NIH Public Access
Author Manuscript
Hum Mov Sci. Author manuscript; available in PMC 2013 June 01.

Published in final edited form as:
Hum Mov Sci. 2012 June ; 31(3): 502–518. doi:10.1016/j.humov.2011.07.005.

AGE EFFECTS ON ROTATIONAL HAND ACTION

Varadhan SKM[1], **Wei Zhang**[2], **Vladimir M. Zatsiorsky**[1], and **Mark L. Latash**[1]

[1]Department of Kinesiology, The Pennsylvania State University, University Park, PA 16802

[2]School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ 85287

Abstract

We investigated age-related differences in finger coordination during rotational hand actions. Two hypotheses based on earlier studies were tested: higher safety margins and lower synergy indices were expected in the elderly. Young and elderly subjects held a handle instrumented with five six-component force sensors and performed discrete accurate pronation and supination movements. The weight of the system was counterbalanced with another load. Indices of synergies stabilizing salient performance variables, such as total normal force, total tangential force, moments produced by these forces, and total moment of were computed at two levels of a hypothetical control hierarchy, at the virtual finger-thumb level and at the individual finger level. At each level, synergy indices reflected the normalized difference between the sum of the variances of elemental variables and variance of their combined output, both computed at comparable phases over repetitive trials. The elderly group performed the task slower and showed lower safety margins for the thumb during the rotation phase. Overall, the synergy indices were not lower in the elderly group. In several cases, these indices were significantly higher in the elderly than in the younger participants. Hence, both main hypotheses have been falsified. We interpret the unexpectedly low safety margins in the elderly as resulting from several factors such as increased force variability, impaired feed-forward control, and the fact that there was no danger of dropping the object. Our results suggest that in some natural tasks, such as the one used in this study, healthy elderly persons show no impairment, as compared to younger persons, in their ability to organize digits into synergies stabilizing salient performance variables.

Keywords

prehension; hand; synergy; safety margin; rotation; elderly

Introduction

A variety of physiological changes occur within the neuromotor system with advanced age (Grabiner and Enoka 1995; Levinson 1978; Welford 1984). These include reduction of muscle mass (Doherty & Brown 1997; Rogers & Evans 1993), slowing down of muscle contractions (Cole 1991; Francis & Spirduso 2000; Seidler-Dobrin et al. 1998), impairment of tactile sensitivity (Cole et al. 1999; Verillo 1979), and neuronal loss in a number of

Address for correspondence: Mark Latash, Department of Kinesiology, Rec.Hall-267, The Pennsylvania State University, University Park, PA 16802, USA, tel: (814) 863-5374, fax: (814) 863-4424, mll11@psu.edu.

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structures within the central nervous system (CNS) leading to plastic changes within the CNS (Booth et al. 1994; Brooks & Faulkner 1994; Eisen et al. 1996; Erim et al. 1999; Dinse 2006). Each of these changes may contribute to the overall decline in hand function associated with aging.

Recently, a series of studies documented changes in indices of multi-digit synergies with age (Shinohara et al. 2003a,b, 2004; Shim et al. 2004; Olafsdottir et al. 2007; Kapur et al. 2010). Within those studies, synergies were defined as co-varied (across repetitive trials) adjustments of elemental variables (forces and moments of force produced by individual digits) contributing to lower indices of variability of the variables produced by all the elements together (reviewed in Latash et al. 2007; Latash 2008, 2010). An index of synergy strength was used reflecting the amount of co-variation among elemental variables that helped reduce variability of potentially important performance variables such as total grip force, total resultant force, and total moment of force.

Most earlier studies addressed age-related changes in the characteristics of grip force during holding or manipulation of the hand-held objects. In particular, elderly persons are known to show excessive grip force magnitudes (Cole 1991; Cole & Beck 1994; Cole et al. 1999; Kinoshita & Francis 1996; Gilles & Wing 2003; Danion et al. 2007; Lindberg et al. 2009; Diermayr et al. 2010), commonly quantified as an increase in the safety margin, which is proportion of grip force above the threshold level for slippage (Johansson & Westling 1984; Burstedt et al. 1999; Pataky et al. 2004). An impairment of multi-digit synergies related to stabilization of grip force has also been documented (Shinohara et al. 2003a,b, 2004; Shim et al. 2004; Kapur et al. 2010).

Rotational hand action plays a major role in a variety of everyday actions such as taking a sip from a glass, turning a door knob, using a screwdriver, writing, etc. Indeed, in most such actions, grip forces, normal to the surface, can change within a relatively large range while the total moment of force has to be controlled precisely to avoid failure. Relatively few studies explored changes in the control of rotational hand actions with age. Two studies reported a significant impairment in the ability of elderly persons to produce accurate values or time profiles of the total moment of force associated with lower indices of corresponding multi-digit synergies (Shim et al. 2004; Olafsdottir et al. 2007). Both studies used tasks that did not require the participants to produce a rotational movement, only to hold a static position and/or apply a prescribed pattern of the total moment of force in isometric conditions.

In this study, we use a recently developed method that allows quantifying biomechanical variables and indices of synergy during accurate rotation of a hand-held object in pronation and supination (Zhang et al. 2009). Based on the cited studies of multi-digit synergies, we expected to see significantly lower synergy indices in elderly participants as compared to young ones, particular for the indices of co-variation of moments of force (Hypothesis #1). We also expected to see smaller changes in the synergy index associated with the action in the elderly group (cf. Olafsdottir et al. 2007a, 2008). In addition, based on earlier studies of safety margins (Cole 1991; Kinoshita & Francis 1996; Gilles & Wing 2003; Danion et al. 2007; Diermayr et al. 2010), we expected to observe significantly higher safety margins in the elderly participants (Hypothesis #2). We also explored possible age related changes in the documented differences between pronation and supination tasks; such differences were reported during isometric accurate moment of force production tasks for young adults (Zhang et al. 2006).

Methods

Subjects

Nine healthy young (5 males and 4 females, Mean± SE: Age: 27.3 ± 1.2 years, weight: 63.5 ± 3 kg, height: 1.71 ± 0.01 m) and nine healthy elderly volunteers (2 males and 7 females, Mean± SE Age: 77.6 ± 0.6 years, weight: 63.3 ± 1 kg, height: 1.65 ± 0.01 m) participated in the study. All participants were right-handed according to their preferred hand use for activities of daily living such as writing and eating. None of the subjects had any long term involvement with finger activities such as playing musical instruments or professional typing. All elderly participants passed a screening process that consisted of a cognition test (mini mental state exam ≥24 points), a depression test (Beck depression inventory ≤20 points), a sensory test (monofilament ≤3.22) and a general neurological examination. All participants gave informed consent according to the procedures approved by the Office for Research Protections of The Pennsylvania State University.

Apparatus

The experimental setup is illustrated in Figure 1. During the experiment, the subject sat comfortably in a height-adjustable chair facing the experimental setup. A single axis torsiometer was attached to measure the hand pronation-supination (PR-SU) angle (A_W). In the initial position, the subject was instructed to fully extend the wrist and hand joints with the palm down on the table. The end pieces of the torsiometer were attached to the midline of the dorsal surface of the hand and to the middle of the forearm. The subject's right forearm was placed into a polyvinyl chloride (PVC) forearm brace fixed to a small table. Two Velcro straps were used to prevent forearm movement in flexion-extension and abduction-adduction directions. The right upper arm was at about 45° of flexion in a sagittal plane and about 90° PR when the subject grasped a PVC handle. A 17" LCD monitor placed about 1 m from the subject displayed the task (initial and target handle orientations) and the subject's current A_W angle recorded by the torsiometer.

Digit forces were recorded by five six-component force transducers (three force and three moment of force components) mounted on the handle. A Nano-25 transducer (ATI industrial automation, NC, USA) was used for the thumb and four Nano-17 transducers (ATI industrial automation, NC, USA) were used for the four fingers. The thumb (TH) transducer was mounted opposite to the transducers for the four digits (I-Index, M-Middle, R-Ring and L-Little). The transducers were attached in such a way that the Y axes of all five transducers were parallel to the central vertical axis of the PVC handle. The TH transducer was attached such that its base was aligned with the frontal axis (z-axis) of the handle. We used 100-grit sandpaper to cover the surface of each transducer to increase friction between the digits and the contact surface of the transducers. The thirty analog signals from the transducers were digitized at 12 bit resolution (PCI – 6225, National Instruments, TX, USA) and processed by a customized LabView based program (LabView 8.0, National instruments, TX, USA).

Two copper cylinders (0.1 kg each) were attached along a diameter of a PVC disc (25 cm in diameter) at a distance of 9.5 cm from the center of the disc. This disc was connected to the handle by an aluminum rod (19 cm in length), attached through the geometric centers of both the disc and handle, perpendicular to their vertical axis. The disc, rod and handle (DRH) formed a rigid body that moved as a whole. To avoid tilt of the DRH system in the frontal and sagittal planes, two horizontal levels were attached to the DRH, parallel and orthogonal to the rod. The levels served as sources of visual feedback. The weight of the DRH system was counterbalanced with a counter-load (0.76 kg) that was hooked by a rock climbing rope through a couple of pulleys fixed to the ceiling. During the experiment, the subject did not have to counteract the weight of the DRH system; they were required only to rotate the system about the long axis of the rod.

Experimental procedure

Before each trial, the handle was vertically oriented and the sensor signals were set to zero in the absence of digit forces. One calibration trial was performed before the experimental trials. In this trial, the subject was instructed to grasp the handle in the most comfortable way and hold it in a vertical orientation for 10 s while keeping the two levels (one on the handle and the other on the disc) horizontal. The angle measured was considered to represent an A_W *of* 0°. Angles were further measured with respect to this position. The averaged A_W over the trial duration was used to set future trials. We call this most comfortable position a neutral (NE) position. The pronation (PR) and supination (SU) were defined with respect to the NE position.

The main task was to produce a rotation of the handle from an initial position to a target position (±30°). The young participants performed this task at two speeds, natural (slow, SL) and as fast as possible (fast, FA). The elderly participants were asked to perform the task only at the fast speed. The display showed the subject two thick yellow lines corresponding to 30° positive (SU) and 30° negative (PR) A_W with respect to the NE position. These lines worked either as initial or target positions depending on the task (PR and SU movements). Two horizontal dashed lines above and below the target lines showed the allowable error range (±5°). A line in-between the two yellow lines corresponded to the NE position. Two dashed vertical lines served as reminders with the first one at 1.5 s from the trial start and the second one 5 s after trial initiation. The angle A_W was shown on-line as a function of time (Figure 1).

For young participants, there were four task conditions, PR-FA, PR-SL; SU-FA and SU-SL. For elderly participants there were only two task conditions, PR-FA and SU-FA. During each trial, the subject rotated the handle from NE position to the initial position and held this position for at least 1.5 s. There was no speed or accuracy requirement for the subject during this preparatory motion. Then the subject rotated the handle at the instructed speed and direction into the target in a self-paced manner. The subject was instructed to produce a smooth motion into the target area and not to correct any inaccuracies in final position. As long as the subject stopped within the error range (±5°), the trial was accepted. Inaccurate trials were rejected and repeated. Five practice trials were given. For each condition, twenty-four successful trials were collected. In young subjects, these were performed in a single block. Elderly subjects performed two blocks, 12 trials each. There was an 8-s interval between trials and 2-min rest interval between blocks.

Data Processing

Data were processed offline using MATLAB and SPSS. The angular velocity ($\mathring{A}_W$) was computed for each trial. The initiation and termination of the movement were defined as the instances where $\mathring{A}_W$ first reached 5% of its maximal value and dropped below 5% of its maximal value in that trial. The trials were aligned by the movement onset (time zero) and time was normalized to 100 points over the movement duration. The intervals before and after the movement were not time normalized. In the following sections and illustrations, we refer to the times of movement initiation and movement termination as t = 0 and t = MT.

The coordinates of the points of digit force application with respect to the center of the transducer surface along the Y axis were computed as,

$$COP_Y = \frac{M_X}{F_Z}, \tag{1}$$

(Zatsiorsky, 2002), where COP stands for center of pressure on the transducer surface, M_X refers to the moment about the X axis and F_Z refers to the force along the Z-axis. The moment of force acting on the handle was computed with respect to the long axis of the rod.

The data analysis was performed at two levels: the individual finger level (IF) and the virtual finger–thumb (VF-TH) level. VF is an imagined digit that produces the same mechanical effect as the individual fingers combined (Arbib et al 1985; Baud-Bovy and Soechting, 2001; Shim et al. 2004). The data were quantified over three time phases, two steady-states (PRE and POS) and the movement phase (ROT) where PRE refers to a 0.5-s interval before movement initiation, ROT refers to the movement interval and POS refers to a 0.5-s interval after movement termination.

Safety margin (SM) is the amount of grip force exerted beyond what is required to prevent object slipping (Johansson & Westling 1984; Burstedt et al 1999; Pataky et al 2004); local SM was computed for the thumb as:

$$SM_{TH} = \frac{(F^N_{TH} - \left|F^T_{TH}\right| / \mu)}{F^T_{TH}} \tag{2}$$

where the superscripts N and T refer to normal and tangential forces of the thumb and μ is the coefficient of static friction between the finger and sandpaper interface. The value of μ was approximately 1.4 for young subjects (average across three earlier studies using similar sensors, Zatsiorsky et al. 2002; Aoki et al. 2006; Savescu et al. 2008) and 0.8 for older subjects (Kinoshita and Francis 1996). SM_{TH} was quantified only over the ROT phase since the weight of the object was counterbalanced, and, as a result, $F^T = 0$ during the steady-states. Prior to statistical analyses, the SM_{TH} data were subjected to Fisher's z-transformation. In the Results section, both transformed data (with error bars) and non-transformed data are presented.

To quantify multifinger synergies, we performed variance analysis described earlier (Latash et al. 2002, Zhang et al. 2009). An index of synergy (ΔV) was computed as the difference between the sum of the variances of the mechanical variables produced by individual digits and the variance of their combined output, both computed across the 24 trials for each 1% of movement duration and for each time sample of the PRE and POS phase. This variance analysis was performed at two hierarchical levels, the VF-TH level and the IF level. The index ΔV was computed for several performance variables which form the left-hand side of the following equations:

VF-TH level

$$F^N = F^N_{VF} + F^N_{TH} \tag{3}$$

$$F^T = F^T_{VF} + F^T_{TH} \tag{4}$$

$$M_{TOT} = M^N_{VF} + M^N_{TH} + M^T_{VF} + M^T_{TH} \tag{5}$$

IF Level

$$F_{VF}^{N}=F_{I}^{N}+F_{M}^{N}+F_{R}^{N}+F_{L}^{N} \quad (6)$$

$$F_{VF}^{T}=F_{I}^{T}+F_{M}^{T}+F_{R}^{T}+F_{L}^{T} \quad (7)$$

$$M_{VF}^{N}=M_{I}^{N}+M_{M}^{N}+M_{R}^{N}+M_{L}^{N} \quad (8)$$

$$M_{VE}=M_{I}^{N}+M_{M}^{N}+M_{R}^{N}+M_{L}^{N}+M_{I}^{T}+M_{M}^{T}+M_{R}^{T}+M_{L}^{T} \quad (9)$$

The superscripts refer to tangential force (T) or normal force (N). The subscripts refer to digits (I – Index, M – Middle, R – Ring, L – Little, VF – Virtual finger, TH – thumb). M_{TOT} refers to total moment of force. All moments of force were computed with respect to the long axis of the rod corresponding to the axis of instructed rotation.

The synergy index was computed for each subject and each movement phase separately. Variance of one of the variables in the left sides of the equations (3–9), a performance variable (PV), was compared to the sum of the variances of the variables in the right side of those equations, elemental variables (EVs) and then normalized by the latter value:

$$\Delta V=\frac{\Sigma Var(EVs)-Var(PV)}{\Sigma Var(EVs)} \quad (10)$$

Positive values of this index (ΔV > 0) indicate predominantly negative covariation among the EVs and may be interpreted as a synergy that stabilizes the PV. Non-positive values of ΔV indicate a lack of such a synergy. Since ΔV indices were limited by +1, to perform statistical comparisons, positive values of ΔV were transformed using Fisher's z-transformation as follows:

$$\Delta V_{Z}=0.5\ \ln\left(\frac{1+\Delta V}{1-\Delta V}\right) \quad (11)$$

To investigate age effects on the modulation of the ΔV indices during movement time, an index ($\Delta\Delta V_Z$) was computed for each performance variable. This index was computed to make the data comparable with earlier studies of ΔV modulation (Olafsdottir 2007a,b, 2008). First, $\Delta V_{Z\text{-}ST}$ was computed as mean of ΔV_Z over the time interval between 500 ms and 300 ms prior to the movement initiation. Min($\Delta V_{Z\text{-}ROT}$) and max($\Delta V_{Z\text{-}ROT}$) were computed as the minimum and maximum values of ΔV_Z during the ROT phase. The difference between $\Delta V_{Z\text{-}ST}$ and either min($\Delta V_{Z\text{-}ROT}$) or max($\Delta V_{Z\text{-}ROT}$) was used to compute $\Delta\Delta V_Z$ depending on whether ΔV decreased or increased during the ROT phase, respectively.

Statistics

Data are presented as means and standard errors. We used ANOVA with repeated measures to study such indices as peak velocity, local safety margin for the thumb, and indices of synergy (ΔV) with factors *Age* (Young and Old), *Time* (PRE, POS, and ROT), and *Direction* (PR and SU). The safety margin and ΔV indices were z-transformed prior to statistical analyses. Pairwise contrasts with Bonferroni corrections were used to explore significant effects. The data were checked for violations of sphericity and the Huynh-Feldt criterion was used to adjust the number of degrees-of-freedom when necessary. All illustrations and statistical analyses use the SL data from young subjects and the FA data of elderly unless explicitly stated otherwise.

Results

Task performance

For all tasks, an ideal performance would be a 60° rotation starting at 30° SU/PR to 30° PR/SU. Figure 2 (panels A and B) shows trajectories for typical individual trials performed by representative young and older subjects for pronation and supination conditions respectively. Note that the elderly took longer to reach the target than the young participant despite the fact that the former moved "fast" and the latter moved "at a natural speed". The same data are presented in Figures 2C and 2D after the movement time was resampled to 100 data points. In all further illustrations, we will use data after resampling.

Movement times (MT) in elderly subjects were 0.97±0.07 s and 0.86±0.08 s in PR and SU directions respectively under the "fast" instruction. In young subjects, the natural speed (SL) movement times were 0.44±0.04 s and 0.41±0.03 s in PR and SU directions respectively. These data indicate that fast (FA) actions of elderly were slower than natural speed actions (SL) of young subjects. This was supported by a two-way repeated measures ANOVA on MT with factors *Age* (2 levels: young, old) and *Direction* (PR, SU) that showed a significant main effect of *Age* ($F_{(1,16)} = 313$; $p < 0.001$). No other effect was significant. The MT difference was also reflected in different magnitudes of the peak velocity in the two groups (Figure 3A). Peak velocity in the SL actions by younger subjects was higher than in the FA actions by elderly. A two-way ANOVA, with factors *Age* and *Direction* revealed a significant main effect of *Age* ($F_{(1,16)} = 14.9$; $p < 0.01$) without other effects.

To mitigate possible influence of movement speed on age-related effects, further we compare performance of the elderly subjects during fast movements with that of young subjects during movements at natural speed. We also compared performance of both subject groups during "fast" movements. There were predictable differences in mechanical variables (such as total moment of force) following straightforward mechanics. Other age-related differences were similar to the differences between FA actions of the elderly and SL actions of the young participants.

Modulation of grip force (F_G, estimated as the normal force produced by the thumb) during movement was smaller in elderly when compared with the younger participants. The modulation was quantified using peak-to-peak change in F_G during the ROT phase in each subject for each trial and condition separately. This modulation was higher for SU movements as compared to PR movements. Figure 3B illustrates the peak-to-peak change in grip force during the ROT phase, averaged across trials and subjects (within each group) for each direction. These observations were supported by a two-way ANOVA with factors *Age* and *Direction* on peak-to-peak F_G during the movement. The ANOVA showed significant main effects of *Age* ($F_{(1,16)} = 6.8$; $p < 0.05$) and *Direction* ($F_{(1,16)} = 6.2$; $p < 0.05$) without a significant interaction. We also compared F_G during steady-states. During PRE, we found that the average grip force was 5.4 ± 1 N in young subjects and 7.2 ± 1.3 N in elderly subjects. This difference, however, was not statistically significant. During POS, we found that the average grip force was 6.6 ± 1.4 N in young and 7.9 ± 1.2 N in elderly subjects. This difference was also not statistically significant.

Safety Margin

Local safety margin for the thumb (SM_{TH}) was quantified as the amount of normal thumb force exerted beyond what was necessary to prevent object slipping given the magnitude of the thumb tangential force (see Methods). SM_{TH} values were computed for each subject, each condition, each trial, and at each time sample of the ROT phase. Overall, elderly subjects showed lower SM_{TH} values as compared to the younger subjects. Lower SM_{TH} values were observed during PR movements. These findings are illustrated in Figure 4, which shows SM_{TH} values averaged over the ROT phase for the young and elderly groups before (panel A) and after (panel B) z-transformation. The effects of *Age* ($F_{(1,16)} = 4.7$; $p < 0.05$) and *Direction* ($F_{(1,16)} = 6.9$; $p < 0.05$) on z-transformed SM_{TH} values were significant according to a two-way ANOVA. None of the other effects were significant.

Synergy Analysis

Multi-digit synergies were quantified using an index (ΔV), which was computed as the normalized difference between sum of the variances of elemental variables and variance of the overall output of the system at each of two levels of hierarchy, the VF-TH level or IF level.

Synergy indices at the VF-TH level—Synergies at the VF-TH level were quantified using ΔV index for total moment of force (M_{TOT}), total normal force (F^N) and total tangential force (F^T). For all three performance variables, the ΔV indices were positive during PRE and POS phases. Overall, the ΔV index for M_{TOT} was higher in the elderly than in the young group. For F^N, we found that ΔV was lower in the elderly than in the young group, and for F^T no differences were found between the groups.

The ΔV time profiles computed for M_{TOT} at the VF-TH level ($\Delta V\_M_{VF\text{-}TH}$) averaged across subjects are shown in Figure 5A. The initially positive ΔV drops down to about zero in the elderly group and to negative values in the young group during movement (ROT), and then it increases back to positive values during the POS phase. These observations were confirmed by a three-way ANOVA on $\Delta V\_M_{VF\text{-}TH}$ with factors *Age, Time* (3 levels: PRE, ROT, POS) and *Direction*. There was a significant main effect of *Age* ($F_{(1,16)} = 6.9$; $p < 0.05$) corresponding to higher $\Delta V\_M_{VF\text{-}TH}$ in the elderly. *Time* effect was also significant ($F_{(1.62,\ 25.86)} = 58.8$; $p < 0.01$), corresponding to lower $\Delta V\_M_{VF\text{-}TH}$ during ROT than during PRE or POS ($p < 0.01$). Due to the larger drop in $\Delta V\_M_{VF\text{-}TH}$ during ROT in the young subjects, the interaction *Age* × *Time* was also significant ($F_{(1.62,\ 25.86)} = 9.7$; $p < 0.01$).

The time profiles of ΔV indices for the normal force ($\Delta V\_F^N{}_{VF\text{-}TH}$) averaged across subjects are presented in Figure 5B. In both groups and in both conditions, the ΔV indices remained positive at both steady-states and during the movement. A three-way ANOVA on $\Delta V\_F^N{}_{VF\text{-}TH}$ with factors *Age, Time* and *Direction* showed a significant main effect of *Age* ($F_{(1,16)} = 14.4$; $p < 0.01$) corresponding to lower ΔV in the elderly. There was also a significant main effect of *Time* ($F_{(1.635,\ 26.16)} = 5.9$; $p < 0.05$) corresponding to lower ΔV in the PRE phase than in the POS phase ($p<0.01$). The interaction *Age* × *Time* was also significant ($F_{(1.635,\ 26.16)} = 4.1$; $p < 0.05$) reflecting the fact that ΔV decreased during ROT in elderly whereas it increased in young subjects ($F_{(1,\ 16)} = 6.2$; $p < 0.05$).

The time profiles of ΔV indices for the tangential force ($\Delta V\_F^T{}_{VF\text{-}TH}$) averaged across subjects are presented in Figure 5C. The ΔV indices remained positive throughout the movement. There was large variability across subjects in the ΔV profiles resulting in no significant effects in the three-way ANOVA with factors *Age, Time* and *Direction*.

Synergy indices at the IF level—At the IF level, ΔV indices were computed for variables produced by the virtual finger. Overall, ΔV indices for F^N and M were higher in the elderly than in the young group. We also found that ΔV indices for F^T, M^N and M were lower during the ROT phase than during the PRE or POS phases.

Time profiles of ΔV indices at the IF level for F^N ($\Delta V\_F^N_{IF}$) and F^T ($\Delta V\_F^T_{IF}$) are presented in Figures 6A and 6B. Note that $\Delta V\_F^N_{IF}$ is negative in all conditions and in all phases in both groups. In contrast, $\Delta V\_F^T_{IF}$ is positive during the PRE and POS phases but goes to negative values during the ROT phase in the younger subjects.

A three-way ANOVA on $\Delta V\_F^N_{IF}$ with factors *Age, Time* and *Direction* showed a significant main effect of *Age* ($F_{(1,16)} = 19.5$; $p < 0.01$) corresponding to a higher ΔV in elderly subjects than in young subjects. There was also a significant main effect of *Time* ($F_{(1.66, 26.63)} = 6.69$; $p < 0.01$) corresponding to a higher ΔV in ROT than POS phase ($p<0.001$). The interaction *Time* × *Direction* was also significant ($F_{(1.81, 28.99)} = 6.69$; $p < 0.01$) reflecting the fact that ΔV increased during ROT in PR whereas it decreased during ROT in SU ($F_{(1,16)} = 9$; $p < 0.01$).

A three-way ANOVA on $\Delta V\_F^T_{IF}$ with factors *Age, Time* and *Direction* showed a significant main effect of *Time* ($F_{(1.66, 26.63)} = 6.69$; $p < 0.01$) corresponding to a lower ΔV in the ROT phase than in the PRE and POS phases ($p<0.01$). The interaction *Time* × *Direction* was significant ($F_{(1.75, 28.07)} = 5.38$; $p < 0.05$) corresponding to a higher drop in ΔV during ROT in PR direction when compared with SU direction ($F_{(1,16)} = 9$; $p < 0.01$). The interaction *Age* × *Time* was also significant ($F_{(2, 32)} = 7.5$; $p < 0.01$) reflecting a larger change in ΔV during ROT in younger subjects when compared with elderly ($F_{(1,16)} = 14.4$; $p < 0.01$)

Figures 6C and 6D present the ΔV indices for M^N ($\Delta V\_M^N_{IF}$) and for M (ΔV_M_{IF}) for the two groups. The data are averaged across subjects within each group. The two ΔV profiles look similar in that they both start with positive values and drop to zero (in elderly) or become negative (in young) during ROT and then recover to positive values during POS.

A three-way ANOVA on $\Delta V\_M^N_{IF}$ with factors *Age, Time*, and *Direction* revealed a significant main effect of *Time* ($F_{(2,32)} = 5.59$; $p < 0.01$) corresponding to a lower ΔV during ROT than during PRE or POS. In addition, the interaction *Time* × *Age* was significant ($F_{(2,32)} = 4.37$, $p < 0.05$) corresponding to a larger drop in ΔV during ROT in young than elderly ($F_{(1,16)} = 6$; $p < 0.05$). The interaction *Time* × *Direction* was also significant ($F_{(2,32)} = 5.99$; $p < 0.01$) reflecting a larger change in ΔV during ROT phase in SU direction when compared with PR direction ($F_{(1,16)} = 14.6$; $p < 0.01$).

A three-way ANOVA on ΔV_M_{IF} indices with factors *Age, Time*, and *Direction* revealed a significant main effect of *Age* ($F_{(1,16)} = 4.64$, $p < 0.05$) corresponding to a higher ΔV in the elderly. There was also a significant main effect of *Time* ($F_{(1.583,25.334)} = 47.8$, $p < 0.01$) corresponding to lower ΔV during ROT than during PRE or POS ($p<0.01$). The interaction *Time* × *Age* was significant ($F_{(1.583,25.334)} = 11$, $p < 0.01$) corresponding to a larger drop in ΔV during ROT in young than elderly ($F_{(1,16)} = 14.4$; $p < 0.01$).

Modulation of the index of synergy—To study the modulation of the synergy index ΔV during movement, we computed an index $\Delta\Delta V_Z$ for each performance variable separately (see Methods). Overall, we found that ΔV modulation ($\Delta\Delta V_Z$) was lower in the elderly group as compared to the younger group for the following performance variables: Total moment of force, total tangential force produced by the VF, moment produced by the normal force and total moment of force of the VF.

Figure 7A presents $\Delta\Delta V_Z$ computed for the performance variables M_{TOT}, F^N and F^T at the VF-TH level. Note higher $\Delta\Delta V_Z$ in the young group than in the elderly group for M_{TOT}. This observation was confirmed by a two-way ANOVA on $\Delta\Delta V_Z$ for M_{TOT} with factors *Age* and *Direction* that showed a significant main effect of *Age* ($F_{(1,16)} = 23$, $p < 0.001$) with no other significant effects. Similar two-way ANOVA on $\Delta\Delta V_Z$ for F^N and for F^T did not show any significant effect.

Figure 7B presents $\Delta\Delta V_Z$ for F^N, F^T, M^N and M_{TOT} at the IF level. The indices are higher for the young subjects. These differences were statistically significant for three of these variables: F^T, M^N and M_{TOT}. Two-way ANOVA with factors *Age* and *Direction* on $\Delta\Delta V_Z$ for F^N showed no significant effects. In contrast, two-way ANOVAs showed a significant effect of *Age* on F^T ($F_{(1,16)} = 17.4$, $p < 0.01$), M^N ($F_{(1,16)} = 8.2$, $p < 0.01$) and M_{TOT} ($F_{(1,16)} = 20$, $p < 0.001$). In each of these ANOVAs, no other effect was significant.

DISCUSSION

Both main hypotheses formulated in the Introduction have been falsified in the experiment. With respect to Hypothesis-1, synergy indices, ΔV were overall not smaller in the elderly participants, and some of them were even significantly higher in the elderly group as compared to the young group. These results look opposite to those reported in earlier studies (Shinohara et al. 2003a,b, 2004; Shim et al. 2004; Olafsdottir et al. 2007; Kapur et al. 2010). Hypothesis-2 was also falsified: Despite earlier reports (Comaish & Bottoms 1971; Cole 1991; Kinoshita & Francis 1996), the elderly subjects in our study did not show significantly higher safety margin values for the thumb. Their local safety margin values were in fact lower than those in the younger participants. Further we discuss implications of these unexpected findings for changes in the control of prehensile actions with aging.

Age-related changes in multi-digit synergies

As in earlier studies (reviewed in Latash et al. 2007), we quantified co-varied adjustments of elemental variables at two levels of the assumed hierarchy (Arbib et al. 1985; Mackenzie and Iberall 1994): At the upper level, the task is shared between the actions of the thumb and virtual finger (TH-VF level), while at the lower level the VF action is shared among the individual finger actions (IF level). Several recent studies documented a trade-off between synergies at two levels of a hierarchical system (Gorniak et al. 2007a,b; 2009). In particular, those studies reported high synergy indices at the upper level of the hierarchy and low (not different from zero) synergy indices at the lower level. Compared to the young participants, elderly participants in our study showed lower synergy indices for the normal force, F^N at the upper level of the hierarchy (VF-TH), a finding similar to earlier reports (Shim et al. 2004; Shinohara et al. 2003a,b). This result in combination with the mentioned trade-off between synergies at the two levels may be the reason why the elderly group showed higher synergy indices for F^N at the lower level (IF).

One of the most surprising results is the higher synergy indices computed for the moment of force in the elderly participants at both levels of the hierarchy. This result is opposite to the earlier reports of lower synergy indices computed with respect to the total moment of force in the elderly persons (Shim et al. 2004; Olafsdottir et al. 2007). In both earlier studies, the synergy indices were computed at the IF level. There is, however, a major difference between the earlier studies and the current one: The previous studies used static tasks that required accurate moment of force production. In the current study, moment of force values were not prescribed but rather accompanied the performance of a relatively natural task of accurate objects rotation. So, we attribute the difference in the findings to the difference in the tasks. Indeed, elderly persons need more practice to improve performance in novel tasks (Etnier & Landers 1998; Marchal-Crespo et al. 2010), and they are impaired in visual tracking and visuomotor processing necessary for correcting salient mechanical variables based on movements of a cursor on the screen (Moschner & Baloh 1994; Ofori et al. 2010). In our experiment, the feedback on the screen was only used to set movement targets while

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the movements were natural and could be produced using natural proprioceptive and visual feedback as in everyday rotational hand actions.

This study is the first to quantify indices of synergies with respect to the load-resisting tangential force in young and elderly persons. At both levels of analysis, we did not find significant differences between the two groups.

Overall, the results suggest that effects of age on multi-digit synergies reported earlier might have been to a large degree due to the nature of artificial laboratory tasks. In more natural tasks, such as the one used in this study, healthy elderly persons show no obvious impairment, as compared to younger persons, in their ability to organize digits into synergies stabilizing salient performance variables. One has to exercise caution generalizing conclusions based on observations of age-related differences in artificial laboratory tasks to everyday motor performance.

Adjustments in grip force and chain effects in the elderly

Another unexpected finding that might be related to the nature of our task is the lower local safety margin values in the elderly participants as compared to the younger ones. Indeed, this observation contrasts increased safety margins in elderly persons reported in several earlier studies (Cole 1991; Kinoshita & Francis 1996; Gilles & Wing 2003; Danion et al. 2007; Diermayr et al. 2010). Note that the weight of the handle in our experiment was counterbalanced, and the subjects did not have to grip it strongly to counteract the force of gravity (we did this to avoid fatigue). So, gripping the object was not necessary at steady-states, and there was no danger of dropping the object. Grip force was required during the movement to allow the production of tangential forces generating an important component of the total moment of force acting on the handle (cf. Zatsiorsky et al. 2002).

We did not measure friction coefficients for individual subjects to shorten the duration of the experiment and avoid fatigue and subject dropout. This is definitely a shortcoming of the design. To test how sensitive this result is to the assumed magnitudes of the friction coefficients, we assumed for both groups the coefficients reported by Kinoshita and Francis (1996) and reprocessed the data. On average, safety margin values remained higher in the young group than in the elderly group (1.56 ± 0.06 vs. 1.44 ± 0.06 after z-transformation), although the difference between the two groups dropped under the level of statistical significance.

To offer an interpretation, we would like to borrow the notion of chain effects from earlier studies of prehension (reviewed in Zatsiorsky & Latash 2008; Latash & Zatsiorsky 2009). A chain effect is a sequence of cause-consequence links resulting in a non-trivial association between variables.

The age-associated changes in the neuromuscular apparatus (Welford 1984; Grabiner & Enoka 1995) result in higher force variability (Shinohara et al. 2003a; Shim et al. 2004; Sosnoff & Newell 2006). When a person holds an object in the field of gravity, not dropping the object is a major priority and, in the face of increased force variability, elderly persons show higher safety margins to ensure that the grip force never drops below the critical value. When the hand-held object is moved, the inertial forces require higher grip forces, and such grip adjustments are generated in a feed-forward fashion (Flanagan & Wing 1993, 1995). Elderly persons, however, are known to show impairments in feed-forward control of action (Woollacott et al. 1988; Gilles & Wing 2003; Danion et al. 2007; Olafsdottir et al. 2008). Several outcomes may be expected. First, elderly persons may be expected to move slower to decrease the inertial forces. Second, their modulation of grip force during movement may be expected to be smaller, supported by our observation of the smaller amplitude of grip force change during the action as compared to the younger participants. Third, to be able to move objects without dropping, elderly persons have to apply higher normal forces prior to movement. All three predictions correspond to differences between the young and elderly participants in our study, although some of the relevant comparisons were under the level of statistical significance.

Movement kinematics and changes in prehension synergies

In this study we define motor synergies, including prehension synergies, as patterns of co-variation of elemental variables stabilizing a performance variable to which the elemental variables contribute. A number of hypotheses have been offered for synergic co-variation of elemental variables ranging from optimal feedback control (Todorov & Jordan 2002) to short-loop back-coupling (Latash et al. 2005) and to purely feed-forward mechanisms (Goodman & Latash 2006). Recently, the idea of synergies has been merged with the framework of the equilibrium-point (referent configuration, Feldman & Levin 1995) hypothesis, assuming a hierarchical control system with feedback loops at each level of the hierarchy (Martin 2009; Latash 2010a,b).

Several earlier studies explored the dependence of finger force variance on the magnitude and rate of force change (Latash et al. 2002; Goodman et al. 2005; Friedman et al. 2009; SKM et al. 2010). Those studies used the framework of the uncontrolled manifold (UCM) hypothesis (Scholz & Schöner 1999; reviewed in Latash et al. 2002, 2007), which allows to quantify two components of variance measured at the level of elemental variables, "good variance" (or variance within the UCM, V_{UCM}) that does not affect a potentially important performance variable, and "bad variance" (or variance orthogonal to the UCM, V_{ORT}) that does. Those studies have shown, in particular, that V_{UCM} changes in proportion to the magnitude of force while V_{ORT} shows a close to linear increase with the rate of force change.

In our experiment, the elderly participants moved much slower than the young ones despite the fact that the former were instructed to move fast and the latter – to move at a natural speed. The difference in the movement speed was naturally associated with different rates of change in all the main mechanical variables. This is the likely cause of the much stronger modulation of the synergy indices during the movement in the younger participants. Note that at the upper level of the assumed hierarchy (VF-TH), the synergy indices computed for F^N dropped during the movement, as compared to the steady-states. This result confirms previous reports (Shim et al. 2005; Gorniak et al. 2010; SKM et al. 2010) and fits the model of Goodman and colleagues (Goodman et al. 2005). At the lower level of the hierarchy (IF), however, the synergy index for F^N increased during the movement. This atypical behavior was likely related to the mentioned trade-off between synergy indices at the two levels: It followed the drop in the synergy index for F^N at the VF-TH level (for a more detailed explanation see Gorniak et al. 2007b).

An opposite behavior was observed for the synergy indices computed for F^T. This observation confirms the earlier reports by Gorniak et al. (2009). In the study of Gorniak and her colleagues, this finding was associated with an important role of F^T in producing the total moment of force. Indeed, at the VF-TH level, stabilization of the moment of force generated by the tangential forces (M^T) requires positive co-variation of the forces produced by the thumb and VF. Stabilization of F^T requires negative co-variation of those forces. So, the system can stabilize only one of those two variables, F^T or M^T. In our experiment, the emphasis was on producing accurate object rotation while the weight of the object was counter-balanced. This was the likely reason for the higher ΔV indices for F^T at the VF-TH level during the movement as compared to the steady-states. The mentioned trade-off between the hierarchical levels resulted in lower ΔV for F^T at the IF level.

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Concluding comments

The main conclusion of our study is: Elderly persons are not as impaired in certain indices of motor performance as earlier studies suggest (cf. Lowe 2001). They may employ more cautious motor strategies to adjust to the physiological changes within the neuromotor system (such as moving slower), but we failed to observe any impairments that would go beyond direct consequences of being cautious. In a recent study (Kapur et al. 2010), the authors suggest that aging may be associated with a shift from synergic control to element-based control due to the death of cortical neurons (Eisen et al. 1996) leading to a disruption of hypothetical synergic intracortical links (Schieber 2001) that facilitate co-varied adjustments of elemental mechanical variables. This may be true. However, our current results suggest that the observed patterns of mechanical variables and their co-variation may depend strongly on particular features of the task, and more artificial tasks may be more likely to reveal those.

Research Highlights

- During free rotation of a hand-held object, elderly persons move slower;
- In such tasks, elderly persons show lower safety margin values;
- Indices of multi-digit synergies are not always decreased in the elderly;
- Results reflect increased force variability and impaired feed-forward control.

Acknowledgments

The study was in part supported by NIH grants AG-018751, NS-035032, and AR-048563. The authors are thankful to the staff and participants at Foxdale Village and The village at Penn State (State College, PA) for their cooperation and participation. The screening of elderly subjects was conducted at the General Clinical Research Center (The Pennsylvania State University).

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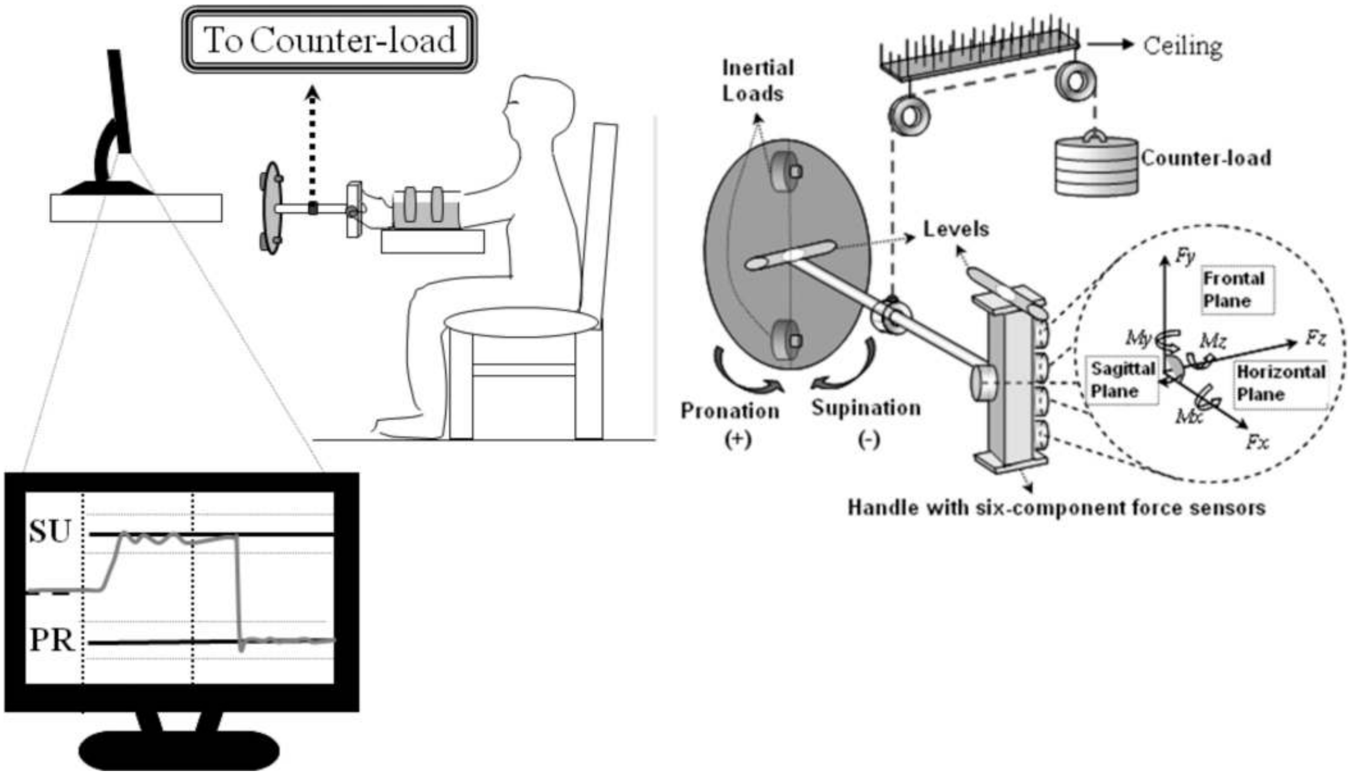

Figure 1.

Experimental setup: The subject sat in a height adjustable chair with the right forearm placed into a polyvinyl chloride (PVC) forearm brace fixed to a small table. A 17-inch LCD monitor placed about 1 m from the subject displayed the initial and target handle orientations and the subject's current pronation-supination angle recorded by the torsiometer fixed to the subject's right hand. Digit forces and moments were recorded by five six-component force sensors mounted on a PVC handle. This handle was connected to a disc with inertial loads through an aluminum rod. The weight of this entire disc, rod and handle (DRH) system was counter-balanced by a counter-load that was hooked by a rope through pulleys attached to the ceiling.

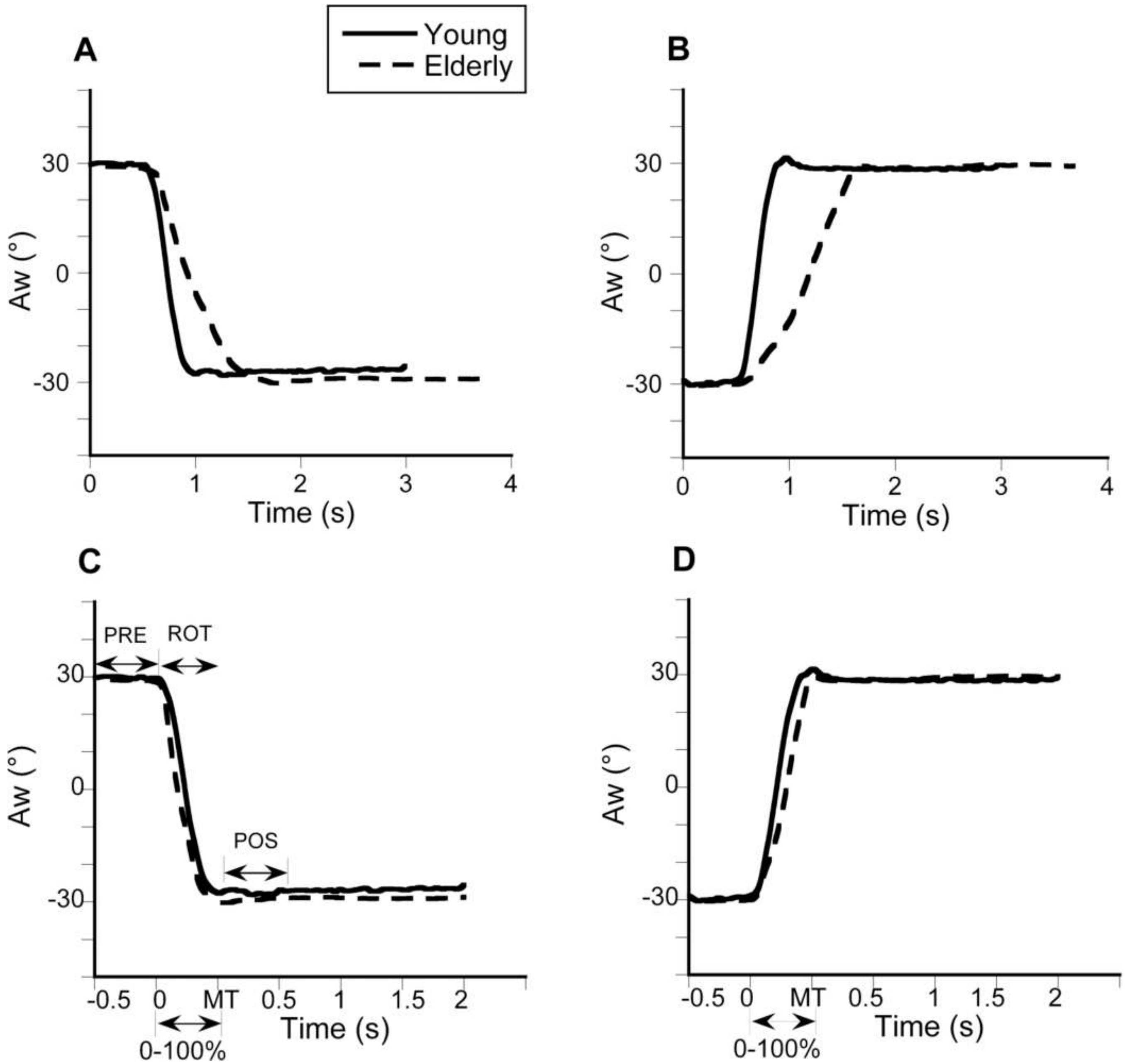

Figure 2.
Movement angle (A_w) plotted against time in a typical trial by representative young (solid line) and elderly participants (dashed line). A: Pronation (PR) movement; B: Supination (SU) movement; C: PR with movement time resampled to 100 points (represented as 0–100% between 0 and movement time (MT) D: SU with movement time resampled to 100 points. Note that elderly take longer to reach the target while there is no obvious change in the time-normalized trajectory. The steady states (PRE, a 0.5-s interval before movement initiation and POS, a 0.5-s interval after movement termination) and movement phase (ROT) are illustrated in panel C.

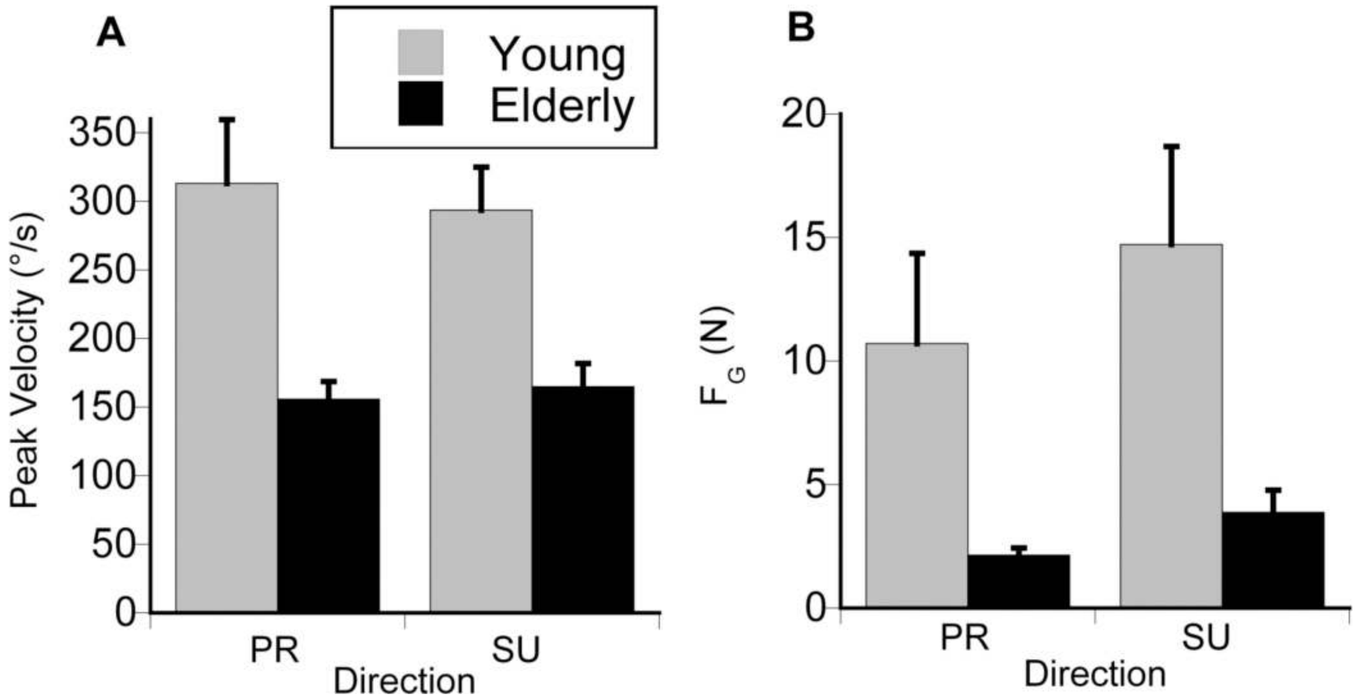

Figure 3.

A: Peak velocity in pronation (PR) and supination (SU) for young (light bar) and elderly (dark bar) groups; means over subjects are shown with standard errors. Peak velocity is lower in the elderly participants despite the fact that the elderly were instructed to move "fast" and the younger participants were asked to move "at a natural speed".

B: Peak-to-peak grip force (F_{GRIP}) for the pronation (PR) and supination (SU) tasks for the young (light bars) and elderly (dark bars) participants; means over subjects are shown with standard errors. F_{GRIP} modulation during movement was lower in the elderly participants.

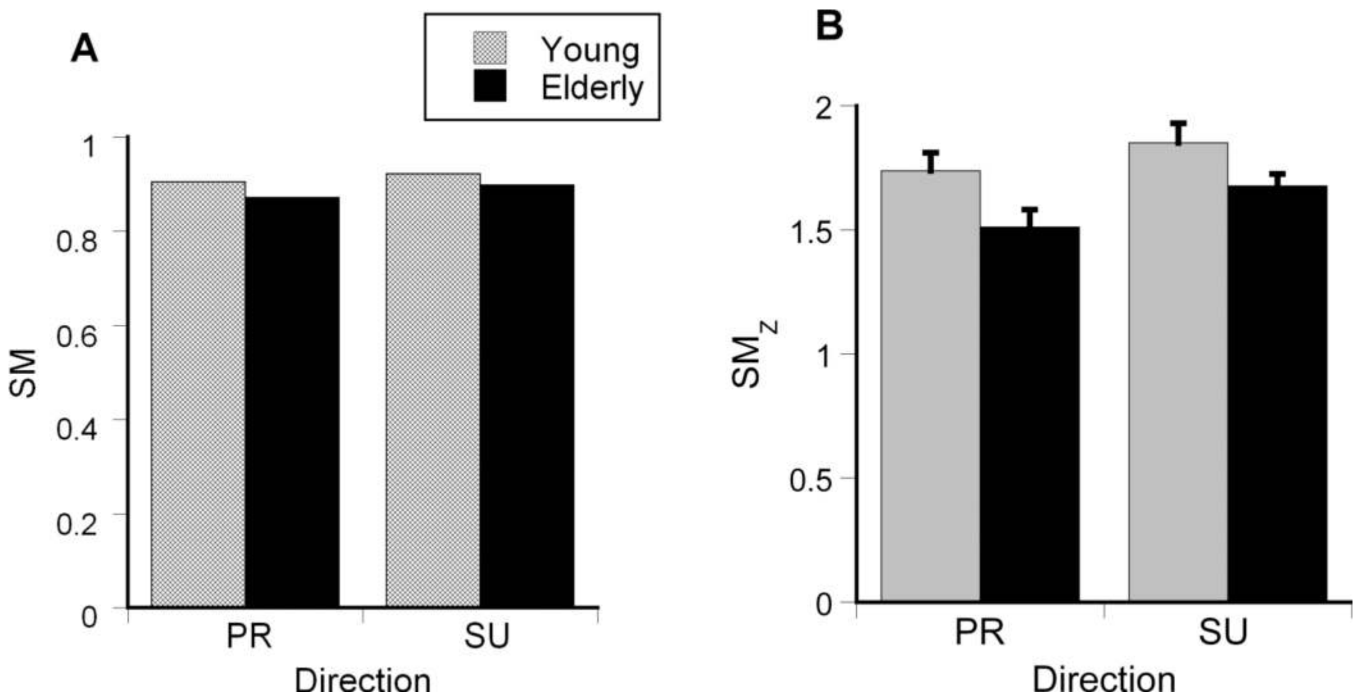

Figure 4.

A: Local safety margin for the thumb (SM_{TH}) for the pronation (PR) and supination (SU) tasks for the young (light bars) and elderly (dark bars), averaged across groups. **B:** *z*-transformed SM_{TH} (SM_z); means over subjects are shown with standard error bars. Note the higher SM_{TH} in SU than in PR and in the young than elderly groups.

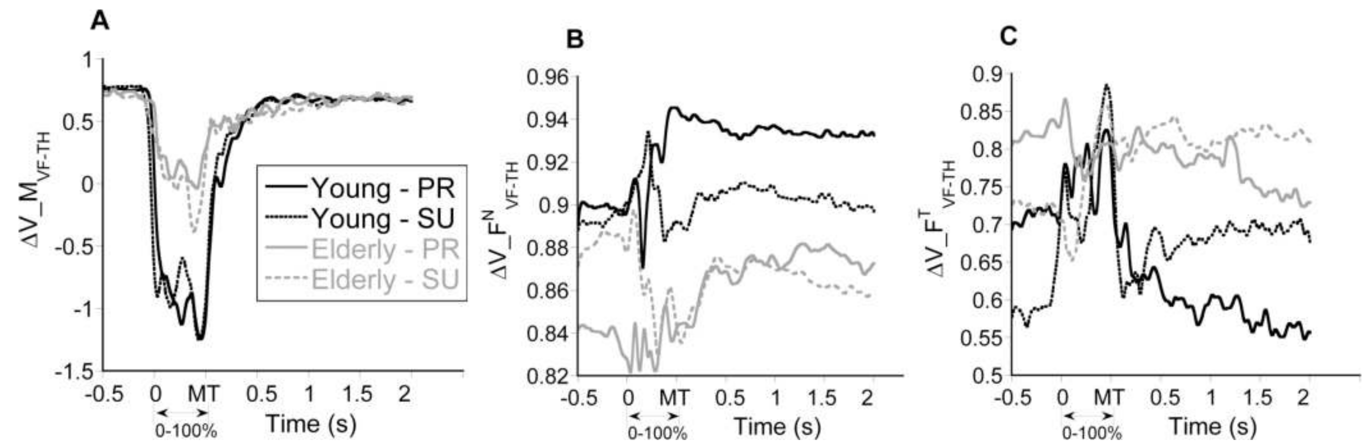

Figure 5.

Time profiles of synergy indices (ΔV) at the virtual finger-thumb (VF-TH) level averaged across participants for the young (dark lines) and elderly (light lines) groups for the pronation (PR – solid lines) and supination (SU – dotted/dashed lines) tasks. **A:** ΔV for the resultant moment of force (ΔV_M_{VF-TH}). The drop in ΔV is lower in the elderly during the ROT phase. **B:** ΔV for total normal force at the VF-TH level ($\Delta V\_F^{N}{}_{VF-TH}$). ΔV is lower for the elderly. **C:** ΔV for total tangential force at the VF-TH level ($\Delta V\_F^{T}{}_{VF-TH}$).

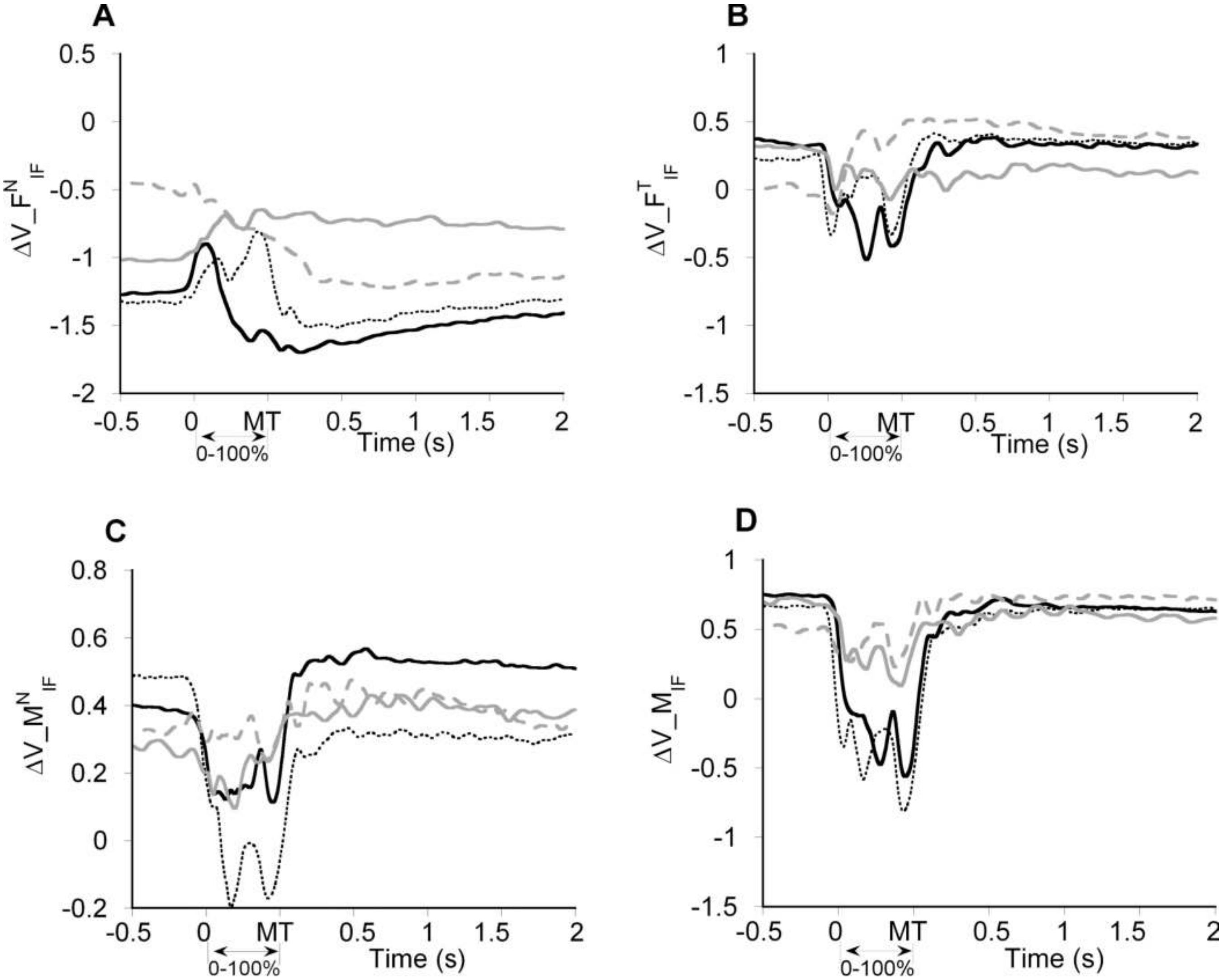

Figure 6.

Time profiles of synergy indices (ΔV) at the individual finger (IF) level averaged across subjects for the young (dark lines) and elderly (light lines) groups for the pronation (PR) and supination (SU) tasks. **A:** ΔV for the normal force $\Delta V\_F^{N}_{IF}$). **B:** ΔV for the tangential force ($\Delta V\_F^{T}_{IF}$). **C:** ΔV for the moment produced by normal force ($\Delta V\_M^{N}_{IF}$). **D:** ΔV for the moment produced by total force (ΔV_M_{IF})

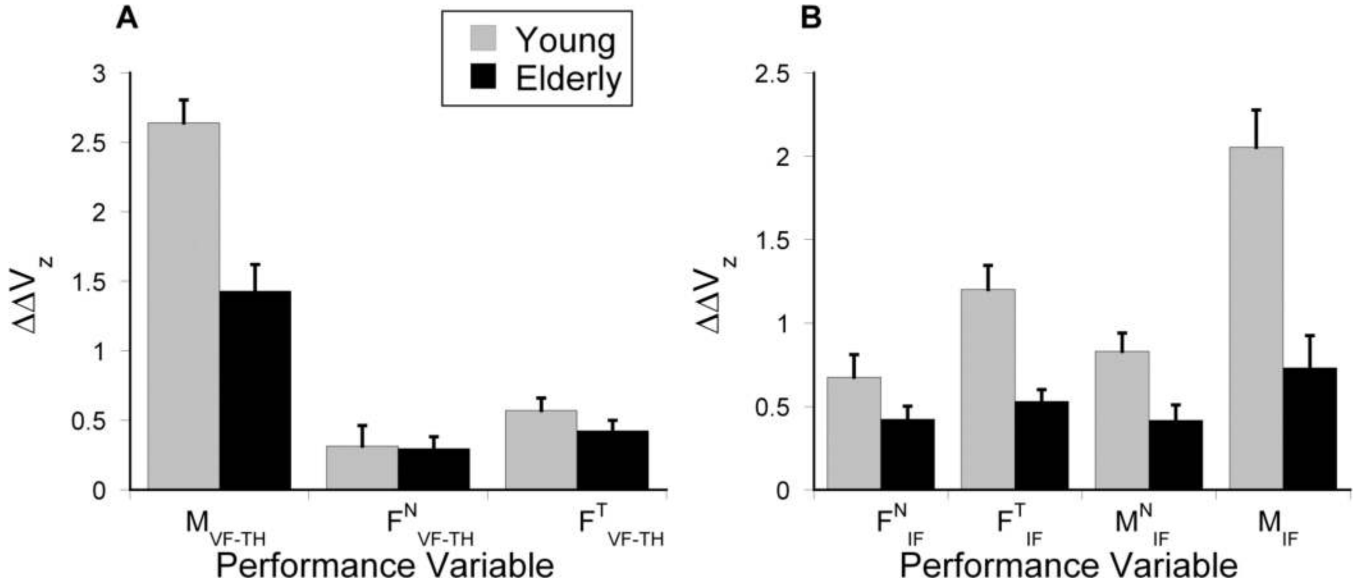

Figure 7.
Modulation of the synergy index ΔV ($\Delta\Delta V_Z$) in the young (light bar) and elderly (dark bar) groups; means over subjects are shown with standard errors. **A:** $\Delta\Delta V_Z$ for total moment, total normal force and total tangential force at the VF-TH level. $\Delta\Delta V_Z$ is higher in young than elderly for total moment. **B:** $\Delta\Delta V_Z$ for total normal force, total tangential force, moment due to normal force and moment due to total force at the IF level. $\Delta\Delta V_Z$ is higher in young than elderly for total tangential force, moment due to normal force and moment due to total force.