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Age-related changes in finger coordination in static prehension tasks

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Abstract

We studied age-related changes in the performance of maximal and accurate submaximal force and moment production tasks. Elderly and young subjects pressed on six dimensional force sensors affixed to a handle with a T-shaped attachment. The weight of the whole system was counter-balanced with another load. During tasks that required the production of maximal force or maximal moment by all of the digits, young subjects were stronger than elderly. A greater age-related deficit was seen in the maximal moment production tests. During maximal force production tests, elderly subjects showed larger relative involvement of the index and middle fingers; they moved the point of thumb force application upward (toward the index and middle fingers), whereas the young subjects rolled the thumb downward. During accurate force/moment production trials, elderly persons were less accurate in the production of both total moment and total force. They produced higher antagonistic moments, i.e., moment by fingers that acted against the required direction of the total moment. Both young and elderly subjects showed negative covariation of finger forces across repetitions of a ramp force production task. In accurate moment production tasks, both groups showed negative covariation of two components of the total moment: those produced by the normal forces and those produced by the tangential forces. However, elderly persons showed lower values of the indexes of both finger force covariation and moment covariation. We conclude that age is associated with an impaired ability to produce both high moments and accurate time profiles of moments. This impairment goes beyond the well-documented deficits in finger and hand force production by elderly persons. It involves worse coordination of individual digit forces and of components of the total moment. Some atypical characteristics of finger forces may be viewed as adaptive to the increased variability in the force production with age.

Keywords

force; moment; human

AGING LEADS TO A DECLINE IN hand dexterity and strength (2,14,15,18,19,32). This is associated with changes in the neuro-muscular apparatus such as a drop in the number of motor units, an increase in the size of the motor units, and a general slowing down of their contractile properties (3,11,12,20,22,30). In our previous studies, we have shown that these peripheral changes are accompanied by changes in indexes of finger interaction during multifinger force production tasks (36–38). These changes were correlated with the drop in the maximal voluntary contraction (MVC) force with age. The changes were more pronounced when the subjects produced MVC forces at the proximal phalanges compared with maximal force production (MVC_F) at the distal phalanges. These observations have been interpreted as indicating a

greater loss of force in intrinsic hand muscles compared with extrinsic muscles consistent with a hypothesis that distal muscles show larger age-related changes compared with more proximal muscles.

In most everyday activities, the human hand is used to grasp and manipulate objects with the thumb commonly acting in opposition to the fingers. One common hand configuration is the so-called prismatic grasp when the four fingers are in opposition to the thumb. Recent studies of the prismatic grasp have suggested that the digits are organized into task-specific flexible synergies that stabilize important performance variables, such as the total grip force and the total moment with respect to the point of thumb contact (34,41,42). Such synergies are learned over the lifespan and associated with coordinated signals to both intrinsic and extrinsic hand muscles. Different age-related changes in the force-producing capabilities of the intrinsic and extrinsic hand muscles may be expected to violate the balance of forces produced by individual digits during natural prehension.

Finger interaction during the production of moments has attracted relatively limited attention, although the importance of moment stabilization in everyday tasks has been emphasized (26, 28). In particular, a principle of stabilization of secondary moments by the fingers in pronation and supination has been suggested as a constraint on patterns of force sharing among fingers (43). A series of studies has shown preferential stabilization of the pronation and supination moment in tasks when the subjects were required to reproduce a pattern of total force and received no instruction or feedback on the total moment (27,33). There have been no studies addressing deficits in moment production associated with normal aging. We view this as a major gap in the current knowledge of the effects of advanced age on hand function.

The present study has two purposes. Because moment production requires accurate coordination of forces and lever arms of individual digits (40), we expect the documented deficits in force production in elderly persons to be accompanied by even higher deficits in moment production tasks. We expect these deficits to be reflected in both maximal force and moment production tests and in tests that require accurate steady-state force and moment production. We also hypothesize that the disproportionate loss of force with age by the intrinsic hand muscles (36) requires the central nervous system of elderly persons to modify many of the control strategies elaborated during the lifetime leading to suboptimal patterns of finger interaction during prehension. These changes may, in particular, lead to less stable forces produced at the fingertips. Hence, we expect elderly persons to trade efficacy for safety and apply excessive forces by digits that act against the required direction of the total moment. This hypothesis is in line with the well documented increase in the safety margin of the normal grip force with age (6,23). We plan to expand these observations to tasks that require the production of maximal and submaximal forces and moments.

METHODS

Subjects

Twelve (6 men and 6 women) young and 12 (6 men and 6 women) elderly subjects took part in the experiment; in some analyses, we will consider four subject subgroups: young men, young women, elderly men, and elderly women. All of the subjects were healthy and right-handed, according to their preferential use of the hand during daily activities, such as writing, drawing, and eating. None of the subjects had a history of long-term involvement in hand or finger activities, such as typing, playing musical instruments, etc. Elderly subjects passed the screening process that involved cognition test (mini-mental status exam ≥ 24 points), depression test (Beck depression inventory ≤ 20 points), quantitative sensory test (monofilament ≤ 3.22), and general neurological examination. Physical characteristics of the subjects are shown in Table 1. Elderly subjects were recruited from a local retirement community. Elderly female

subjects (78.3 ± 2.9 yr) were younger compared with elderly male subjects (86.7 ± 9.6 yr, $P < 0.05$) due to the availability of subjects in the retirement community. This resulted in a significant difference in age between male and female subjects, but there was no age difference between young male (26.5 ± 3.1 yr) and young female subjects (26.0 ± 2.4 yr). The hand length and width were significantly shorter in female subjects compared with male subjects ($P < 0.01$). The hand length was measured between the middle fingertip and the distal crease of the wrist with the hand extended, and the hand width was measured between lateral aspects of index and little finger metacarpophalangeal joints (Table 1). All of the subjects gave informed consent, according to the procedures approved by the Office for Regulatory Compliance of the Pennsylvania State University.

Apparatus

Four six-component (three forces and three moments) transducers (Nano-17, ATI Industrial Automation, Garner, NC) for fingers and one larger six-component transducer (Nano-25, ATI Industrial Automation) for a thumb were attached to a titanium handle to which an aluminum horizontal beam ($5.0 \times 85.0 \times 0.6$ cm) was affixed (Fig. 1A). The diameter of the thumb sensor was 25 mm, whereas the diameter of each finger sensor was 17 mm. The moments generated on each sensor were measured with respect to orthogonal axes passing through the center of the contact surface of the sensor. A load (0.25 kg) was attached to the beam with an eyehook that could be moved horizontally along a slot in the beam. Sliding the load along the beam produced different torques on the handle system. The total weight of the handle system was 12.1 N.

To control for possible interactions between effects of age on the force and moment production and also to minimize fatigue, we designed a task that required only moment production in the absence of a requirement to produce a load force, i.e., the gravitational load of the handle system was always zero. A load with the same weight as the handle system was used to counterbalance the weight of the system with a lever system (Fig. 1A). Therefore, subjects did not need to lift the handle against the gravity while holding it. Two balance levels were positioned at the ends of the beam, and subjects were required to monitor the balance levels and to avoid rotation of the handle and beam during the trials. The vertical distance between the adjacent finger sensors was 3 cm, and the thumb transducer was placed at the midpoint between the middle and ring finger transducers. The grip width, defined as the shortest horizontal distance between the contact surfaces of the thumb and finger transducers, was 86 mm. Sandpaper (100-grit) was placed on the contact surface of each transducer to increase the friction between the digits and the sensors. The finger pad-sandpaper static friction coefficient was ~ 1.4 – 1.5 [measured in an earlier study (41)].

Another handle made of wood with the same dimensions as the titanium handle was fixed to a small six-component force plate (PY6, Bertec, Columbus, OH) and used to measure maximal voluntary torques (MVC_T) during pronation and supination efforts (Fig. 1B).

The total of 36 analog signals from the sensors and the force plate (6 sensors $\times$ 6 components) were routed to the 12-bit analog-digital converter (PCI-6031, National Instrument, Austin, TX) and processed by a microcomputer (Dell Dimension8330, Austin, TX). The sampling frequency was 100 Hz.

Procedure

Subjects washed their hands with soap and warm water to normalize the skin condition of the hands. The subjects were given a standardized familiarization session that explained the experimental procedure and apparatus to ensure that they were able to accomplish the experimental tasks.

The subjects sat on a chair and placed their right upper arm into a wrist-forearm brace fixed to a table. The forearm was secured with Velcro straps, and the wrist was locked in the brace. The upper arm was abducted $\sim 45^\circ$ in the frontal plane and flexed 45° in the sagittal plane. The forearm was aligned parallel to the sagittal axis of the subject. When the subjects held the titanium handle, the angle of the beam attached to the bottom of the handle with the frontal plane was $\sim 45^\circ$. This configuration was the same when subjects held the wooden handle during MVC_T trials. The left hand rested naturally on the left thigh.

The horizontal location of the center of mass of the titanium handle without the load was measured, and the top of the handle above the center of mass was connected to the lever system with a counterload on the other side. The lever was maintained horizontal during trials with the use of a balance level. The 0.25-kg load was suspended from the beam at two different positions that generated two different external torques in the clockwise (negative torques) and counterclockwise (positive torques) directions from the subject's perspective. During testing, hyperextended joint configurations were not allowed for any joints of the hand. The order of conditions was balanced across subjects.

MVC_F and MVC_T—During tests with MVC_T, subjects placed the fingers and the thumb of the right hand at designated positions on the wooden handle and were required to try to turn the handle “as hard as possible” into pronation (positive direction) or supination (negative direction). Three trials were collected for each torque direction for 5 s, and the maximum values across the trials for each of the directions were chosen for further analysis. The torque produced by the subject was shown on the monitor located in front of the subject.

During tests with maximal grip force production (MVC_F), subjects held the titanium handle with their fingers and thumb positioned over the force sensors in the absence of any external torque. Subjects were instructed to grip the handle as strongly as possible with all fingers together. The total normal force was displayed on the screen, and the subjects were required to reach their maximal force within 5 s after a trial had started while keeping the handle vertical. Subjects performed three trials and were required to keep the handle vertical by watching the balance levels attached to the beam. Two-minute rest was administered between trials, with an additional 5-min rest between the sets of three trials at each task. The order of MVC_T and MVC_F tasks was balanced across the subjects.

Constant-moment production—The subjects were required to hold the handle with the load attached at locations that corresponded to external torques of 10% of MVC_T in pronation or in supination. The subjects were asked to hold the handle with minimal effort for 10 s while watching the balance levels to make sure that the orientation of the handle remained vertical. Two trials were performed for each external torque direction with 20-s intervals between the trials. The order of pronation and supination tasks was balanced across the subjects.

Ramp force production—During the ramp trials, an oblique line was shown on the monitor screen, and the task was to follow the line with a cursor representing the current total finger normal force. The line corresponded to an increase in the total normal force of the four fingers from the smallest value observed in the constant-moment production trials to 20% of the MVC_F over 6 s. The subjects held the handle with the load attached at locations that produced the external torques of 10% MVC_T in pronation and in supination and no external torque. Each trial started with a “get ready” signal, and then a trace showing the total normal force started to move over the screen. The ramp started 4 s after the trial initiation. Each subject performed 12 trials with 20-s intervals between the trials.

The order of the tests was always the same: the MVC tests followed by the constant-moment production tests and then the ramp force production tests. This order was necessary due to the later tests requiring data from the earlier tests to set the tasks.

Data Processing

The force data were digitally low-pass filtered with a second-order Butterworth filter at 15 Hz. For MVC_F and MVC_T trials, the instant of peak total force or total torque was defined for each trial. Individual digit forces and the total force and torque produced by all digits were measured at that instant. Data from three trials were averaged and used for further analysis. Force shares of individual fingers during MVC_F trials were calculated by dividing the instantaneous force of each finger by MVC_F. This was done separately for the normal and tangential force components. The subjects were never instructed to produce tangential forces, but these forces always appeared during the MVC_F tasks. Force and moment variables in further tests were normalized by MVC_F and MVC_T for across-subjects comparisons.

The positions of the points of thumb force application along axis *Y* with respect to the sensor center were solved as $y = -M_Z/F_X$, where M_Z is the moment of thumb force about axis *Z* and F_X is the normal force component. The average thumb position during the 4-s period before ramp initiation and the thumb position at the instant of peak MVC_F production were computed and the displacement and difference of the two positions was also computed.

To estimate the variability of performance in tasks that required accurate force and moment production, root-mean-square (RMS) errors were computed over each trial with respect to the required performance and then averaged across trials. Average RMS errors were normalized by corresponding MVC indexes for across-subjects comparisons.

For the trials with constant-moment production, the total antagonistic moment (M_{Ant}), M_{Ant}^n produced by normal forces, and M_{Ant}^t produced by tangential forces were computed. M_{Ant} have been defined as moments produced by a subset of digits acting in the same direction as the external torque. These indexes were averaged over the two trials collected for each external torque direction.

For the 12 ramp force production trials, time profiles of the variances of individual finger forces [$VarF_i(t)$, where i = index, middle, ring, and little] and of the variance of the total force [$VarF_{tot}(t)$] were computed across the trials at each point in time for each subject. The sum of the $VarF_i(t)$ [$\Sigma VarF_i(t)$] was computed in the same way. The difference between $\Sigma VarF_i(t)$ and $VarF_{tot}(t)$ was computed and normalized by $\Sigma VarF_i(t)$ for further analyses, $\Delta VarF(t) = [\Sigma VarF_i(t) - VarF_{tot}(t)]/\Sigma VarF_i(t)$. Note that, when $\Delta VarF(t) < 0$, positive covariations among the time profiles of individual finger forces dominate, and, when $\Delta VarF(t) > 0$, negative covariations prevail. To analyze the variance profiles of the moments of normal and tangential forces, the time profiles of the variances of the moment of normal forces [$VarM^n(t)$], the moment of tangential forces [$VarM^t(t)$], and the moment of total forces [$VarM_{tot}(t)$] were computed over the trials within a set for each subject. The sum of $VarM^n(t)$ and $VarM^t(t)$, $\Sigma VarM^{n,t}(t) = VarM^n(t) + VarM^t(t)$, was also computed. The difference between $\Sigma VarM^{n,t}(t)$ and $VarM_{tot}(t)$ was computed and normalized by $\Sigma VarM^{n,t}(t)$, $\Delta VarM(t) = [\Sigma VarM^{n,t}(t) - VarM_{tot}(t)]/\Sigma VarM^{n,t}(t)$. For statistical analyses, the time profiles of $\Delta VarF(t)$ and $\Delta VarM(t)$ during 6 s were averaged within each 0.5-s period.

Statistics

Standard descriptive statistics and mixed-design ANOVAs with or without repeated measures were used. Factors were chosen based on particular comparisons. Factors included age (2 levels: elderly and young), gender (2 levels: men and women), torque direction (2 levels:

pronation and supination), and time (12 levels: 0.5-s time segments during 6-s ramp period). For comparison of force-sharing patterns, multivariate ANOVA (MANOVA) was used with the factors of age and gender, and Rao's R was used to assess significance. Only three shared forces (shared forces by the middle, ring, and little fingers) were used for comparison of sharing patterns because the four individual shares do not constitute a set of independent variables (the sum of the four finger shared forces is always 100%). Post hoc analysis was performed by using Newman-Keuls test or t -tests with the Bonferroni correction. Level of significance was set at $P = 0.05$. Kolmogorov-Smirnov test and Shapiro-Wilk test showed that there was no violation of the normal distribution assumption ($P > 0.05$), and Levene's homogeneity test showed that the assumption of variance homogeneity was not violated ($P > 0.05$) in the normalized MVC values. The data are presented as means and SDs in the text and Tables 1–3. The data in Figures 2, 3, 5–7, 9, and 10 are presented as means and SEs.

RESULTS

MVC_F and MVC_T

During tasks that required the production of maximal force or maximal moment by all of the digits (MVC_F and MVC_T), young subjects were stronger than elderly, whereas men were stronger than women, as illustrated in Fig. 2A. In particular, during MVC_F trials, young male subjects produced 96.5 ± 22.2 N of peak force, whereas elderly male subjects produced 81.7 ± 14.5 N, young women produced 64.0 ± 11.3 N, and elderly women produced 51.3 ± 5.7 N. During MVC_T trials into pronation, the data for the four subject subgroups were 5.01 ± 1.04 , 3.46 ± 0.78 , 2.97 ± 0.58 , and 2.26 ± 0.78 N·m, respectively. When the subjects produced maximal moment in supination, the data were 5.87 ± 1.17 , 3.71 ± 0.61 , 2.85 ± 0.49 , and 2.36 ± 0.72 N·m, respectively. The difference between the two directions of torque production was just under the level of significance [$F(1,20) = 3.9$; $P = 0.06$], according to a three-way ANOVA with two between-factors, age and gender, and one within-factor, torque-direction.

To compare the age-related difference between the MVC_F and MVC_T tasks, the data for all subjects were normalized with respect to the mean performance of young male subjects (shown in Fig. 2B). These comparisons showed that the MVC_T task was associated with a larger age-related drop in the peak performance index compared with the MVC_F task. In particular, compared with the young men, elderly men showed, on average, a 33.9% smaller MVC_T and only a 15.4% smaller MVC_F, a more than twofold difference ($P < 0.05$ in a three-way age $\times$ gender $\times$ task ANOVA). Compared with young women, elderly women showed a 23.9% smaller MVC_T and a 19.9% smaller MVC_F, although this difference was not significant.

In the four-finger MVC_F task, there were significant age-related differences in the shifts of the point of thumb force application. On average, young subjects rolled the thumb closer to the ring and little fingers (down), whereas elderly subjects rolled it closer to the index and middle fingers (up). Elderly men showed the largest absolute shift in the thumb force application point, on average by 3.8 ± 2.09 mm up, followed by young women (2.61 ± 3.56 mm down), young men (1.82 ± 3.95 mm down), and elderly women (0.87 ± 3.11 mm up). Age-related differences were confirmed with a twoway ANOVA with two factors, age and gender [$F(1,20) = 11.7$; $P < 0.01$]. No significant effect of gender or age $\times$ gender interaction was observed.

Force Sharing in Four-finger MVC Tests

There were significant differences in the patterns of the total force sharing among the four fingers related to both age and gender. Sharing patterns were quantified separately for the normal and tangential components of finger forces, although the subjects were instructed to produce normal forces only. For both force components, elderly subjects tended to use their index and middle finger more than the young subjects. The opposite was true for the ring and

little fingers. For the normal forces, on average, young subjects produced with the ring and little fingers ~42% of the total force, whereas the elderly subjects produced with those two fingers only 34.5%. These findings are illustrated in Fig. 3A, which shows average shares (in percent) of each finger for each of the four subject subgroups.

MANOVA with factors age and gender showed significant effects of age on the share of the middle finger [$F(1,20) = 6.4$; $P < 0.05$] and of the ring finger [$F(1,20) = 6.4$; $P < 0.05$]. Age-related differences for the little finger share were slightly below the level of significance [$F(1,20) = 3.7$; $P = 0.07$].

Tangential force analysis showed a large contribution by the index finger in all subject subgroups. The share of the index finger ranged from 51.9% in young men to 68.8% in elderly women. On average, the combined share of the ring and little fingers in young subjects was ~30%, whereas it was only ~22% for the elderly. These findings are illustrated in Fig. 3B. MANOVA showed significant effects of age on the share of the ring finger [$F(1,20) = 8.6$; $P < 0.01$] and of the little finger [$F(1,20) = 5.2$; $P < 0.05$]. Age-related differences for the index finger share were below the level of significance [$F(1,20) = 3.2$; $P = 0.09$].

There were also gender-related differences (Fig. 3). In particular, women showed larger involvement of the index finger for both normal and tangential force components [$F(1,20) = 6.4$; $P < 0.05$ and $F(1,20) = 5.3$; $P < 0.05$, respectively]. In the production of the normal force, men showed larger shares for the middle finger [$F(1,20) = 6.5$; $P < 0.05$], whereas, in the production of the tangential forces, they showed larger shares of the little finger [$F(1,20) = 5.2$; $P < 0.05$]. Values of the individual finger normal and tangential forces are presented in Table 2.

Constant-moment Production

These tests required the subjects to keep the handle vertical against an external torque of 10% of MVC_T while the weight of the handle system was counterbalanced. Hence the subjects did not need to resist the gravitational load. They needed, however, to produce a moment equal and opposite to the external torque. This moment [total moment produced by digits (M_{tot})], computed with respect to the thumb point of contact, can be viewed as the sum of two components, the moment produced by the normal forces of the fingers (M^n) and the moment produced by the tangential forces (M^t).

The sharing of the M_{tot} between the two components depended on the direction of torque. For supination efforts, M^n accounted for 89% of the total torque in young men, 71% in elderly men, 77% in young women, and 66% in elderly women. For pronation efforts, the sharing of the M_{tot} between the two components became more even with M^t , accounting, correspondingly, for 52, 35, 59, and 58% in the four subject subgroups. These results are summarized in Table 3. Elderly subjects used M^t significantly more than young subjects. This was particularly pronounced in tasks that required supination efforts. Across genders, the share of M^t in elderly subjects was 47% larger than in young subjects. For pronation tasks, this difference was ~17%. A three-way ANOVA with between-factors age and gender and a within-factor torque-direction confirmed main effects of age [$F(1,20) = 6.0$; $P < 0.05$] and of torque-direction [$F(1,20) = 26.3$; $P < 0.001$] without an effect of gender.

Despite the fact that the weight of the handle system was counterbalanced, the subjects produced substantial grip forces, on average 16.98 ± 6.60 N. There were no significant age- or gender-related differences in the mean grip force. Typical force profiles by a young subject and by an elderly subject are presented in Fig. 4. Figure 4A shows the force time series for a representative young subject who produced a pronation torque, whereas Fig. 4B shows the data for a representative elderly subject who produced a supination torque. Note that both subjects

produced nonzero normal forces with fingers that generated moments in a direction opposite to that required by the task (antagonist fingers, index and middle for supination efforts, and ring and little for pronation efforts, compare Refs. 40,42). Such antagonist moments were larger in elderly subjects but only for tasks that required pronation efforts. In those tasks, elderly subjects produced, on average, ~25% higher antagonist moments compared with young subjects. Note that the higher antagonist moments were produced by elderly subjects, despite the fact that they acted against smaller external moments (defined as 10% of the MVC_T). When the magnitude of the antagonist moments was normalized by the actual applied external moment, the difference between the young and elderly subjects reached ~83%. This difference was significant according to an age $\times$ gender ANOVA [$F(1,20) = 5.1, P < 0.05$]. The difference was not seen for tasks with supination efforts.

Variability in the moment production was assessed separately for the M^n and M^l and for M_{tot} . Elderly subjects showed significantly higher variability in the moment production quantified by using RMS error computed over a 6-s steady-state period. Figure 5 shows average values of RMS- M_{tot} (A), RMS- M^n (B), and RMS- M^l (C), in newton meters, for the four subject subgroups and after normalization by the corresponding MVC_T values. When RMS values were expressed in newton meters, young male subjects showed the highest indexes of variability during the steady-state moment production. When these values were normalized by the external moment, against which the subjects acted, the relation reversed, and the young male subjects showed the lowest indexes. Elderly subjects showed, on average, 22% higher RMS- M_{tot} indexes compared with young subjects. Female subjects showed, on average, 33% higher RMS- M_{tot} indexes than male subjects. The normalized RMS- M_{tot} , RMS- M^n , and RMS- M^l showed significant effects of age [$F(1,20) = 4.5, P < 0.05$ for RMS- M_{tot} ; $F(1,20) = 5.0, P < 0.05$ for RMS- M^n ; $F(1,20) = 4.6, P < 0.05$ for RMS- M^l] and gender [$F(1,20) = 4.6, P < 0.05$ for RMS- M_{tot} ; $F(1,20) = 8.0, P < 0.05$ for RMS- M^n ; $F(1,20) = 6.3, P < 0.05$ for RMS- M^l] in a three-way ANOVA with between-factors age and gender and a within-factor torque-direction. There was no significant effect of torque-direction.

Ramp Force Production

These tests were somewhat similar to those run in a previous study (36). However, the present experiments differed in two major aspects. First, the subjects performed the task while grasping the handle rather than pressing on a set of fixed sensors. Second, the task required the production of a ramp total force profile while keeping the orientation of the handle unchanged, i.e., it also required the production of a constant total moment.

Elderly subjects performed the explicit task, i.e., the production of a prescribed ramp pattern of the total normal force, less accurately than young subjects. Figure 6 illustrates RMS values computed over the ramp duration and averaged across the subjects for each of the four subject subgroups. Elderly subjects showed higher values of RMS expressed in newtons (solid symbols), and the difference became even more pronounced when these values were normalized by the maximal force (MVC_F) for each of the subjects (open symbols). The normalization was done because the subjects performed the ramp force task over different force ranges scaled to MVC_F (see METHODS), and force variability is known to scale with the force level (29). Three-way age $\times$ gender $\times$ torque-direction ANOVA with repeated measures confirmed the main effect of age [$F(1,20) = 18.0; P < 0.01$].

We also analyzed how well the subjects kept the required value of the total moment while they produced the ramp force. After normalization by the value of the external moment, RMS indexes for the total moment were significantly higher in elderly subjects compared with young subjects (by ~55%) and in women compared with men (by ~27%). The former difference was significant according to the age $\times$ gender $\times$ torque-direction ANOVA with repeated measures [$F(1,20) = 9.2; P < 0.01$], whereas the latter was not. These findings are illustrated in Fig.

7A. Figure 7, *B* and *C*, shows the M^n and M^t that contributed to the M_{tot} . Note that the differences between young and elderly subjects and the differences between male and female subjects were amplified after the normalization (open squares).

To quantify finger interaction during the force production task, an index (ΔVar) reflecting the difference between the sum of the variances of the individual finger forces and the variance of the total force (see METHODS) was computed. Figure 8 shows typical $VarF_{tot}(t)$ and $\Sigma VarF_i(t)$ computed over a series of 12 trials by a representative young male subject (Fig. 8A) and a representative elderly female subject (Fig. 8B). The difference between the two indexes of variance is shown by the bold line. This difference [$\Delta VarF = \Sigma VarF_i - VarF_{tot}$] was used for analysis of covariation among finger forces (28,37).

For further quantitative analysis, average values of $\Delta VarF$ were computed for each subject over 0.5-s time intervals and divided by the average $\Sigma VarF_i$ computed for the same time interval. These data, averaged across subjects for each of the four subject subgroups, are presented in Fig. 9. Note that $\Delta VarF$ was positive from the very beginning of the ramp, indicating predominantly negative covariation among finger forces. $\Delta VarF$ increased over the duration of the ramp for all subjects, reaching values of >0.9 . This means that the $VarF_{tot}$ was only $\sim 10\%$ of the $\Sigma VarF_i$, i.e., there was a strong negative covariation of finger forces. Young subjects (solid symbols) showed higher $\Delta VarF$ values over the whole ramp duration compared with the elderly (open symbols). This result indicates that a higher proportion of the $VarF_{tot}$ in young subjects did not affect the total force. These findings have been confirmed with a four-way ANOVA with two between-factors (age and gender) and two within-factors (torque-direction and time), which showed main effects of age [$F(1,20) = 6.6$; $P < 0.05$] and of time [$F(11,220) = 16.2$; $P < 0.01$].

We also quantified the interaction between the two contributors to the M_{tot} , M^t , and M^n using a similar approach. Time profiles of the variances of M^t , M^n , and M_{tot} were computed over the 12 trials by each subject. The sum of the variances of M^t and M^n was also computed [$\Sigma Var(M^n, M^t)$]. The difference between $\Sigma Var(M^n, M^t)$ and $VarM_{tot}$ was computed and divided by $\Sigma Var(M^n, M^t)$. This index ($\Delta VarM$) is analogous to $\Delta VarF$ in the analysis of force covariation.

Figure 10 illustrates the time profiles of $\Delta VarM$ for the four subject subgroups; each point is the average over a 0.5-s time window, further averaged across the subjects. The magnitudes of $\Delta VarM$ were positive for all subject groups, implying predominantly negative covariation between M^n and M^t . There were no visible trends in $\Delta VarM$ over the duration of the ramp. Both male and female young subjects showed significantly higher values of $\Delta VarM$ than their elderly counterparts. These results have been supported with a four-way ANOVA with two between-factors (age and gender) and two within-factors (torque-direction and time), which showed a significant effect of age [$F(1,20) = 12.7$; $P < 0.01$] and a significant torque-direction effect [$F(1,20) = 9.4$; $P < 0.01$].

DISCUSSION

Many everyday tasks, such as eating with a spoon, drinking from a glass, and writing with a pen, require precise control of the moments produced by the digits and acting on the handheld object. If this control is impaired, the drink will be spilled, the food will make a mess, and the pen will leave a poorly discernible scribble on the paper. The main goal of the present study has been to document and analyze age-related differences in digit interaction during prehensile tasks that require moment production. We purposefully selected a set of laboratory tasks that involved both maximal moment production and the production of accurately controlled submaximal values of the moment. These tasks could be performed alone or on the background

of another task that required accurate production of certain prescribed time patterns of the total normal force produced by the fingers on the handheld object (the handle).

The study has demonstrated that age is associated with an impaired ability to produce both high moments and accurate time profiles of moments. This impairment goes beyond the well-documented deficits in finger and hand force production by elderly persons (8,31,37). In the following discussion, we consider different aspects of the impaired moment production in elderly persons and their possible origins.

Aging and Performance in MVC Tasks

MVC tasks are commonly defined as reaching a peak value of a particular performance variable produced by muscle forces. Such tasks are always associated with activation of multiple muscles, and the overall effect is defined by both the levels of muscle activation and muscle coordination. A number of factors contribute to a decrease in the peak muscle force in elderly persons. These involve, in particular, a progressive loss of the number of motor units in muscles, accompanied by processes of reinnervation, leading to the emergence of larger and slower motor units (5,17,25,30). Muscles lose both cross-sectional area and fiber numbers; most affected are type II fibers. This leads to a higher percentage of type I fibers (reviewed in Refs. 1,24). All of these factors were likely to contribute to the observed decrease in both the MVC_F and the maximal moment production (MVC_T) tasks in elderly persons. However, in the MVC_T tasks, subjects showed a greater age-related difference in the performance compared with the MVC_F task. Several factors could have contributed to this additional decline in the performance.

First, elderly subjects produced higher forces by fingers that generated moments directed opposite to the required direction of moment production, for example index and ring finger forces for the task of moment production in supination. Such antagonist moment production in submaximal prehension tasks was reported earlier and interpreted as a consequence of enslaving, which leads to unintended force production by antagonist fingers as a result of intended commands to agonist fingers (40). However, aging has been shown to lead to a drop in enslaving (36,37), casting doubt on this interpretation. We did observe excessive antagonist moments in elderly subjects during accurate moment production tasks, but these moments were likely produced by commands to those fingers.

Second, changes in the relative involvement of individual fingers could have affected the peak moment values. Elderly subjects showed a larger involvement of the index and middle fingers in the four-finger MVC_F task compared with young subjects. This observation contrasts the earlier report on unchanged sharing patterns in the pressing tasks with age (37). The difference may be due to the difference in the tasks and associated mechanical requirements. During the prehension MVC_F task in the present study, the subjects were required to maintain the orientation of the T-shaped handle system, i.e., an additional requirement of rotational equilibrium was imposed. There was also a significant difference between the elderly and control subjects in the change of the point of the thumb force application. Compared with the young subjects, elderly participants rolled the thumb up, i.e., closer to the index and middle fingers. This increased the lever arms of the forces produced by the little and ring fingers and decreased the lever arms for the other two fingers. This can be viewed as an adaptive strategy to compensate partly for the relatively lower involvement of the ring and little fingers in the elderly. The difference in MVC_T between the subject groups was indeed larger during supination tasks, when the little and ring fingers produce moments in the required direction, but it was also present for pronation tasks.

Third, the maximal moment production task (MVC_T) may be viewed as more complex and less intuitive than MVC_F. However, MVC_T was performed by using the fixed handle, which

did not need to be stabilized, whereas the MVC_F task was performed by using the T-shaped handle system, which was free to move, i.e., with the additional requirement of moment stabilization. The MVC_F task was, therefore, associated with two mechanical requirements, maximal total force and unchanged total moment, whereas the MVC_T task had only one requirement, maximal total moment.

We think that all three factors could have contributed to the observed greater impairment in the maximal moment production of the elderly. Additional factors could also include the documented drop in the tactile and vibration sensitivities (21) with age. It is possible that excessive involvement of fingers that produce antagonist moments could be due to changes in skin friction and/or to production of comparably strong sensory signals in the elderly (6).

In some of the comparisons, age-related differences were larger for the men than for the women (e.g., Fig. 2). This could be related to the fact that our male subjects were, on average, older than the female subjects. We should note, however, that, despite our male subjects being older, they were in generally good health and far from being frail. Also, in other comparisons (Figs. 5–9), age-related differences were at least as pronounced in women as in men.

Aging and Impaired Performance in Accurate Force and Moment Production Tasks

Two tasks required the accurate production of the total force and moment simultaneously: the task of holding the handle system against a nonzero external torque and zero external load (constant moment production) and the ramp force production task while keeping the orientation of the handle system constant. In both tasks, elderly subjects showed less accurate performance as quantified by the RMS error index computed with respect to both total force and total moment. These observations are in good correspondence with earlier reports on the lower accuracy and higher variability in force production tasks by elderly subjects (4,13,39). Our findings extend these reports to moment production tasks.

The impaired accuracy in the performance of these tasks by elderly persons was associated with changed interaction among components of the total force and of the total moment. To analyze the coordination of finger normal forces during the 6-s ramp force production tests, we compared the time profiles of the variances of the individual finger forces and of the total finger force. Both elderly and young subjects showed predominantly negative covariation among the four finger forces, leading to much lower indexes of the variance of the total force than could be expected if the finger forces were produced independently of each other.

The negative covariation was present from the very beginning of the trial. This result contrasts the earlier reports of predominantly positive covariations of finger forces early in the ramp trial during pressing tasks (26–28). In another study, it has been suggested that the central nervous system needs a certain time (between 150 and 850 ms) to establish a task-specific negative covariation of finger forces in such tasks (35). There is an important difference between the pressing and prehensile tasks. The former starts with all of the fingers fully relaxed, whereas the latter starts with the fingers producing a nonzero background force and acting against an external torque. Our results show that, if the fingers are already involved in a synergetic activity, the central nervous system can organize their adequate interaction from the very beginning of the force ramp trial.

Young subjects showed higher indexes of negative finger force covariation over the duration of the ramp, indicating better finger force coordination to stabilize the time profile of the total force. In an earlier study, a similar result was observed during four-finger pressing tasks (38). The present study shows that the impairment in finger coordination in elderly persons persists in prehension tasks that can be considered more relevant to everyday hand function.

Our analysis operated with variables (finger forces) that are not truly independent because of the phenomenon of enslaving (compare Ref. 44). In earlier studies (26–28,33,38), our laboratory used a different approach based on the uncontrolled manifold (UCM) hypothesis. The hypothesis assumes that the controller acts in the space of independent elemental variables and creates in that space a subspace (a UCM) corresponding to a desired value of a global performance variable. Then it limits the variability of the elemental variables orthogonal to the UCM more than within the UCM. Earlier studies used the notion of force modes (see also Ref. 9) as hypothetical independent elemental variables. These variables were computed based on estimates of the enslaving effects in single-finger force production tasks. In the present study, however, we could not assess enslaving in single-finger tasks because the requirement of keeping the orientation of the handle system would not allow the subjects to use one finger at a time and lead to erroneous assessments of the enslaving. That is why we used a “poor man’s UCM approach,” which operates with finger forces, not force modes. We should mention, however, that enslaving favors positive covariation of finger forces. Because enslaving is higher in young subjects (36,37), taking it into account could only increase the difference in the total force stabilization index (ΔVar) between the young and elderly subjects.

A similar analysis was run to assess the covariation of the two components of the total moment produced by the tangential and normal digit forces, respectively, M^t and M^n . This analysis has also shown higher indexes of negative covariation between M^t and M^n in young subjects compared with elderly subjects throughout the ramp trial. Hence, we can conclude that elderly subjects are impaired in their ability to organize force covariation and moment covariation in a task-specific way. It is important to note that the gravitational load was removed in this experiment. It is possible, therefore, that, if the subjects were also to act against gravity, many of the age-related differences would have been even greater due to the well-documented impairment in hand force production in the elderly (15,23,38).

Preference for Safe Motor Patterns in the Elderly

Kinoshita and Francis (23) compared force control during prehension in young and elderly subjects. They found that elderly subjects showed lower skin friction, higher safety margins, more fluctuations in the grip-force curve, and longer times of force application. Higher safety margins were also reported by others (6,16) that could be related to changes in skin friction and/or to the production of comparably strong sensory signals in the elderly. In more recent studies, however, Cole and colleagues (7,8) have challenged a hypothesis that the decline in the ability of older persons to grip and lift objects is solely due to their impaired tactile sensitivity.

In our experiments, elderly subjects also demonstrated excessive grip forces, even in conditions when the grip force was not necessary because the load was zero (the weight of the handle system was counterbalanced by the counterload). In these conditions, the nonzero grip force could partly result from the other task component, the production of a nonzero moment, and from the enslaving effects (compare Ref. 42). Excessive grip forces by the elderly could be related to their higher moments produced by antagonist fingers, i.e., by fingers that produced moment opposite to the required moment direction. The production of excessive antagonist moments implies stronger central commands sent to those fingers. Because the total moment was to be equal to the external torque, commands to all four fingers were likely increased, resulting in the higher grip force.

Both higher grip forces and higher antagonist moments may be viewed as energetically suboptimal but leading to more stable performance. Higher grip forces would prevent the object from slipping out of the hand if the load force changes, for example, due to acceleration of the object in the vertical direction or due to the variability of the grip force. Both could be expected from the less steady performance by the elderly (4,6,13). On the other hand, antagonist

moments can be viewed as increasing the apparent stiffness of the hand, i.e., its passive resistance to small variations in the applied torque. Overall, the results indicate that elderly subjects use higher safety margins with respect to possible variations in both force and torque. Such patterns may be viewed, not as abnormal, but as adaptive to the overall decline in the control of finger forces and moments. Recent studies have suggested that age-related changes in the neuromotor apparatus are accompanied by adaptive changes in the control strategies that help alleviate the detrimental effects (10,37).

A recent report has suggested that the impaired ability of the elderly to control pinch force accurately can be improved with specialized training (31). It remains to be seen whether tasks that require coordination of digits to produce combinations of force and moment can also show improvement with practice in the elderly. This is a challenge for future studies.

Limitations of the Study

The task selected for this study has a number of features that may be criticized for making it rather artificial and not directly relevant for the everyday hand motor function. In particular, to emphasize the moment production task component, we purposefully designed a task that did not involve an explicit requirement to act against the field of gravity. We would like to note, however, that, whereas many everyday tasks involve manipulation of objects against the field of gravity, some tasks do not. For example, when turning a handle to open the door, one needs to produce a moment, while the weight of the handle is supported by the structure of the door.

The two force production tasks involved the generation of maximal voluntary forces (MVC_F) and accurate force ramps. These tasks are indeed artificial. The main purpose of the MVC_F and MVC_T tasks was to prescribe the relative submaximal force and moment for other tasks. The importance of MVC for everyday prehensile tasks is not obvious, although our earlier studies have shown a strong relation between patterns of finger interaction and MVC forces (36,37). To be able to compare indexes of variability during accurate force and moment production, we had to prescribe our subjects a standardized task, and a linear ramp increase in the total force looked like an adequate candidate, which we used in earlier studies (36–38). It is challenging to find a more ecologically valid task that would allow a similar type of analysis. Maybe this will be accomplished in the future.

Within our design, we tried to minimize wrist involvement in the tasks. This was done to simplify analysis and interpretation of the data. However, in everyday prehensile tasks, wrist muscles are likely to play a major role, particularly in the production of pronation and supination moments. As in most movement studies, we faced a trade-off between making the task similar to those performed during everyday life and limiting our analysis to a reliably measured set of variables. We view this study as a natural extension of our earlier experiments with multifinger pressing tasks and a step toward more natural motor tasks. However, the gap is large and cannot be covered in a single step.

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Fig. 1.

A: the handle with the T-shaped horizontal beam was instrumented with 5 force and torque sensors. A load was moved along the beam to create different external torques. Another load (the “counterload”) was used to counterbalance the weight of the handle with the attachments and the first load. The external frame, the handle, and the counterload were connected by vertical threads. **B:** the force plate was attached to a wooden handle and used to measure maximal voluntary torque production by the subjects.

Fig. 2.

A: maximal forces [maximal force production (MVC_F)] and maximal moments [maximal torque production (MVC_T)] in N and N·m, respectively. *B:* the corresponding values normalized by the mean performance of the young male (YM) subjects. YF, young female; EM, elderly male; and EF, elderly female subjects. Values are means $\pm$ SE.

Fig. 3. Finger normal force (A) and tangential force (B) sharing during four-finger MVC_F tests. F_I , index; F_M , middle; F_R , ring; and F_L , little finger force shares. Values are means $\pm$ SE.

Fig. 4. Individual finger forces during the production of a constant moment. *A*: representative young subject during pronation effort. *B*: representative elderly subject during supination effort. F_{tot} , sum of all finger forces.

Fig. 5.

Root mean square (RMS) errors of the total moment produced by the digits (M_{TOT} ; *A*), the moment produced by the normal forces (M^n ; *B*), and the moment produced by the tangential force (M^t ; *C*) during constant-force production. The data are shown in N-m and after normalization by the maximal torque (MVC_T). Values are means $\pm$ SE across external torque conditions, and subject subgroups are presented.

Fig. 6. RMS errors of the total normal force (F^n) in N and after normalization by the maximal force (MVC_F) during the ramp force production trials. Values are means $\pm$ SE across external torque conditions, and subject subgroups are presented.

Fig. 7.

RMS errors of M_{tot} , (A) M^n (B), and M^l (C) during ramp force production. The data are shown in N·m and after normalization by the maximal torque (MVC_T). Values are means $\pm$ SE across external torque conditions, and subject subgroups are presented.

Fig. 8.

Typical time profiles of the sum of the variances of individual finger forces [$\Sigma \text{VarF}_i(t)$], of the total force variance [$\text{VarF}_{\text{tot}}(t)$], and of the difference between $\Sigma \text{VarF}_i(t)$ and the $\text{VarF}_{\text{tot}}(t)$ [$\Delta \text{VarF}(t) = \Sigma \text{VarF}_i(t) - \text{VarF}_{\text{tot}}(t)$]. The variance profiles were computed over 12 trials during the ramp force production test for a representative YM subject (A) and for a representative EF subject (B).

Fig. 9.

Normalized $\Delta\text{VarF}(t)$ between $\Sigma\text{VarFi}(t)$ and the $\text{VarF}_{\text{tot}}(t)$ $\{\Delta\text{VarF}(t) = [\Sigma\text{VarFi}(t) - \text{VarF}_{\text{tot}}(t)]/\Sigma\text{VarFi}(t)\}$ computed over 12 trials during the ramp force production. Averages over 0.25-s time intervals are shown with SE bars. Values are means $\pm$ SE across external torque conditions, and subject subgroups are presented.

Fig. 10.

Normalized difference between the sum of the variances of the moments produced by the normal and by the tangential forces and the variance of the total moment produced by the digits, $\Delta\text{VarM}(t) = \{[\Sigma\text{VarM}^{n,t}(t) - \text{VarM}_{\text{tot}}(t)]/\Sigma\text{VarM}^{n,t}(t)\}$, computed over 12 trials during the ramp force production. Averages over 0.25-s time intervals are shown with SE bars. Values are means $\pm$ SE across external torque conditions, and subject subgroups are presented.

Table 1

Physical characteristics of the subjects

	Mass, kg	Height, cm	Hand Length, cm	Hand Width, cm
Elderly men	72.7±13.2	175.2±10.0	20.8±1.6	9.0±0.4
Elderly women	62.2±14.6	162.2±5.8	18.5±1.8	8.0±0.3
Young men	72.6±4.4	177.2±4.8	19.8±1.1	9.1±0.3
Young women	60.0±5.1	164.8±4.3	18.6±0.8	7.9±0.4

Values are means ± SD across subjects within each subgroup.

Table 2
Finger normal and tangential forces during four-finger maximum voluntary contraction tests

	Normal Forces, N				Tangential Forces, N			
	Index	Middle	Ring	Little	Index	Middle	Ring	Little
Young men	29.40±7.27	27.42±8.44	24.48±7.28	15.20±5.59	14.53±5.42	4.14±1.85	4.57±2.41	4.77±2.39
Young women	26.27±4.84	20.47±8.58	21.45±2.59	13.50±5.23	7.69±3.33	1.33±1.11	1.58±0.53	1.56±0.84
Elderly men	16.28±4.95	22.28±6.94	14.19±7.78	7.25±5.81	8.18±2.82	2.12±0.86	1.38±0.68	1.71±0.41
Elderly women	20.57±7.42	13.69±2.28	10.21±1.81	6.84±1.80	7.88±3.45	1.77±0.87	0.88±0.51	0.92±0.21

Values are means ± SD across subjects within each subgroup.

Table 3

Sharing of the total moment between the moment of the normal forces and the moment of the tangential forces

	Pronation		Supination	
	M ⁿ	M ^t	M ⁿ	M ^t
Young men	51.54±19.79	48.46±19.79	89.12±13.26	10.88±13.26
Young women	58.97±19.65	41.03±19.65	76.79±7.06	23.21±7.06
Elderly men	34.60±17.15	65.40±17.15	70.76±19.47	29.24±19.47
Elderly women	58.10±8.35	41.90±8.35	65.68±22.21	34.32±22.21

Values are means ± SD of average across subjects shares of the moment of the normal forces (Mⁿ) and the moment of the tangential forces (M^t) for each of the 4 subject subgroups.