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RESEARCH ARTICLE

Hand digit control in children: age-related changes in hand digit force interactions during maximum flexion and extension force production tasks

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Abstract We studied the finger interactions during maximum voluntary force (MVF) production in flexion and extension in children and adults. The goal of this study was to investigate the age-related changes and flexion–extension differences of MVF and finger interaction indices, such as finger inter-dependency (force enslaving (FE): unintended finger forces produced by non-instructed fingers during force production of an instructed finger), force sharing (FS; percent contributions of individual finger forces to the total force at four-finger MVF), and force deficit (FD; force difference between single-finger MVF and the force of the same finger at four-finger MVF). Twenty-five right-handed children of 6–10 years of age and 25 adults of 20–24 years of age participated as subjects in this study (five subjects at each age). During the experiments, the subjects had their forearms secured in armrests. The subjects inserted the distal phalanges of the right hand into C-shaped aluminum thimbles affixed to small force sensors with 20° of flexion about the metacarpophalangeal (MCP) joint. The subjects were instructed to produce their maximum isometric force with a single finger or all four fingers in flexion or extension. In order to examine the effects of muscle–force relationship on MVF and other digit interaction indices, six subjects were randomly selected from the group of 25 adult subjects and asked to perform the same experimental protocol described above. However, the MCP joint was at 80° of flexion. The results from the 20° of MCP joint flexion showed that (1) MVF increased and finger inter-dependency decreased with children's age, (2) the increasing and decreasing absolute slopes (*N*/year) from regression analysis were steeper in flexion than extension while the relative slopes (%/year) with respect to adults' maximum finger forces were higher in extension than flexion, (3) the larger MVF, FE, and FD were found in flexion than in extension, (4) the finger FS was very similar in children and adults, (5) the FS pattern of individual fingers was different for flexion and extension, and (6) the differences between flexion and extension found at 20° MCP joint conditions were also valid at 80° MCP joint conditions. We conclude that (a) the finger strength and independency increase from 6 to 10 years of age, and the increasing trends are more evident in flexion than in extension as indexed by the absolute slopes, (b) the finger strength and finger independency is greater in flexion than in extension, and (c) the sharing pattern in children appears to develop before 6 years of age or it is an inherent property of the hand neuromusculoskeletal system. One noteworthy observation, which requires further investigation, was that FE was slightly smaller in the 80° condition than in the 20° condition for flexion, but larger for extension for all subjects. This may be interpreted as a greater FE when flexor or extensor muscles are stretched.

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Introduction

For a successful performance of a manipulation task with existing motor redundancy/abundance (Bernstein 1935, 1967; Turvey 1990; Latash 2000), the central nervous system (CNS) must be capable of performing a certain level of individual finger actions (Schieber and Poliakov 1998; Hager-Ross and Schieber 2000; Schieber and Santello 2004) in addition to synergic interactions between fingers (Zatsiorsky et al. 2003; Latash et al. 2004; Shim et al. 2005a, b). For example, if an intended finger flexion induces large unintended flexion of other fingers during keyboard typing, the unintended finger movements can cause typing of the wrong keys (Fish and Soechting 1992; Flanders and Soechting 1992; Engel et al. 1997; Li et al. 2004). To avoid typing a wrong key by unintended finger actions, additional activation of finger extensors will be required by the CNS to move the finger into extension or to maintain the extended positions of the other fingers, most likely leading to a less efficient use of the neuromuscular system. It has been documented that humans are incapable of complete independent control of the fingers such that we can neither move a single finger without changing the kinematics of the others (Hager-Ross and Schieber 2000; Li et al. 2004; Schieber and Santello 2004) nor produce one finger force without producing forces with the other fingers (Li et al. 1998; Reilly and Hammond 2000).

Manipulation tasks in school have been increasingly crucial for children's success in the classroom not only because of the obvious handwriting skills required throughout, but also for performing laboratory experiments in science classes, drawing in art class, playing musical instruments, handling balls and racquets in physical education class, etc. Previous studies have documented that manipulation coordination is closely related to children's success in the classroom (Henderson and Sugden 1992; Geuze and Borger 1993; Cantell et al. 1994; Piek and Edwards 1997). Poor skills in handwriting and keyboarding have been reported to interfere especially with academic achievements of children (Roussounis et al. 1987; Smits-Engelsman et al. 2001).

Maximum voluntary finger force production in children has been investigated in many previous studies (Lazarus et al. 1995; Deutsch and Newell 2001; Deutsch and Newell 2002, 2003; Smits-Engelsman et al. 2003; Potter et al. 2006). Smits-Engelsman et al. (2003) reported an increase in index finger maximum voluntary contraction force (MVF) and improvement of submaximal force control of the index finger with children's increasing age (5–12 years). These increases are attributed to the development of both peripheral and central aspects of the neuromotor system (Smits-Engelsman et al. 2003). That is, neuromuscular changes such as hypertrophy of the muscular system (Parker et al. 1990; Lexell et al. 1992; Sjostrom et al. 1992) and maturation of neuronal connections and pathways (Muller and Homberg 1992; Caramia et al. 1993; Muller et al. 1994; Gibbs et al. 1997) accompany functional improvements in the children's motor control. In adults, age-related changes of finger independency have been studied through comparisons between young and elderly adults for their finger interaction indices during single-finger and multi-finger MVC force production in flexion (Shinohara et al. 2003a, b). Potter et al. (2006) recently performed a study on age-related changes of precision-grip and power-grip strength and control in younger children (3–5 years), and the study reported increases in their strength and force control with age. However, our knowledge on changes or development in children's finger interaction indices such as finger inter-dependency [so-called 'enslaving', unintended finger forces or motions produced by non-instructed fingers during force production or movements of an instructed finger (Hager-Ross and Schieber 2000; Zatsiorsky et al. 2000)], force sharing (FS; percent contributions of individual finger forces to the total force at four-finger maximum force), and force deficits (FD; force difference between single-finger maximum force and the force of the same finger at four-finger maximum force) are very limited. In addition, the studies mentioned above on finger interaction indices investigated only the finger-tip pressing into flexion without considering extension while skillful finger actions in everyday manipulation activities require both flexion and extension dexterity.

The present study involves single-finger and four-finger maximum force production in two directions (flexion and extension) performed by children and adults. The goal is to investigate the age-related changes and flexion–extension differences of MVF and finger interaction indices. We expect that children's age is associated with changes in some of these variables. In particular, we expect to observe (a) increases in finger MVF in both flexion and extension, (b) an decrease in finger inter-dependency with children's age considering that independent finger actions are necessary for skillful manipulation coordination, (c) a larger finger independency for finger flexion than extension considering that everyday manipulation tasks, such as holding an object, often requires precise control of digit-tip force production in flexion, and (d) a smaller finger inter-dependency in adults than in children.

Methods

Subjects

Twenty-five typically developing children (age 6–10 years; 15 males and 10 females with 5 subjects at each age) and 25 college students (age 20–24 years; 13 males and 12 females) participated in this study (Table 1). As the exclusion criteria, all children were assessed by the movement assessment battery for children (Henderson and Sugden 1992). Any children below the 20th percentile were excluded. All of the subjects were right-handed in performing everyday activities such as writing, using a spoon, and brushing hair. The right-hand length was measured from the middle finger tip to the lunate of the wrist. The width was measured between the metacarpophalangeal (MCP) joints of the index and little fingers. All children's parents and adult subjects gave informed consent based on the procedures approved by the University of Maryland's Internal Review Board (IRB).

Experimental setup

The experimental setup included four two-directional (tension and compression) force sensors (black rectangles in Fig. 1a) for four fingers (2nd–5th digits) with amplifiers (Models 208 M182 and 484B, Piezotronics, Inc.). The sensors were mounted on a customized aluminum frame (14.0 × 9.0 × 1.0 cm) along four slits which allowed adjustments of the sensor positions along the long axis of fingers according to the individual hand and finger sizes of the subjects. Adjacent slits were separated medio-laterally by 20 mm (along *z*-axis in Fig. 1b). The frame was attached to a large aluminum panel (21.0 × 16.0 × 2.0 cm) with a vertical slit (14.0 cm), which allowed the frame two degrees-of-freedom: one for vertical translation and the other for rotation about the *z*-axis. C-shaped aluminum thimbles were attached on the bottom of each sensor. The frame was tilted at 25° with respect to the antero-posterior axis (*x*-axis) such that all finger joints (distal inter-phalangeal, proximal inter-phalangeal, and MCP joints) were slightly flexed when the distal phalanges were positioned inside the thimbles. After the position adjustment, the frame was mechanically fixed to the panel using a nut–bolt structure.

Table 1 Subject age, hand length, and hand width

Age group (years)	Age (years)	Hand length (cm)	Hand width (cm)
Children (*n* = 25)			
6	6.5 ± 0.3	13.2 ± 0.8	6.4 ± 0.2
7	7.3 ± 0.3	13.7 ± 1.2	6.6 ± 0.4
8	8.6 ± 0.2	14.2 ± 0.6	7.3 ± 0.3
9	9.4 ± 0.4	15.5 ± 1.5	7.4 ± 0.4
10	10.3 ± 0.3	16.5 ± 0.7	7.5 ± 0.4
Adults (*n* = 25)			
20–24	22.5 ± 2.0	18.9 ± 1.5	8.1 ± 0.5

The hand length and width increase with children's age. Mean ± SD

Signals from the sensors were conditioned, amplified, and digitized at 1,000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp.) and a custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.). A desktop computer (Dimension 4700, Dell Inc.) with a 19 in. monitor was used for data acquisition. The individual finger force or the total of all-four finger forces applied on the sensors was displayed on the monitor screen online. MatLab (MatLAB 7, MathWorks, Inc.) programs were written for data processing and analysis.

Experimental procedure

All subjects sat in a chair facing a computer screen with the shoulder abducted 35° in the frontal plane and elbow flexed 45° in the sagittal plane such that the forearm was parallel to the frame (Fig. 1b). The forearm rested on the customized wrist-forearm brace (comprised of a piece of foam that was attached to a semi-circular plastic cylinder) fixed to a wooden panel (29.8 × 8.8 × 3.6 cm). Velcro straps were used to avoid forearm and wrist movements.

The subjects were asked to rest the distal phalange of each finger in a thimble such that all joints were slightly flexed and formed a dome shape with the hand (Fig. 1a). The MCP joints were flexed at about 20°. In order to remove the gravitational effects of the fingers and any possible favor to finger flexion or extension due to passive stretching of the finger intrinsic and extrinsic muscles, the force signals for the initial 0.5 s were averaged for each finger and subtracted from the later signals. Thus, only the force signals after subtraction were shown on the computer monitor as real-time feedback.

Subjects performed ten conditions of the MVF task: five conditions for task fingers (I, M, R, and L for single-finger tasks and IMRL together for a four-finger task) in two finger force directions (flexion and extension). One trial was performed for each

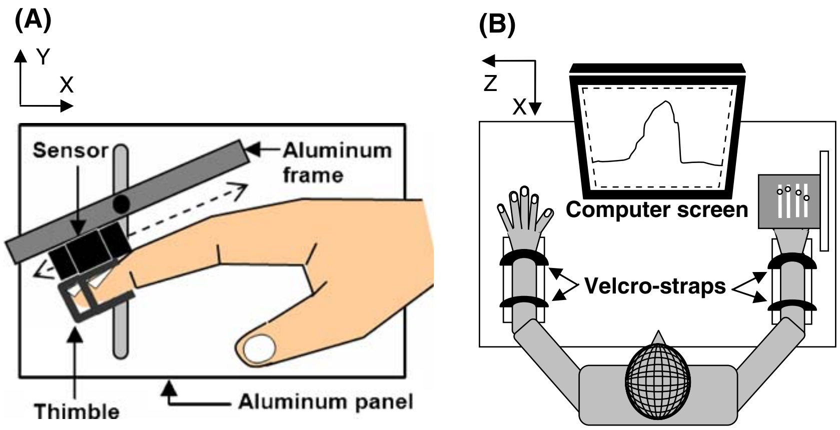

Fig. 1 **a** The experimental settings for the right hand: the two-directional (tension and compression) sensors shown as *black rectangles* were attached to an aluminum frame and the C-shaped thimbles were attached to the bottom of the sensors. The subject inserted the distal phalange of each finger in the thimbles. **b** The wrists and the forearms of the subject rested in a wrist–forearm brace and held by Velcro-straps. The subject sat in a chair and watched the computer screen to perform the task

condition. The order of the conditions was balanced across subjects. During each trial, all fingers were in the thimbles, and subjects were asked to produce maximum isometric force with a task finger(s) in flexion or extension over a 3-s interval while watching the force feedback of the task finger(s) on the computer screen. The experimenter watched the subjects' right hand carefully for any joint movements. Trials with visible finger or wrist joint movements were rejected (~2% of the total number of trials) and performed again by the subjects. The subjects were instructed to concentrate on the task finger and not to pay attention to non-task fingers. The task finger force produced was displayed on-line on the computer screen in front of the subject. At the beginning of each trial, the computer generated a 'get ready' sound, and the task finger force was shown graphically on the screen.

Data processing

The force data were digitally low-pass filtered with a second-order, zero-lag Butterworth filter at 25 Hz cutoff frequency (Winter 1990; Shim et al. 2005b). For each trial, the instantaneous maximum force produced by each finger was measured at the moment when the maximum force was reached by the task finger(s). The data were used to detect or calculate the maximum voluntary force (MVF), FS, FD, and force enslaving (FE).

The MVF value was determined as the maximum force produced by the task finger(s). Force deficit for each finger was calculated by taking the difference of the forces of each finger during the single-finger task and the four-finger task. This value was normalized by the single-finger MVC and averaged over fingers to calculate FD. FS of each finger was calculated as the percent contribution of each finger force to the sum of the finger forces during the four-finger task. The finger inter-dependency indices for each finger were calculated as the average non-task finger forces. These values were averaged across all fingers to calculate the overall finger inter-dependency indices FE (Eq. 1).

$$\mathrm{FE} = \frac{\sum_{j-1}^{n}\left[100\% \times \sum_{i=1}^{n}\left(F^{ij}/F^{i}_{\max}\right)/(n-1)\right]}{n}, \qquad (1)$$

where $i \neq j$, $n = 4$, where $F^{i}_{\max}$ is the maximum force produced by the finger, i, and F^{ij} is the force produced by the non-task finger, i, during the j finger maximum force task (Zatsiorsky et al. 2000; Shinohara et al. 2003a, b). Note that FE for each finger represents the averaged percent force of non-task fingers for the same trial with respect to the task finger MVF. Some previous studies employed a 'finger independency' index (Hager-Ross and Schieber 2000; Li et al. 2004) rather than 'finger inter-dependency', but this study used the finger inter-dependency index (FE) to compare the current study with other previous studies involving finger inter-dependency in young and elderly adults (Zatsiorsky et al. 2000; Shinohara et al. 2003a, b).

Statistics

Age-related 'changes' in dependent variables were examined with regression analysis for children and adults. The 'differences' between experimental conditions and different groups were investigated with mixed-effects ANOVAs and multivariate ANOVAs (MANOVAs).

Linear regression was used to characterize the relations of children or adults' age with MVF, FE, FS, and FD. Pearson coefficients of correlation were computed and then corrected for noise and error propagations (Taylor 1997). The uncertainty or error affects the values of coefficients of correlation, i.e., the coefficients decrease with error propagations. The true coefficients of correlation, after the errors were eliminated, were computed [see Shim et al. (2003) for computational details]. The true coefficients of correlation are usually higher than the coefficients initially computed. Separate regression analyses for children and adults were performed to avoid a large interpolation of missing data between the children and adults. At $n = 25$, the absolute critical values of significance for the empirical coefficients of correlation are equal to .396 for $P = .05$ and .505 for $P = .01$. For the regression lines showing significant relationships, we tested whether the two regression lines for flexion and extension tasks were different (Neter and Wasserman 1974).

Standard descriptive statistics and mixed-effects ANOVAs with the within-factors of DIRECTION (flexion and extension) and TASK (I, M, R, and L) and the between-factor of AGE (children and adults) were used to analyze MVF, FE, and FD. Although significant changes of MVF and FE with children's age exist (Figs. 2, 3), that is, the older children tested in this study may not be different from adults in MVF and FE, we took the liberty to perform mixed-effects ANOVA with direction, task, and age factors for the consistency of statistical analysis on all dependent variables. Sharing patterns were compared using MANOVAs. Since the sum of individual finger FS is always 100%, the sharing values of only middle, ring, and little fingers were used for the MANOVAs (Danion et al. 2001). The Bonferroni corrections were used for significance adjustments for multiple comparisons. The level of significance was set at $P = .05$ for both regression analyses and ANOVAs.

Results

Maximum voluntary force

The non-task fingers during single-finger MVF tasks increased with task finger forces for both flexion and extension, Fig. 2.

MVF values showed significant increases with children's age for all finger force direction conditions (flexion and extension) and tasks (single-finger and four-finger tasks), Fig. 3. These findings were supported by linear regression analysis which showed significant positive coefficients of correlations (r) for single-finger and four-finger flexion and extension tasks in children ($P < .01$). In general, the slopes of the regression lines were greater in flexion than in extension. We tested the statistical differences of the slopes of regression lines between the flexion and extension tasks. The slopes of the regression lines of the index finger, middle finger, and four-finger tasks were greater in flexion than in extension ($P < .05$) while the slopes for ring and little finger tasks did not show significant differences due to the smaller coefficients of correlation. When the absolute slopes (*N*/year) were normalized as the relative slopes (%/year) with respect to adults' MVF values, the results were somewhat different. All individual fingers showed larger slopes for extensions (I: 9.5, M: 17.1, R: 9.3, and L: 8.4 %/year) than flexion (I: 7.9, M: 9.1, R: 5.8, and L: 5.2 %/year). MVF values from adults did not show significant increases or decreases with their age for any experimental conditions.

For single-finger flexion tasks, index and middle fingers showed relatively large values of MVF while the ring and little fingers showed smaller values in both children and adults. MVF values were greater in flexion than in extension and greater in adults than in children. The differences between children and adults were larger in flexion than in extension. These findings were supported by three-way mixed-effects ANOVA which

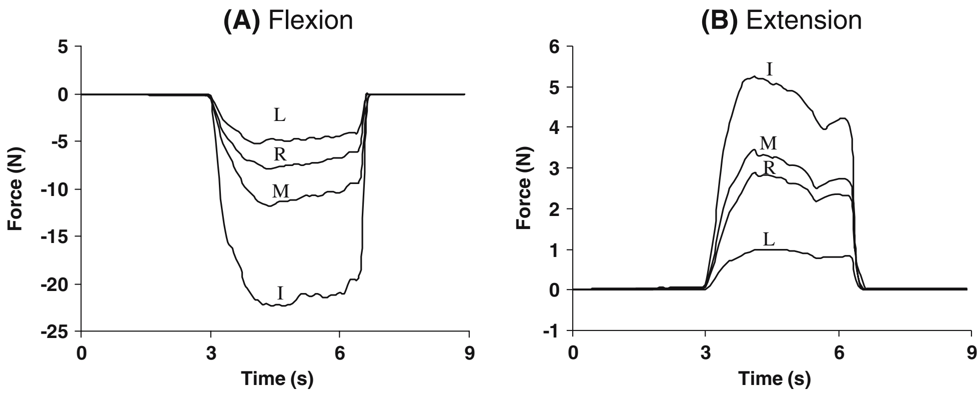

Fig. 2 Individual finger force profiles of a representative subject during index finger maximum voluntary force (*MVF*) production tasks in **a** flexion and **b** extension. *I*, *M*, *R*, and *L* stand for index finger, middle finger, ring finger, and little finger, respectively

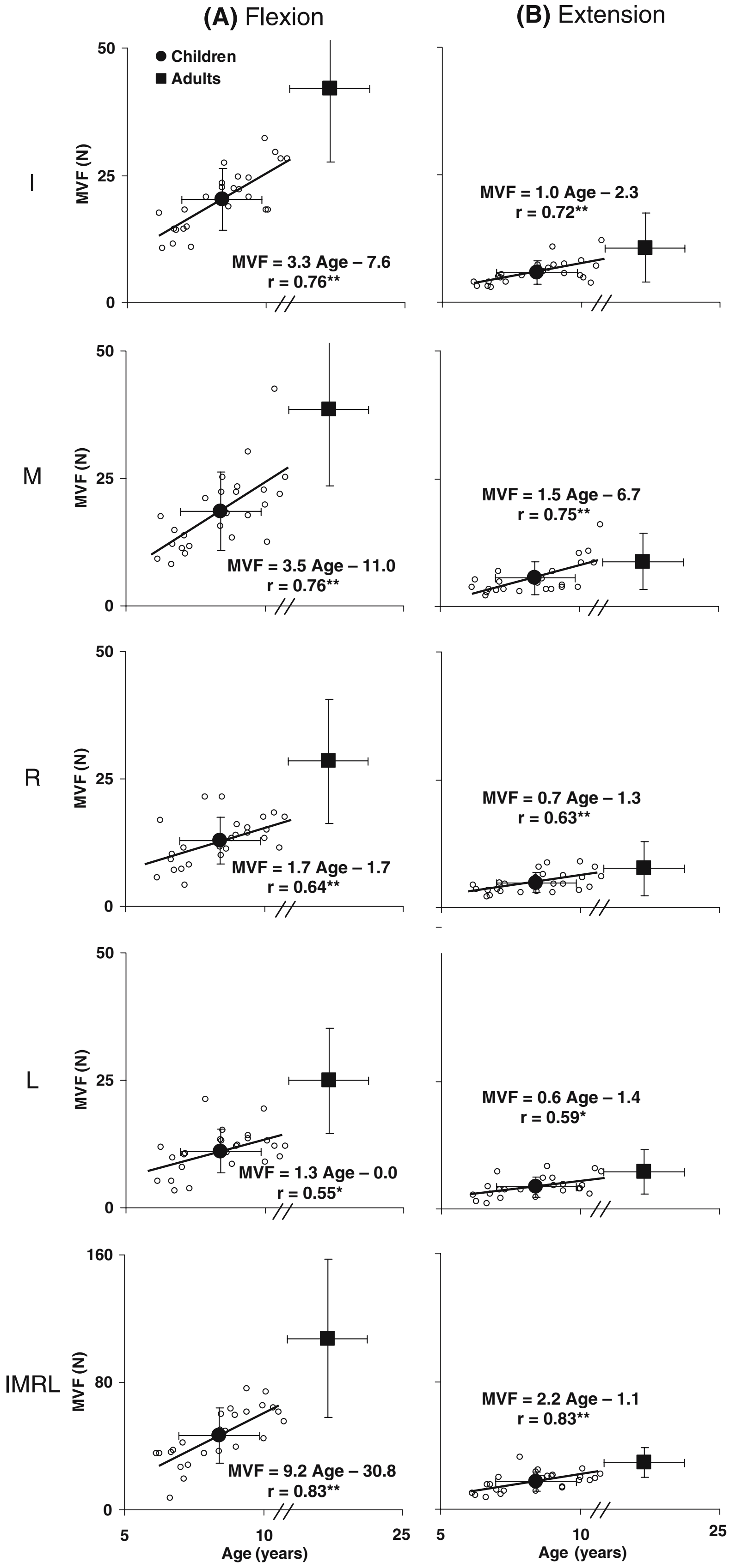

Fig. 3 Relationship between the children's age and MVF of the index finger (*I*), middle finger (*M*), ring finger (*R*), little finger (*L*), and four fingers (IMRL) and average values of finger MVF for children and adults during **a** flexion and **b** extension tasks. *Small open circles* represent individual children data and the corrected coefficients of correlation for all 25 children are shown in each panel (**$P < .01$). The average values for children and adults are presented with standard deviation bars in *closed circles* and *closed squares*, respectively. Note that the slopes of the regression lines for flexion are significantly greater for I, M, and IMRL tasks ($P < .05$) than for extension

showed significant effects of DIRECTION [$F(1,48) = 196.7$, $P < .001$], TASK [$F(3,144) = 83.1$, $P < .001$], and AGE [$F(1,48) = 44.6$, $P < .001$], and significant interactions of DIRECTION × TASK [$F(3,144) = 50.7$, $P < .001$], DIRECTION × AGE [$F(3,48) = 34.9$, $P < .001$],and TASK × AGE [$F(3,144) = 8.0$, $P < .001$].

Inter-finger dependency/enslaving

During the single-finger maximum force production tasks, the instructed (task) finger force production was accompanied by significant uninstructed (non-task) finger forces as shown in Fig. 2. The non-task finger forces were normalized by their own maximum forces to calculate FE (Eq. 1). The regression analysis showed that both FE values had significant decreasing trends with children's age as shown in Fig. 4 while FE values did not show significant increases or decreases with adults' age. The decreasing trend of FE with children's age was more evident in flexion ($r = -0.69$) than in extension ($r = -0.41$), Fig. 4. The rate of FE change was also larger in flexion than in extension and this finding was supported by the slope difference between the regression lines ($P < .05$).

FE values for children were greater in extension than in flexion while the FE values were similar in adults for flexion and extension. These findings were supported by two-way mixed-effects ANOVA which showed significant effects of DIRECTION [$F(1,48) = 19.3$, $P < .001$], AGE [$F(1,48) = 37.7$, $P < .001$], and DIRECTION × AGE [$F(3,48) = 25.6$, $P < .001$].

Force sharing

When subjects performed four-finger tasks, all four fingers produced forces, and FS of an individual finger force was presented as a percentage of the four-finger total force. FS values of individual fingers showed no significant relationship with children's or adults' age either in flexion or in extension.

The regression analysis showed that FS had no significant relationship with children's or adults' age for any force directions or fingers. Force sharing patterns for children and adults were very similar (Figure 5). In general, the index and middle finger FS (I: 30% and M: 30% on average) was larger than the ring and little finger FS (R: 23% and L: 17% on average). The little finger showed the smallest FS for both flexion and extension. The middle finger FS was greater in flexion than in extension while ring and little finger FS values were smaller in flexion than in extension. These findings were supported by MANOVA showing significant effect of DIRECTION [M: $F(1,48) = 56.2$, $P <.001$; R: $F(1,48) =7.8$, $P <.005$; L: $F(1,48) = 5.6$, $P <.05$], but no significant effect of AGE. No significant DIRECTION × AGE interaction was found.

Force deficit

The maximum forces of individual fingers during the single-finger tasks were larger than the maximal forces of individual fingers during the four-finger tasks, which cause deficits of finger forces during the four-finger tasks. The FD was presented as the difference between the peak forces in single-finger and four-finger tasks,

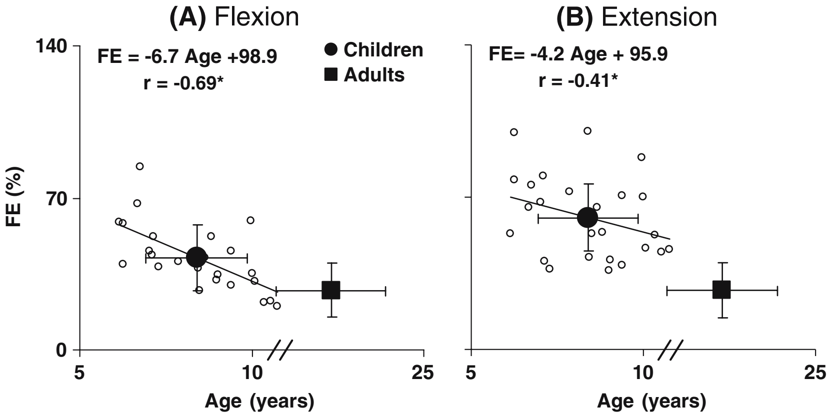

Fig. 4 Relationship between children's age and inter-finger dependency (*FE*) and average values of FE for children and adults during **a** flexion and **b** extension tasks. *Small open circles* represent individual children data and the corrected coefficients of correlation for all 25 children are shown in each panel (**$P < .01$; *$P < .05$). The average values for children and adults are presented with standard deviation bars in *closed circles* and *closed squares*, respectively

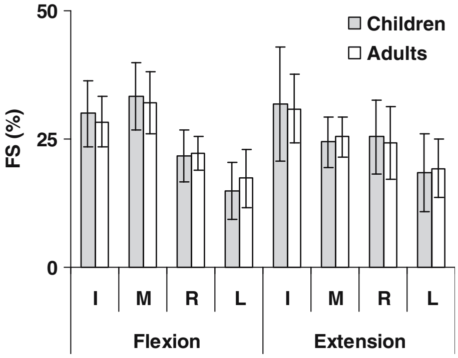

Fig. 5 Force sharing (*FS*) of the I, M, R, and L fingers during four-finger flexion and extension MVC force production tasks. Averaged group data are shown with standard error bars

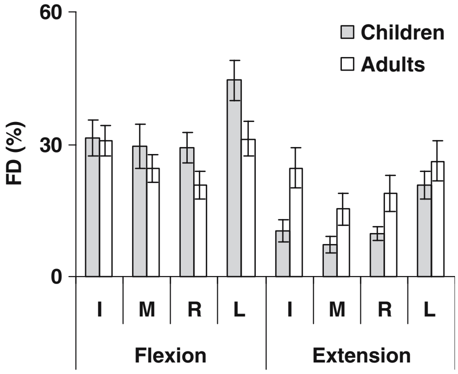

Fig. 6 Force deficit (*FD*) of the I, M, R, and L fingers during flexion and extension tasks. Averaged group data are shown with standard error bars

and it was expressed as a percentage of the maximum single-finger force.

The regression analysis showed that FD values had no significant relationship with children's or adults' age for any force directions or fingers. On average, FDs in the flexion direction were larger than in the extension direction (Fig. 6). Children showed larger FDs in flexion, but smaller FDs in extension compared to adults. Index and little fingers showed relatively large FDs (I: 24% and L: 31%) while middle and ring fingers had smaller FDs (M: 19% and R: 20%). These finding were supported by three-way mixed effects ANOVA which showed significant effects of DIRECTION [$F(1,48) = 30.6$, $P < .001$], TASK [$F(3,144) = 14.0$, $P < .001$], and significant interactions of DIRECTION × TASK [$F(3,144) = 50.7$, $P < .001$], DIRECTION × AGE [$F(3,48) = 10.6$, $P < .001$], and TASK × AGE [$F(3,144) = 8.0$, $P < .001$]. There was no significant effect of age or other interactions found.

Discussion

In this study, we investigated the age-related changes in maximum finger forces and finger interaction indices (FE, FS, and FD) from single-finger and four-finger MVC force production tasks in flexion and extension directions. The capability of maximum finger force production and finger independency increase with children's age while it does not change with adults' age. Maximum finger forces and finger independency are larger in flexion than in extension in both groups. In general, the rates of age-related change in maximum finger forces and finger independency in children are larger for flexion than extension. The total force during the four-finger task comprised of different percentages of individual finger forces. These percentages are consistent throughout ages.

Developments of maximum force production and finger interaction indices

The increase of the maximum finger forces with children's age found in this study is compatible to the reports of previous studies (Smits-Engelsman et al. 2003). In general, all absolute slopes between MVF values and children's age were larger in flexion than in extension. Thus, the strength of finger flexor muscles (i.e., extrinsic flexor digitorum profundus/superficialis and intrinsic midpalmar muscles) develops at a higher rate as indexed by the absolute slopes. This claim is also supported by the larger differences of finger forces between children and adults in flexion than in extension. On the other hand, the larger relative slopes in extension in all individual fingers indicate that the relative strength of finger muscles of children with respect to the adults' strength level develops at a higher rate in extension than flexion.

The MVF differences for index, middle, ring, little, and four-finger tasks for flexion were about four-folds larger than for extension. The oldest child age group in our study, 10-year-old children, showed an average four-finger MVF around 25 N which was only 22% of finger flexion strength of the adult subjects in this study and 29% of the strength (~85 N) of young adults reported in previous studies (Shinohara et al. 2003a, b).

The smaller *inter-dependency* of fingers with children's age reflects the larger *independency* of fingers. Thus, the age-related decreases in finger inter-dependency index (FE) in children indicate the increase of finger independency with children's age. The previously reported improvements of manipulation coordination in children may partially benefit from the increase in finger independency during children's development. The level of finger independency development in 10-year-old children was very close to that of adults in flexion. The FE value (26%) averaged across the 10-year-old children is very close to the averaged FE value (28%) of adults in flexion tasks. However, in extension, the averaged FE value of children almost doubles that of adults (children 52% and adults 27%). Thus, the finger independency during flexion is already developed to the level of adults at 10 years of age while it requires additional years of development to reach the adults' finger independency levels in extension.

Multi-digit manual dexterity cannot be explained solely by digit independency because there are other aspects of digit control which are critical for multi-digit dexterity. For example, when a manipulation task requires actions of multiple digits, all digits should work together to compensate each other's errors in order to achieve the same manipulation task goal (Shim et al. 2004, b; Shinohara et al. 2004). Impairment of this synergic action with multiple digits can compromise performance in fine manipulative skills. Although the increase in digit independency previously found in elderly adults (Shinohara et al. 2003b), if any, should be related with an increase in their manual dexterity, it has been reported that the performance of the hand in everyday activities declines in elderly adults (Hackel et al. 1992). Thus, it appears that the diminished hand dexterity in elderly adults is contributed more by the previously reported decrease in synergic actions of multiple digits in elderly persons (Shinohara et al. 2004).

The values of FS or FD did not show significant relationships with children's or adults' age. The FS values (I: 30%, M: 33%, R: 22%, and L: 15%) found during four-finger flexion MVC tasks in this study were also very similar to the FS values (I: 30%, M: 30%, R: 25%, and L: 15%) reported in a previous study on adults (Shinohara et al. 2003a). Thus, the finger FS pattern in children is developed in their early ages, at least before 6 years of age, or it is an inherent characteristic. The FD values of individual fingers of children were different from those of adults in this study as well as a previous one (Shinohara et al. 2003a). However, our study found no significant changes in FD values with children between 6 and 10 years of age. It is currently necessary to perform a follow-up study and investigate subjects between 10 and 20 years of age to understand continuous developmental trajectories/changes of finger FD.

Differences of maximum force production and finger interaction indices between flexion and extension

Compared to the maximum force (10.3 N averaged across fingers) produced by fingers in the extension direction, the maximum force (15.7 N) produced in flexion was one and a half times larger in children. This phenomenon was more obvious in adults: the maximum force of flexion was four times larger in flexion (33.5 N) than in extension (8.5 N). Thus, the finger flexion strength is larger than the finger extension strength for both children and adults. Most of everyday manipulation tasks such as grasping an object, handwriting, and keyboarding require force productions in finger flexion while few everyday tasks require finger force production in extension. This finding seems congruent with greater necessities on finger force production in flexion in everyday life.

Finger independency is constrained by central and peripheral factors [reviewed in Schieber and Santello (2004)]: the central factors include the CNS control of individual fingers, whereas the peripheral factors consist of biomechanical connections of soft tissues. For example, neurons in the primary motor cortex (M1) with outputs diverging to innervate the spinal motor neuron pools of different finger muscles (Shinoda et al. 1979; Fetz and Cheney 1980; Buys et al. 1986), interconnections of finger tendons (von Schroeder et al. 1990; von Schroeder and Botte 2001), insertions of one muscle to multiple fingers such as the flexor digitorum profundus (Kilbreath et al. 2002) can decrease the finger independency. The greater finger independency during flexion found in children reflects better CNS control and/or biomechanical connections for finger independency during flexion than extension. The increase in finger independency with children's age may also reflect the peripheral and central changes for finger independency. Although finger flexion strength of 10-year-old children seems to require more years to become similar to adults' strength, the maturation of the extension maximum strength in 10-year-old children already reaches the adult level. However, the opposite phenomenon was found in finger independency. The flexion digit independency level in 10-year-old children was already similar to the adult level while the extension digit independency seems to require more years to reach the adult level. In everyday manipulation activities, greater finger independency during flexion is demanded. For example, when holding an object, one of the most common tasks of manipulation, requires contacts of fingertip pads with the hand-held objects. This functional demand of muscles in everyday manipulation tasks may have provided children with learning experiences for finger independency in flexion while accompanying plastic changes of the CNS. However, these speculations on the finger independency may be more appropriately quantified with an experiment composed of passive and active/voluntary finger actions: a passive finger action reflects more biomechanical connections between fingers (peripheral factor) and an active finger action involves both peripheral and central factors (Lang and Schieber 2004). The demand in everyday manipulation activities on flexion also seems to contribute to setting a large difference between flexion and extension in adults' maximum finger strength as compared to children. The difference between the flexion and extension strengths is relatively small in children, but becomes much larger in adults (Fig. 3).

The FD and FS also showed differences in flexion and extension. The FD was three to four times larger in flexion than in extension. The previous study by Shinohara et al. (2003a) showed the positive and negative correlations of MVF with FD and FE, respectively. We also tested the relationship between the FDs and MVF by performing regression analyses. However, we found neither significant coefficients of correlation between FD and MVF nor between FE and MVF in children or adults. Previous studies have shown that FD exists whenever multiple fingers are involved in finger force production tasks (Zatsiorsky et al. 2000; Danion et al. 2003; Shinohara et al. 2003b). However, the FDs may be minimized by a large FE since the voluntary force produced by a task finger can induce a large involuntary force produced by non-task fingers, which may contribute to the total force produced by multiple fingers. In this sense, the smaller extension FD found in this study seemed to be contributed by the larger FE in extension as compared to flexion.

Shinohara et al. (2004) previously reported gender differences in MVF, FE, and FD in both young and elderly adults. While gender differences were not a theoretical interest to us, we nonetheless examined the data for possible differences. Except for MVF in adults, we found no discernible data clusters for any of the variables. Not surprisingly, adult males had higher MVF than adult females. In children the data, clusters of males and females were very similar for all variables.

Implications to the control of fingers in sub-maximal force production

Force enslaving of a task finger is induced by unintended forces in non-task fingers. Thus, the larger FE accompanies the larger positive covariation among finger forces during manipulation. Previous studies used the force ratios between task fingers and non-task fingers to construct an inter-finger matrix or enslaving matrix which has been considered as a default interconnection between fingers during finger flexion force production tasks (Danion et al. 2003; Kang et al. 2004). Our study, however, shows that the FE is quite different for flexion and extension tasks. Thus, at least two different enslaving matrices should be used for the analysis of manipulation tasks requiring both flexion and extension. The investigation on how the enslaving matrix changes in time during finger flexion and extension, however, may require an appropriate task which include both flexion and extension force production (e.g. oscillatory flexion and extension force production) and proper modeling (e.g. modeling of a dynamical system).

Force sharing can be considered as a compound effect of finger MVF and FE of non-task fingers during single-finger tasks as well as FD during four finger tasks. Hypothetically, the enslaving effects should induce a larger maximum force during the four-finger task than the sum of the maximum finger forces during single-finger tasks. However, due to FD, the four-finger maximum force is always smaller than the sum of individual finger maximum forces. Considering the differences in FE and FD between children and adults, the constant FS pattern for children and adults found in this study was unexpected.

One might question the validity of the findings in this study for object manipulation tasks requiring sub-maximal finger force productions. The previous studies on finger interactions in adults (Li et al. 1998; Danion et al. 2001) and this study on children (Fig. 2) showed that the task and non-task finger forces increase in a fairly linear fashion during MVC tasks. Thus, we can assume that the finger interaction indices reported in this study may not differ from sub-maximal finger force production tasks.

Limitations of the current study to address the muscle force–length relationship

The current study investigated the age-related changes of maximum finger forces and finger interaction indices as well as the differences between finger flexion and extension. However, this study is limited to addressing the issue of muscle force–length relationship (Ralston et al. 1947) as the maximum finger force and finger interaction indices can change with wrist and finger positions (Li 2002; Kursa et al. 2006). When the subjects were completely relaxed with the hand, all phalangeal joints of the fingers in flexed positions were observed in our experiments. In order to standardize the phalangeal joint angles of fingers across all subjects, we asked subjects to insert the distal phalanges in the aluminum thimbles with somewhat extended positions of MCP (20°), proximal phalangeal and distal phalangeal joints (Fig. 1) from the resting positions. Therefore, these finger joints may have allowed the hand system to have advantages in flexion than extension for maximum force production.

In order to check the effects of joint angles on maximum finger force and interaction indices, we arbitrarily selected six adult subjects from our adult subject group and tested them again with the same experimental protocols described in Methods. The only difference was that all MCP joints were positioned at about 80° of flexion. The greater MVF values in flexion than extension found in the 20° condition were also observed in the 80° condition for all fingers. The average MVF across all fingers in flexion was 405% of that in extension for the 80° condition while it was 396% for the 20° condition. However, the MVF values were greater in the 20° condition than the 80° condition for both flexion and extension in all fingers. Thus, the phalangeal joint angles in the 20° condition allowed the hand and forearm system to have an overall advantage in muscle force-length relationship as compared to the 80° condition. Other finger interaction indices also changed with MCP joint angles. One noteworthy observation was that the FE values were slightly smaller in the 80° condition than in the 20° condition for flexion, but larger, in all subjects, for extension. This result may be interpreted as a greater FE when flexor or extensor muscles are stretched. Another noteworthy outcome was observed in FS which showed very similar values regardless of the MCP joint angles. Based on the observed systematic changes of MVF and other finger interaction indices between two different joint angles, it is currently necessary to perform a series of experiments to investigate changes in maximum finger force and finger interaction indices with phalangeal joint angles and wrist joint angles in adults as well as age-related changes of the variables in children.

Conclusion

In summary the results showed that (1) MVF increased and finger inter-dependency decreased with children's age, (2) the increasing and decreasing absolute slopes (*N*/year) from regression analysis were steeper in flexion than extension while the relative slopes (%/year) with respect to adults' maximum finger forces were higher in extension than flexion, (3) the larger maximum voluntary finger forces, FE, and FD were found in flexion than in extension, (4) the finger FS was very similar in children and adults, (5) the FS pattern of individual fingers was different for flexion and extension, and (6) the differences between flexion and extension found at 20° MCP joint conditions were also valid at 80° MCP joint conditions. We conclude that (a) the finger strength and independency increase from age 6 to 10 years of age, and the increasing trends are more evident in flexion than in extension as indexed by the absolute slopes, (b) the finger strength and finger independency is greater in flexion than in extension, and (c) the sharing pattern in children appears to develop before 6 years of age or it is an inherent property of the hand neuromusculoskletal system.

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