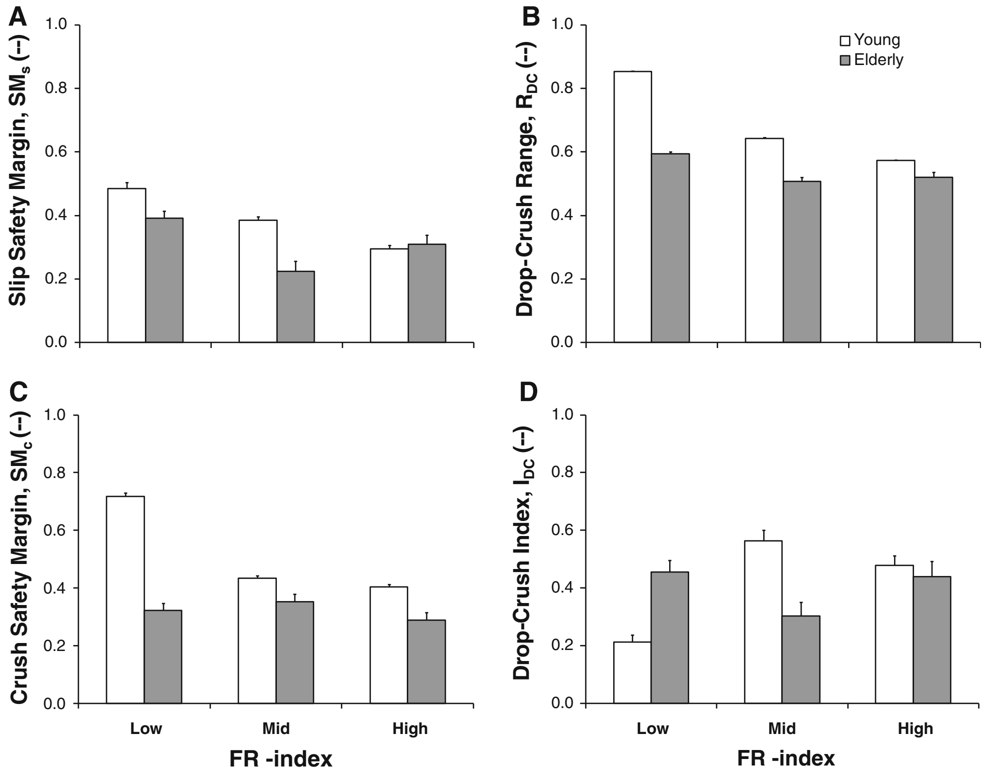

Fig. 3 Mean values (with standard errors) of slip safety margin (SM_s), crush safety margin (SM_c), the drop–crush range (R_{DC}), and drop–crush index (I_{DC}). Data are shown for the three different FR-indices for young and elderly subjects, respectively. **a** SM_s. **b** R_{DC}. **c** SM_c. **d** I_{DC}

Drop–crush range and index

We also computed two indices reflecting the combined effect of both the slip and crush thresholds on total grip force, the drop–crush range (R_{DC}) and the drop–crush index (I_{DC}). For R_{DC}, the numerator is the difference between the crush and slip thresholds of the handle and the denominator is the magnitude of the crush threshold of the handle. The R_{DC} index provides information regarding the allowable range of forces that can be applied to the handle between the crush and slip thresholds; note that it changes with the natural modulation of the load force during movements. In contrast, I_{DC} provides information regarding the amount of grip force applied to the handle above the slip threshold with respect to the total available range of grip force. For the I_{DC} index, the numerator is the difference between the total grip force and the slip threshold, and the denominator is the difference between the crush threshold and the slip threshold.

R_{DC} was lower in elderly subjects (on average, by 22%) as compared to young subjects (*Age:* $F_{1.0,24.0} = 387.1$, $P < 0.001$); R_{DC} also decreased as handle fragility increased (on average by 24%; *FR-index:* $F_{2.0,24.0} = 214.9$, $P < 0.001$). Similar to the results of SM_c, the effect of fragility on R_{DC} was larger in young subjects as compared to elderly subjects. In particular, stronger modulation of allowable grip force range (via R_{DC} analysis) across handle fragility settings was demonstrated by young subjects (Fig. 3b). The interaction effect was confirmed by ANOVA, *Age* × *FR-index* ($F_{2.0,24.0} = 64.3$, $P < 0.001$). Pair-wise Tukey contrasts indicated that R_{DC} (Low FR-index) > R_{DC} (Mid FR-index) > R_{DC} (High FR-index).

Analysis of I_{DC} indicated that this index was nearly identical at high fragility settings for the young and elderly subjects. At low- and mid-fragility indices, the young and elderly groups exhibited opposite trends in I_{DC}, as shown in Fig. 3d. In light of these results, the average effect of *Age* did not significantly affect I_{DC}, while main effects of object fragility (*FR-index*: $F_{2.0,24.0} = 6.4$, $P < 0.01$) and the *Age x FR-index* ($F_{2.0,24.0} = 15.1$, $P < 0.001$) interaction were significant. Pair-wise Tukey tests indicated that, on average, I_{DC} (Low FR-index) < I_{DC} (Mid FR-index) ~ I_{DC} (High FR-index).

Correlation between grip and load forces

Overall, the total grip force was correlated with the load force during the entire movement of the handle across all subjects and conditions; however, the strength of correlation was lower for elderly subjects ($R^2 = 0.60 \pm 0.04$) as compared to young subjects ($R^2 = 0.79 \pm 0.03$, $P < 0.005$). No effects due to object fragility were found (see Fig. 4a). The main effect of *Age* ($F_{1.0,24.0} = 10.7$, $P < 0.005$) was confirmed by a mixed-effects ANOVA on the Fisher-transformed R^2 values.

Linear regression of total grip force on total load force yielded results indicating that, given the equation $F^G = b + kF^L$, elderly subjects produced larger grip force intercepts (b) with no difference in slope of the regression equation (k) as compared to young subjects, see Fig. 4c (*Age* (b): $F_{1.0,24.0} = 16.8$, $P < 0.001$). The intercept (b) decreased as handle fragility increased in both age groups, on average by 42% (*FR-index* (b): $F_{2.0,24.0} = 12.6$, $P < 0.001$). No interactions were found. Pair-wise testing indicated that $b(\text{FR} = \text{Low}) > b(\text{FR} = \text{Mid}) \sim b(\text{FR} = \text{High})$.

Part III: synergies

The synergy index (ΔV) for the grip force was defined in such a way that positive values reflected predominantly negative covariation among the normal forces produced by the individual digits. This analysis was performed at both levels of the assumed hierarchy (VF-TH and IF levels). Overall, there were F^G stabilizing synergies ($\Delta V > 0$) at both hierarchical levels across the tested conditions [$\Delta V(F^G)_{\text{VF-TH}} = 0.84 \pm 0.02$, $t = 52.3$, $P < 0.001$; $\Delta V(F^G)_{\text{IF}} = 0.13 \pm 0.05$, $t = 2.4$, $P < 0.01$]. However, a paired t test did indicate that synergies were stronger at the higher hierarchical level. (H_0: $\Delta V(F^G)_{\text{VF-TH}} = \Delta V(F^G)_{\text{IF}}$; H_1: $\Delta V(F^G)_{\text{VF-TH}} > \Delta V(F^G)_{\text{IF}}$, $t = 12.9$, $P < 0.001$). Age-related differences in synergy indices were found only at the VF-TH level; F^G stabilizing synergy indices were larger in young subjects as compared to elderly subjects ($\Delta V(F^G)_{\text{VF-TH}}$ *Age:* $F_{1.0,24.0} = 4.4$, $P < 0.05$). No effects of object fragility were found at the VF-TH level. In contrast, at the lower (IF) hierarchical level, no significant differences between the age groups were found; however F^G stabilizing synergies emerged as object fragility increased ($\Delta V(F^G)_{\text{IF}}$ *FR-index:* $F_{2.0,24.0} = 3.8$, $P < 0.05$). The main effects of *Age* and *FR-index* on the ΔV synergy indices are illustrated in Fig. 4b and d. Note that Fisher-transformed ΔV values were subjected to ANOVA; no interactions were found.

Analysis of grip force variance

Analysis of total variance of finger forces at the IF level revealed that elderly subjects had twice as much total

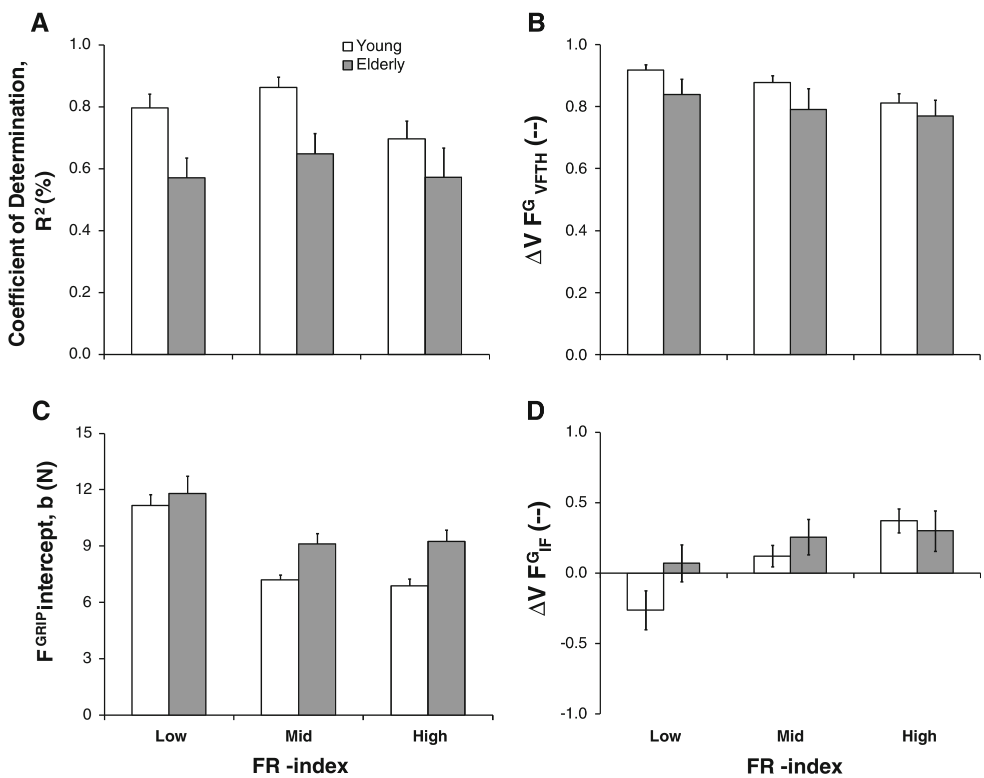

Fig. 4 Mean values (with standard errors) of the coefficient of determination (R^2, Panel **a**), force intercept (b, Panel **c**), and indices of covariation of grip forces ($\Delta V(F^G)$) at the VF-TH and IF hierarchical levels ($\Delta V(F^G_{\text{VF-TH}})$ and $\Delta V(F^G_{\text{IF}})$), Panels **b** and **d**, respectively). Data in each panel are shown for the three different FR-indices for young and elderly subjects. **a** Average coefficient of determination (R^2). **b** $\Delta V(F^G)$ at the VF-TH level. **c** Average grip force intercept (b). **d** $\Delta V(F^G)$ at the IF level

variance at the IF level as compared to young subjects across all fragility settings (*Age:* $F_{1.0,24.0} = 6.0$, $P < 0.05$). Analysis of total variance (V^{TOT}) at the VF-TH level and variance of performance (V^{P}) at both hierarchical levels did not show any significant effects of age or fragility.

Discussion

The goal of this study was to investigate age-related changes in both kinetics and kinematics of prehension while handling a fragile object. Of the three hypotheses formulated in the introduction, one has been confirmed and two have been partially falsified. This experiment has shown age-related effects on kinetic and kinematic characteristics while handling objects with different crush thresholds. In particular, elderly participants exhibited a decrease in handle acceleration paired with an increase in movement time, an increase in grip force production, and a decrease in the correlation between grip and load forces. There was a decrease in indices of multi-digit synergies at the higher level of the assumed hierarchy (VF-TH level), and an increase in individual digit grip force variability in the elderly participants as compared to young controls. In addition, the safety margin indices were lower in elderly subjects without age-related changes in movement smoothness. In the following subsections, we address implications of the main results for handling fragile and non-fragile objects in young and elderly populations.

Age effects on prehension

For this study, we intentionally selected elderly individuals who were in excellent physical condition. Despite the selected elderly sample, major differences in kinetics and kinematics were found between the young and elderly participants. Overall, elderly participants employed cautious strategies when holding and moving each of the objects used in this study. This was reflected in significantly lower object acceleration and larger movement time, and an increase in grip force magnitude. Such behavior is consistent with previous studies of elderly persons (Cole 1991; Gilles and Wing 2003; Kinoshita and Francis 1996). However, the reduction of safety margin values and grip-to-load force correlation values suggest that, while elderly subjects appear to be more cautious in handling objects, they are actually at a higher risk of damaging the object by poor grip and load force coordination. In particular, this is reflected by lower values of both slip safety margin (SM_s) and crush safety margin (SM_c). While overall grip force was higher in the elderly, causing a decrease in SM_c, the decrease in SM_s was due to the reduced coefficient of friction in elderly subjects.

The smaller values of both SM_s and SM_c may seem counterintuitive, since reductions in both values suggest an increase in the conflicting risks of dropping and crushing the object (for SM_s and SM_c, respectively). Further analysis of these competing risks was done using the drop–crush range (R_{DC}) and drop–crush index (I_{DC}). R_{DC} was used to evaluate the range of grip forces that could be applied to the object between the two risk thresholds while I_{DC} was used to directly evaluate whether the applied grip force was closer to the slip threshold or to the crush threshold. Overall, the range of grip forces between the two risk thresholds was smaller for elderly participants, a direct effect of the drop in the skin friction coefficient. The reduction of the range of forces elderly individuals can use to handle objects puts this population at an increased risk for both crushing and dropping objects as compared to young subjects. However, the decrease in I_{DC} values for elderly subjects indicates that they prefer to be at a lower risk of crushing an object even if this leads to a higher risk of dropping it.

In addition to changes in both kinetic and kinematic measures, an increase in trial-to-trial grip force variance of individual finger forces was evident in elderly participants. Such an increase in force variability likely reflects impaired neural control of the finger forces with aging; however, the relative contribution of sensory and motor factors to this decline remains unclear (Cole and Beck 1994; Cole et al. 1999; Gilles and Wing 2003; Kinoshita and Francis 1996). An increase in grip force variability coupled with weaker multi-digit synergies in the elderly (Olafsdottir et al. 2007a, b, 2008; Kapur et al. 2010a, b) suggest that the CNS shifts from a feed-forward mode of finger control to a feedback mode of control with aging (Cole 1991). This is supported by the reduction in grip and load force coupling with age, suggesting that the two types of force production are not modulated simultaneously, but, that changes in grip forces may be secondary to load force modulation (Gorniak et al. 2009a; Shim et al. 2005; Zatsiorsky and Latash 2004, 2008).

We expected to see normalized jerk values (NMSJ) to be larger in elderly individuals due to their excessive submovements, higher motor noise, and reduced perceptual efficiency documented for upper limb tasks (Cooke et al. 1989; Fradet et al. 2008; Walker et al. 1997). However, no age-related changes in NMSJ in elderly participants were found. Possibly, this was due to the selected group of elderly participants who were in a very good physical shape.

Age-related changes in synergies and possible physiological mechanisms

According to the principle of abundance (Gelfand and Latash 1998), the apparently redundant design of the neuromotor system is viewed not as a source of computational problems for the CNS, but as a powerful apparatus that allows producing stable values of important performance variables with variable, flexible combinations of elemental variables. Indices of covariation among elemental variables have been used to quantify synergies stabilizing specific performance variables (reviewed in Latash et al. 2002b, 2007). Several earlier studies documented smaller synergy indices computed with respect to task-related variables (for example, total force and total moment of force) in multi-digit tasks performed by elderly persons (Shinohara et al. 2003a, b, 2004; Shim et al. 2004; Olafsdottir et al. 2007b; Kapur et al. 2010b; Park et al. 2011). In our study, the indices of covariation stabilizing normal force quantified at the task-specific, upper level of the assumed two-level hierarchy were smaller in the elderly participants confirming the cited earlier studies.

In contrast, synergy indices at the lower level, on average, were nearly equal between the two age groups. There was a significant trend of an increase in the synergy index computed at the lower (IF) level of the hierarchy with an increase in the object fragility. There are two reasons for this phenomenon. First, when moving a non-fragile object, there is a strong constraint on the total normal force produced by the five digits: It has to be very close to zero. This constraint is reflected in highly positive synergy indices at the VF-TH level (Fig. 4b). The synergy index at the IF level is expected to be low due to the inherent trade-off between synergy indices within a hierarchical system (Gorniak et al. 2007a, b, 2009b). When moving a fragile object, two constraints are important: The total normal force of the five digits has to be close to zero and the total normal force of the four digits forming the VF has to be below the crushing threshold. The latter constraint is reflected in the positive synergy indices at the IF level, while there is a trend for the synergy indices at the VF-TH level to drop with an increase in the fragility index (compare panels B and D in Fig. 4) compatible with the idea of a trade-off between the two levels of the hierarchy.

Several studies have quantified unintended force production by non-instructed fingers (enslaving, Zatsiorsky et al. 1998, 2000) in elderly persons. They reported lower indices of enslaving in the elderly as compared to younger persons (Shinohara et al. 2003a, b; Kapur et al. 2010b). This was a much unexpected finding suggesting better individualized finger control in the elderly. Since enslaving has been attributed to a large degree to neural factors (Latash et al. 2002a; Schieber and Santello 2004), the origin of this finding may be searched for in age-associated changes within the CNS.

There are documented changes with age at different levels of the neuromotor hierarchy, from cortical neurons to alpha-motoneurons (Booth et al. 1994; Brooks and Faulkner 1994; Eisen et al. 1996; Erim et al. 1999; Dinse 2006). It is natural to expect that a decrease in the number of cortical neurons would be associated with plastic changes. Based on recent studies of the cortical organization, Marc Schieber (2001) suggested a metaphor of a cortical piano: Individual cortical neurons are recruited by inputs into the primary motor cortex (and maybe also premotor cortex) in “chords” that produce elements of meaningful coordinated muscle activations. The neuronal loss with age may force a shift from such synergic control to a more element-specific, somatotopic control. We view the combination of findings in the elderly, lower enslaving and lower synergy indices, as a reflection of a general trend of a shift from more complex, synergic control to more element-based control, possibly related to the progressive death of neurons at different levels of the neural axis.

Concluding comments

Fragility may be viewed as a rather common constraint for everyday actions that is likely to affect both patterns of digit forces and their covariation profiles. This study is a first attempt at understanding behavioral changes exhibited during fragile object manipulation as a result of physiological changes to the musculoskeletal and nervous systems that accompany healthy aging. The data presented here consistently suggest that the control of hand and finger actions, particularly the application of grip forces, changes during manipulation of fragile objects. As object fragility increases, grip forces generally drop, but not in proportion to the crush threshold of the hand-held object. Consequently, at higher indices of object fragility, participants are more likely to crush an object than to drop it. This phenomenon is common for both young and elderly persons. However, since the amount of exerted load-bearing force elderly participants produced per unit of normal force was larger than in young participants, elderly persons are actually at an increased risk of dropping fragile objects compared to young persons (confirmed by everyday observations). Thus, the trade-off between crushing and dropping an object may be a combination of both physiological and psychological factors. Further work to disambiguate the interplay between these two factors may provide a rich field to study the sensorimotor and cognitive components in the control of dexterous action.

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