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RESEARCH ARTICLE

Hand digit control in children: motor overflow in multi-finger pressing force vector space during maximum voluntary force production

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Abstract The aim of this study was to investigate the contralateral motor overflow in children during single-finger and multi-finger maximum force production tasks. Forty-five right handed children, 5–11 years of age produced maximum isometric pressing force in flexion or extension with single fingers or all four fingers of their right hand. The forces produced by individual fingers of the right and left hands were recorded and analyzed in four-dimensional finger force vector space. The results showed that increases in task (right) hand finger forces were linearly associated with non-task (left) hand finger forces. The ratio of the non-task hand finger force magnitude to the corresponding task hand finger force magnitude, termed motor overflow magnitude (MOM), was greater in extension than flexion. The index finger flexion task showed the smallest MOM values. The similarity between the directions of task hand and non-task hand finger force vectors in four-dimensional finger force vector space, termed motor overflow direction (MOD), was the greatest for index and smallest for little finger tasks. MOM of a four-finger task was greater than the sum of MOMs of single-finger tasks, and this phenomenon was termed motor overflow surplus. Contrary to previous studies, no single-finger or four-finger tasks showed significant changes of MOM or MOD with the age of children. We conclude that the contralateral motor overflow in children during finger maximum force production tasks is dependent upon the task fingers and the magnitude and direction of task finger forces.

Keywords Motor overflow · Mirror movement · Finger · Hand · Children · CNS

Introduction

Day to day prehension and manipulation tasks require the central nervous system (CNS) to successfully control individual fingers independent of other fingers, in ipsilateral as well as contralateral limbs. For example, involuntary movements or force produced by non-intended fingers may cause interference to unimanual and bimanual tasks. However, previous studies have shown that independent finger movements or force production in the ipsilateral or contralateral limbs may not be easily achieved. The interdependent actions of fingers have been reported in different populations including children (Lazarus and Whitall 1999; Garvey et al. 2003; Mostofsky et al. 2003; Shim et al. 2006), young adults (Armatas et al. 1996b; Nelles et al. 1998; Zatsiorsky et al. 2000; Li et al. 2004), elderly persons (Bodwell et al. 2003; Shinohara et al. 2003a, b), and patients with neurological or psychiatric disorders (Cohen et al. 1967; Dennis 1976; Farmer et al. 1990; Caramia et al. 2000; Mostofsky et al. 2003). The phenomenon of involuntary motor outputs in ipsilateral and contralateral limbs is known as motor overflow or associated movements (Fog and Fog 1963; Abercrombie et al. 1964; Hoy et al. 2004), which generally refers to the involuntary or unintended outputs of

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motor effectors (e.g., forces, electromyographic activities, kinematic movements, etc.) during voluntary or intended outputs of other motor effectors (read Addamo et al. 2007 for reviews).

Previous studies on contralateral motor overflow (i.e., motor overflow between same limbs on the right and left side) showed that mirror movements are prevalent in children under the age of 10 (Connolly and Stratton 1968; Lazarus and Todor 1987; Muller et al. 1997). Lazarus and Todor (1987) inferred a decrease in contralateral motor overflow in children between the ages of 6 and 16 years for thumb-index pinching forces. Our recent study on 6–10-year-old children also showed a decrease in ipsilateral motor overflow (i.e., motor overflow between fingers in the same limbs) with children's age (Shim et al. 2006). This study also showed that the ipsilateral motor overflow was smaller in finger flexion than extension. However, it is currently unknown whether contralateral motor overflow is specific to the flexion and extension directions of finger actions. The ipsilateral motor overflow among fingers in a same task hand has been called finger enslaving (Zatsiorsky et al. 1998, 2000; Li et al. 2004) while the contralateral motor overflow between task and non-task hands has been called mirror movement (Meyer 1942; Gunderson and Solitare 1968; Nass 1985; Mayston et al. 1997; Muller et al. 1997). Although the nomenclature, "mirror" moment, was given to the contralateral overflow because of the similar movements or muscle activations observed between two limbs during one-limb actions, the similarity of movements between a task limb and a non-task limb has not been systematically investigated, especially for motor tasks involving multiple motor effectors.

This paper on "contralateral" motor overflow in children is an extensionto our previous study on "ipsilateral" motor overflow in children (Shim et al. 2007). The main purpose of this study was to investigate the motor overflow in children during single-finger and four-finger maximum voluntary force (MVF) production. Specifically, we aimed (1) to identify the relationship between the task-hand and non-task hand force force. We hypothesize that the increase in task hand finger force would be associated with the increase in non-task hand finger force; (2) to examine finger dependent (i.e., index, middle, ring, and little) and finger force direction dependent changes in motor overflow. We hypothesize that the motor overflow would be dependent on task fingers and finger force directions; (3) to describe age-related changes in contralateral motor overflow. We hypothesize that the motor overflow would decrease with children's age; and (4) to test the superposition of motor overflow during multi-finger tasks (i.e., is the sum of motor overflow during individual finger tasks the same as the motor overflow of during a multi-finger task?).

Methods

Subjects

Forty-five typically developing children of ages between 5 and 11 years (8.4 ± 0.3 years; mean ± SE) participated in this study. The age range was selected for a comparison between data from previous studies with similar age ranges. All the subjects were right-handed based on 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 (14.6 ± 0.3 cm). The width was measured between the metacarpophalangeal joints of the index and little fingers (7.0 ± 0.1 cm). All children and their parents gave informed consent based upon the procedures approved by the University of Maryland's Internal Review Board (IRB).

Experimental setup

The experimental setup was similar to the one used in our previous study on ipsilateral motor overflow study and the details can be obtained from Shim et. al (2007). The setup included eight two-directional (tension and compression) force sensors (black rectangles in Fig. 1a), with amplifiers (Models 208 M182 and 484B, Piezotronics, Inc) for four fingers (second to fifth digits) of each hand. Adjacent slits were separated medio-laterally by 2 cm (along *Z*-axis in Fig. 1b). The frame for each hand 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 *Z*-axis rotation. C-shaped aluminum thimbles were attached on the bottom of each sensor and the distal phalanges were positioned inside the thimbles. After the position adjustments, the frame was mechanically fixed to the panel using a nut-bolt structure.

Signals from the sensors were conditioned, amplified, and digitized at 100 Hz using 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 with a 19″ monitor was used for data acquisition and the forces applied were displayed on the monitor as online visual feedback

Experimental procedure

All subjects were seated in a chair facing a computer screen with their shoulder abducted at 35° in the frontal plane and elbow flexed at 45° in the sagittal plane, such that the forearm was parallel to the frame (Fig. 1b). The forearms

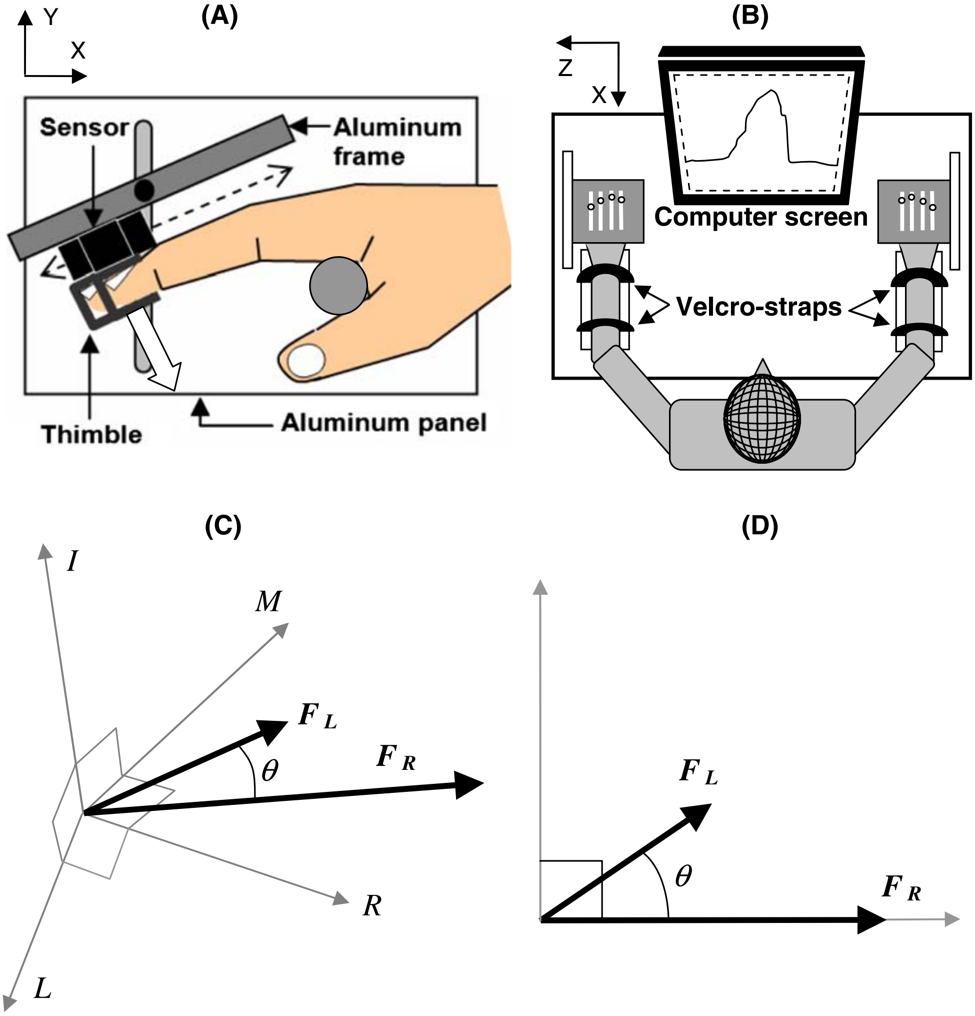


Fig. 1 **a** The experimental setting for the right hand: the two-directional (tension and compression) sensors shown as *black rectangles* were attached to an aluminum frame and the C-shaped thimbles were attached to the bottom of the sensors. The subject inserted the distal phalange of each finger in the thimbles. The experimental settings for the left hand were similar. **b** The wrists and the forearms of the subject rested in wrist-forearm braces and held by two pairs of Velcro-straps. The subject sat in a chair and watched the computer screen while performing the task. **c** Schematic representations of task (*right*) and non-task (*left*) finger force vectors (F_R and F_L) in a four-dimensional finger force space and **d** in a plane of two force vectors. I, M, R, and L represent the axes for index, middle, ring, and little finger forces, respectively. θ is the angle between F_R and F_L

rested on the customized wrist-forearm braces fixed to a wooden panel (29.8 × 8.8 × 3.6 cm). Velcro straps were used to avoid forearm and wrist movements.

Two or three practice trials were given to each subject prior to recorded trials to allow subjects to familiarize themselves with the experimental settings. The subjects were asked to rest the distal phalange of each finger in a thimble such that all joints were slightly flexed (Fig. 1a). In order to remove the gravitational effects of the fingers and 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 used the right hand to performten conditions of the MVF task: five conditions for task fingers (four single-finger tasks and one four-finger task) in two finger force directions (flexion and extension). One trial was performed for each 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 the 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. We employed the MVF task of increasing finger force at a comfortable rate of force development to test the dependency between individual finger forces over the whole finger force range, although the task itself may not be frequently used in everyday manipulative activities. Additionally, previous studies on finger force enslaving (i.e., finger force overflow in the same hand) have shown that non-task finger forces are linearly related to task finger force over the whole range of finger forces (Li et al. 1998; Danion et al. 2003; Shim et al. 2006). The experimenter monitored the subjects' right hand carefully for any joint movements. Trials with visible finger or wrist joint movements were rejected (~3% of the total number of trials) repeated. 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. No child reported discomfort during MVF tasks.

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. 2005). In order to investigate the relationship between the task-hand force magnitude and the non-task hand force magnitude, we used linear regression analysis. For each trial, the force produced by each finger when the maximum force was reached by the task finger(s) was used for further dependent variable calculations. The data were used to detect or calculate the maximum voluntary force [maximum force value of task finger(s) (MVF)], motor overflow magnitude (MOM; Eq. 1), motor overflow direction (MOD; Eq. 2), and motor overflow surplus (MOS; Eqs. 3, 4). The MVF value was determined as the maximum force produced by the task finger(s). For the calculation of MOM, MOD, and MOS, we used a four-dimensional finger force vector space, where the task hand finger force (F_{R}) and non-task hand finger force (F_{L}) were projected (Fig. 1c, d).

Motor overflow magnitude (MOM)

The motor overflow was quantified in the four-dimensional vector space of finger forces normal to the flat surface of the C-shape thimble. Thus, the space here does not represent physical three-dimensional dimensions. In order to quantify the "amount" of motor overflow, we calculated the motor overflow magnitude (MOM) (Eq. 1), the magnitude of the non-task hand force normalized by the finger force magnitude of the task hand in the four-dimensional finger force space.

$$\mathrm{MOM} = \|F_{\mathrm{L}}\|/\|F_{\mathrm{R}}\|, \tag{1}$$

where F_{L} and F_{R} are left-hand and right-hand finger force vectors in the four-dimensional finger force space (i.e., $F_{\mathrm{L}} = \left[F_{\mathrm{L}}^{\mathrm{index}}, F_{\mathrm{L}}^{\mathrm{middle}}, F_{\mathrm{L}}^{\mathrm{ring}}, F_{\mathrm{L}}^{\mathrm{little}}\right]^{\mathrm{T}}$ and $F_{\mathrm{R}} = \left[F_{\mathrm{R}}^{\mathrm{index}}, F_{\mathrm{R}}^{\mathrm{middle}}, F_{\mathrm{R}}^{\mathrm{ring}}, F_{\mathrm{R}}^{\mathrm{little}}\right]^{\mathrm{T}}$ where the subscript L and R represent left and right hands and the superscript T stands for a matrix transpose). $\|F_{\mathrm{L}}\|$ and $\|F_{\mathrm{R}}\|$ are the norms (lengths) of F_{L} and F_{R}, respectively. When MOM = 1, F_{L} and F_{R} lengths are the same and the motor overflow in the non-task hand is the same as the task hand force in four-dimensional finger force space; when MOM = 0, F_{L} length is 0 and the non-task hand does not produce any overflow. Thus, MOM quantifies "how much motor overflow occurs in non-task hand with respect to the task hand".

Motor overflow direction (MOD)

In order to quantify the similarity in multi-finger force sharing patterns between the task-hand force vector and the non-task hand force vector in the four-dimensional finger force vector space, we calculated the angle between the task hand finger force and the non-task hand finger force in four-dimensional finger force vector space, defined as motor overflow direction (MOD) (Eq. 2).

$$\mathrm{MOD} = \frac{\pi/2 - \cos^{-1}\left[(F_{\mathrm{L}} \cdot F_{\mathrm{R}})/(\|F_{\mathrm{L}}\| \cdot \|F_{\mathrm{R}}\|)\right]}{\pi/2}, \tag{2}$$

where $\cos^{-1}\left[(F_{\mathrm{L}} \cdot F_{\mathrm{R}})/(\|F_{\mathrm{L}}\| \cdot \|F_{\mathrm{R}}\|)\right]$ is the angle (θ in Fig. 1c, d) between F_{R} and F_{L} in the four-dimensional finger force vector space. MOD ranges from -1 to 1: when MOD = 1, F_{L} and F_{R} directions are the same; when MOD = 0, F_{L} and F_{R} are mathematically orthogonal to each other; when MOD = -1, F_{L} and F_{R} directions are opposite. Thus, MOD quantifies "how similar the directions of non-task hand force and the task hand force are in four-dimensional finger force vector space". This variable quantifies the "mirrorness" of the non-task hand to the task hand in the four-dimensional finger force vector space.

Motor overflow surplus (MOS)

We also calculated the norm of F_{L} in the four-dimensional finger force vector space to quantify the motor overflow in Newton (N). The motor overflow magnitudes for all single-finger tasks were arithmetically summed up and compared with the motor overflow magnitudes for four-finger task to investigate whether the sum of motor overflow calculated from single-finger tasks $\left(\sum_{j=1}^{n} \|F_{\mathrm{L}}^{j}\|\right)$ was the same as the motor overflow from the four-finger task $\left(\|F_{\mathrm{L}}^{\mathrm{four}}\|\right)$. Motor overflow surplus (MOS) in N was calculated for this quantification (Eq. 3). However, since this quantification can be biased due to the difference in the sum of single-finger MVF values and a four-finger MVF value [also known as "force deficit" (Zatsiorsky et al. 2000; Li et al. 2001; Latash et al. 2002)], we also calculated the MOS in a normalized form using the difference between the MOM averaged across all single-finger MVF tasks and the MOM for four-finger task (Eq. 4). Note that the average across all

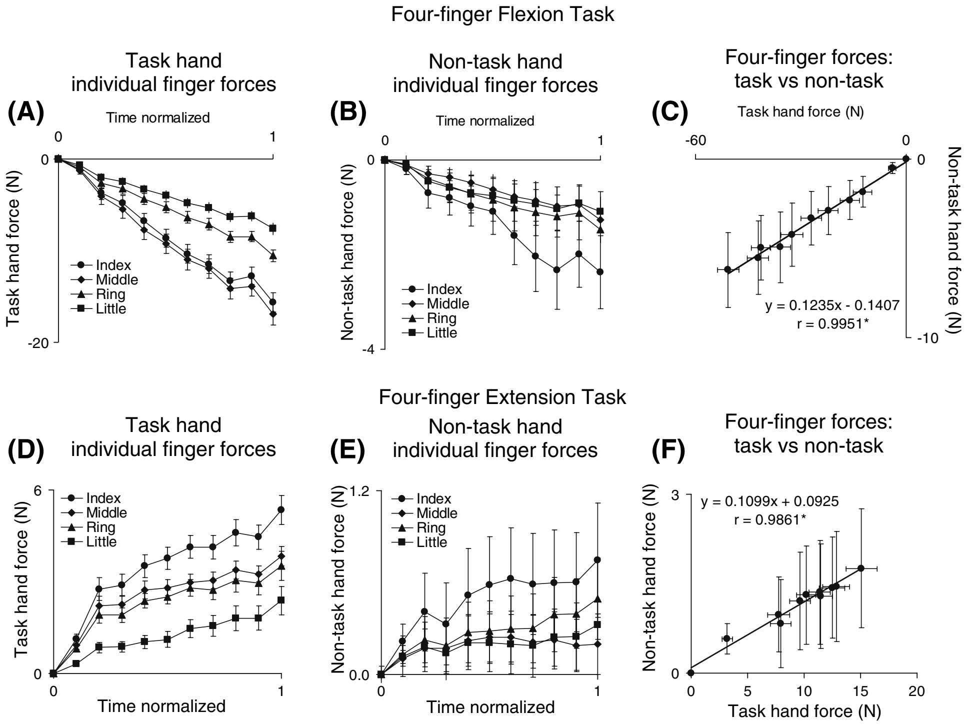


Fig. 2 The task hand finger forces versus the time normalized for the total time from the force production initiation to the time of maximum force production for **a** flexion and **d** extension tasks during four-finger tasks. The non-task hand finger forces versus the normalized time for **b** flexion and **e** extension tasks. The sum of task hand finger forces versus the sum of non-task hand finger forces for **c** flexion and **f** extension. Flexion and extension forces are shown as negative and positive forces, respectively. Means and SE's across subjects are shown at ten time intervals. $^*P < 0.01$

single-finger MVF tasks, rather than the sum, was used because this calculation involved MOM values which were already normalized by the task hand finger MVF (Eq. 1). MOS in N:

$$\mathrm{MOS} = \left\|F_{\mathrm{L}}^{\mathrm{four}}\right\| - \sum_{j=1}^{n} \left\|F_{\mathrm{L}}^{j}\right\| \tag{3}$$

MOS normalized:

$$\mathrm{MOS} = \mathrm{MOM}^{\mathrm{four}} - \left(\sum_{j=1}^{n} \mathrm{MOM}^{j} \Big/ n\right), \tag{4}$$

where j represents single-finger MVF tasks (i.e., j = {index, middle, ring, little}) and four represents a four-finger MVF task. n is the number of single-finger tasks (i.e., $n = 4$).

MOM, MOD, and MOS are new variables which have not been quantified in our or other groups' previous studies. Although motor overflow in finger actions has been quantified in previous studies, we developed these variables to particularly quantify the multi-finger motor overflow between hands. In addition, these new variables provide "overall" motor overflow in multi-finger flexion/extension force vector space.

Statistics

The "differences" between experimental conditions were examined with repeated-measures ANOVA. Standard descriptive statistics and repeated-measures ANOVAs with the within-factors of DIRECTION (flexion and extension), FINGER (index, middle, ring, and little fingers), and TASK (single-finger and four-finger MVF tasks) were performed. Age-related "changes" in dependent variables (MVF, MOM, and MOD) were examined with simple linear regression analysis and Pearson's coefficients of correlation were computed. At $n = 45$, the absolute critical values of significance for the empirical coefficients of correlation are equal to 0.29 for $P = 0.05$ and 0.38 for $P = 0.01$. 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). The level of significance was set at $P = 0.05$ for both ANOVAs and regression analysis.

Results

Relationship between task and non-task hand finger forces

The period between the time of the force production initiation and the time of the maximum force achievement varied in different trials and subjects since the subjects were allowed to produce maximum forces at self-selected rates. We normalized the time by the period from force initiation to the time when maximum force was reached, and we calculated the force values at the 100 msec

Fig. 3 Sum of task hand single-finger forces versus sum of non-task hand single-finger forces for flexion (**a**, **c**, **e**, **g**) and extension (**b**, **d**, **f**, **h**) index (**a**, **b**), middle (**c**, **d**), ring (**e**, **f**), little (**g**, **h**) finger tasks. Coefficients of correlation are all statistically significant (*$P < 0.01$). Flexion and extension forces are shown as negative and positive forces, respectively. Means and SE's across subjects are shown at ten time intervals

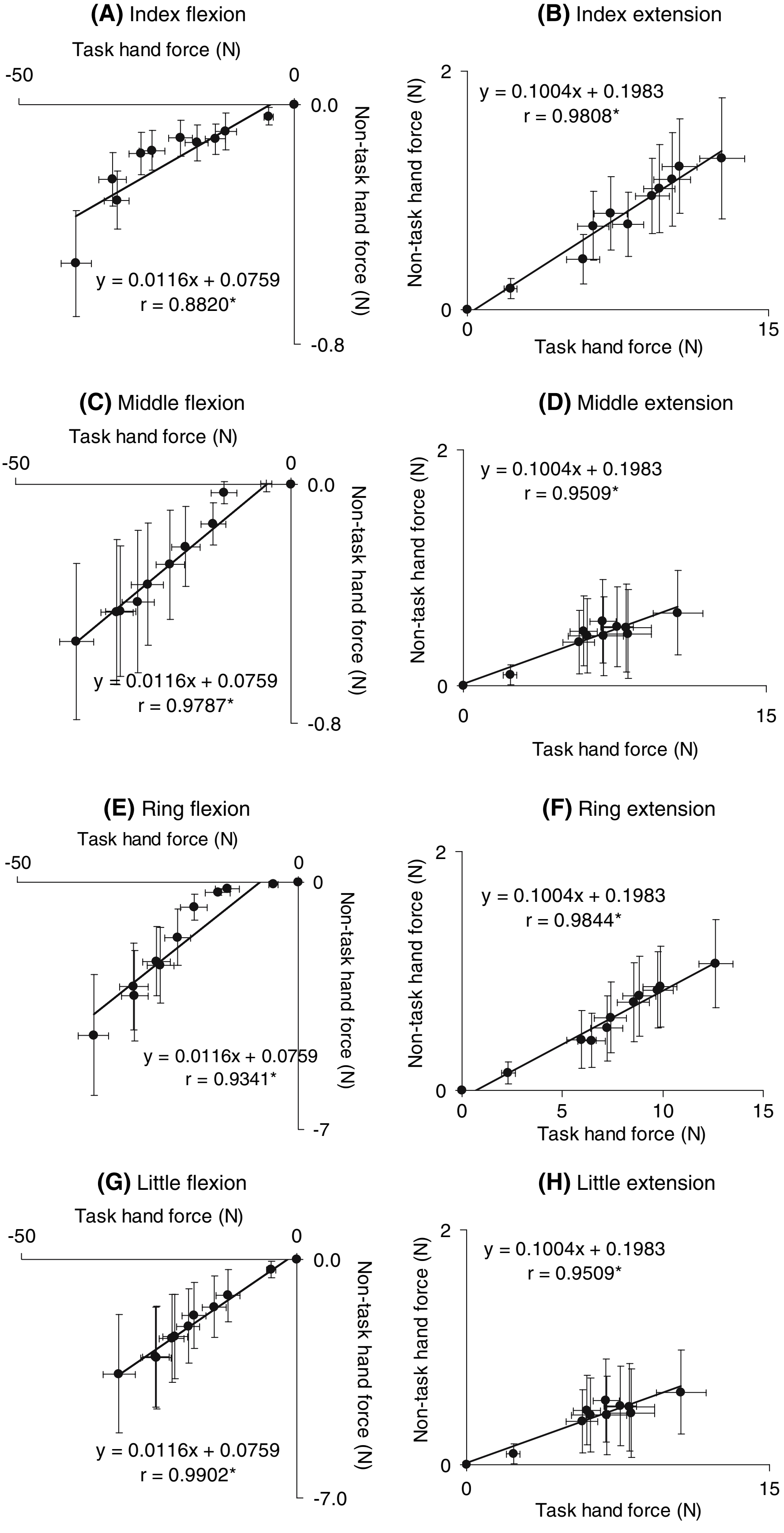


Table 1 Individual finger forces at the time of task finger maximum voluntary force production

Tasks	Non-task (left) hand				Task (right) hand			
	I	M	R	L	I	M	R	L
F								
I	−0.66 ± 0.20	0.03 ± 0.04	0.07 ± 0.06	0.05 ± 0.06	***−20.25 ± 1.20***	−8.31 ± 1.10	−3.48 ± 0.54	−3.30 ± 0.35
M	−0.07 ± 0.08	−0.31 ± 0.11	−0.27 ± 0.07	−0.22 ± 0.06	−5.58 ± 0.81	***−16.63 ± 1.42***	−8.11 ± 0.58	−3.35 ± 0.38
R	−0.81 ± 0.43	−1.10 ± 0.51	−1.30 ± 0.47	−1.05 ± 0.42	−4.09 ± 0.91	−10.36 ± 1.01	***−12.29 ± 0.71***	−5.77 ± 0.61
L	−0.73 ± 0.37	−0.61 ± 0.43	−0.60 ± 0.32	−0.50 ± 0.30	−3.10 ± 0.68	−5.31 ± 1.00	−7.42 ± 0.63	***−11.12 ± 0.67***
E								
I	0.87 ± 0.20	0.15 ± 0.09	0.09 ± 0.06	0.07 ± 0.05	***5.61 ± 0.54***	2.78 ± 0.25	1.76 ± 0.27	0.97 ± 0.24
M	0.26 ± 0.14	0.32 ± 0.13	0.31 ± 0.12	0.23 ± 0.11	2.96 ± 0.47	***3.22 ± 0.64***	2.47 ± 0.31	1.18 ± 0.24
R	0.10 ± 0.13	0.15 ± 0.13	0.32 ± 0.10	0.25 ± 0.09	1.82 ± 0.30	2.85 ± 0.23	***3.98 ± 0.27***	1.92 ± 0.24
L	0.19 ± 0.10	0.05 ± 0.09	0.14 ± 0.08	0.05 ± 0.07	1.27 ± 0.46	1.24 ± 0.31	2.66 ± 0.31	***3.45 ± 0.43***

Task finger MVF's are bold and italicized. The force values are presented in Newtons (N)

F and *E* flexion and extension tasks; *I*, *M*, *R*, and *L* index, middle, ring, and little finger MVF tasks

Values are mean ± SE

intervals one for both flexion (Fig. 2a–c) and extension (Fig. 2d–f) in four-finger MVF tasks. Both task and non-task hand finger forces increased with time. The voluntary increase in task hand finger forces were accompanied by the involuntary increase in non-task hand finger forces (Fig. 2c, f). Linear regression analysis, performed between the sum of single-finger forces in task hand and the sum of single-finger forces in non-task hand showed very strong relations for both flexion ($r = 0.99$) and extension ($r = 0.98$).

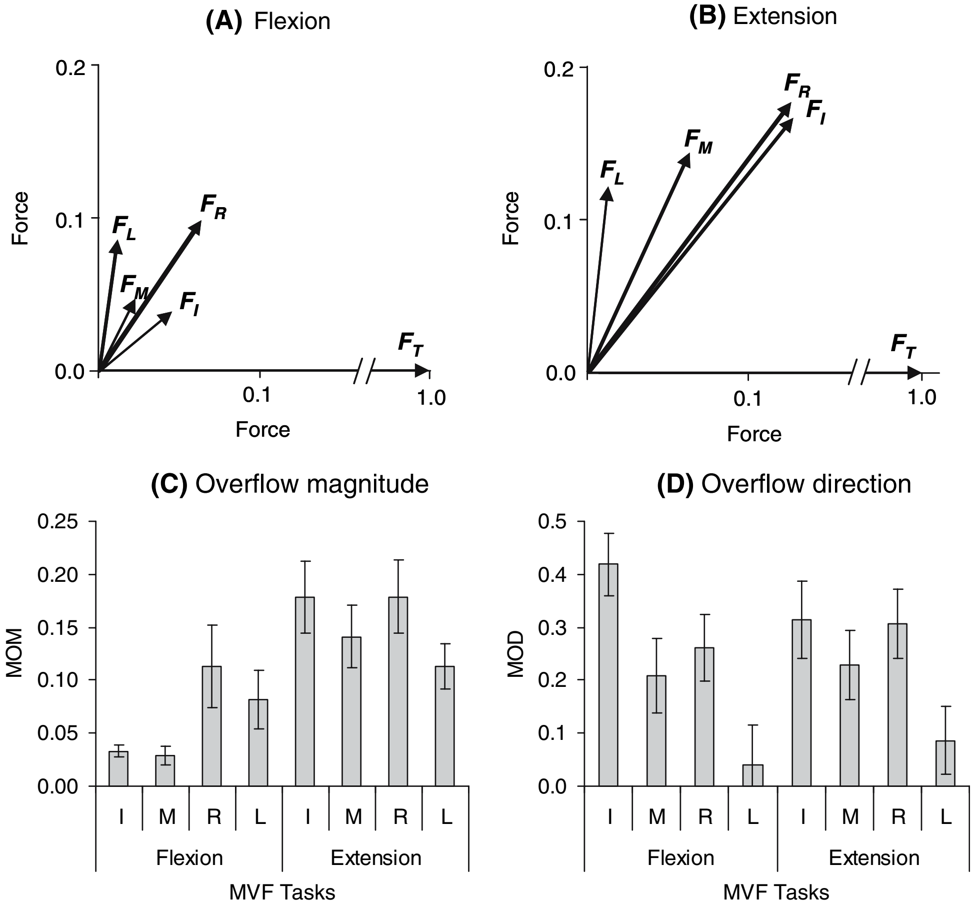


Fig. 4 The non-task hand finger forces for (**a**) flexion and (**b**) extension tasks normalized by the task hand finger force (F_T) magnitude. F_I, F_M, F_R, and F_L represent the non-task hand forces for index, middle, ring, and little finger maximum force value (*MVF*) tasks, respectively. The non-task hand forces in the plane composed by task and non-task hand forces are shown. The task hand force direction is parallel to the horizontal axis. The length and the width of the non-task hand force vectors represent the mean and the SE across all subjects, respectively. **c** Motor overflow magnitude (*MOM*) and **d** motor overflow direction (*MOD*) for single-finger MVF tasks. *I*, *M*, *R*, and *L* represent index, middle, ring, and little finger tasks, respectively. Means and SE's across subjects are shown

Table 2 Individual finger forces at the time of four-finger maximum voluntary force production

Tasks	Non-task (left) hand				Task (right) hand			
	I	M	R	L	I	M	R	L
F	−2.26 ± 0.71	−1.29 ± 0.49	−1.44 ± 0.53	−1.08 ± 0.41	−15.43 ± 0.98	−16.72 ± 1.17	−9.99 ± 0.61	−7.44 ± 0.62
E	0.72 ± 0.34	0.17 ± 0.19	0.48 ± 0.25	0.32 ± 0.21	5.05 ± 0.44	3.61 ± 0.29	3.31 ± 0.46	2.49 ± 0.43

The force values are presented in Newtons (N)

F and *E* flexion and extension tasks. *I*, *M*, *R*, and *L* index, middle, ring, and little finger MVF tasks

Values are mean ± SE

Single-finger MVF tasks also showed the same trend. The task hand finger forces increased both for flexion and extension, and the increase in task hand finger forces were accompanied by the increase in non-task hand finger forces, for both flexion (Fig. 3a, c, e, g) and extension (Fig. 3b, d, f, h). Regression analysis performed between the sum of single-finger forces in task hand and the sum of single-finger forces in non-task hand showed strong correlations between them ($r > 0.8$ for all conditions, $P < 0.01$).

Motor overflow changes due to task fingers and finger force directions

During the single-finger MVF tasks, the force production of instructed fingers in the task hand was accompanied by considerable magnitudes of uninstructed finger forces in the task hand (i.e., ipsilateral motor overflow or force enslaving) as well as small, but non-zero magnitudes of finger forces (i.e., contralateral motor overflow) in the non-task hand as shown in Table 1.

Motor overflow magnitude (MOM) was calculated in order to quantify the finger force magnitude in the non-task hand with respect to the finger force magnitude in the task hand (Fig. 4a, b). In general, MOM values were greater in extension than flexion (Fig. 4c). This finding was supported by two-way repeated-measures ANOVA with the factors of DIRECTION and FINGER which showed significant effect of DIRECTION [$F(1,39) = 12.47$, $P < 0.001$] and DIRECTION x FINGER [$F(3,117) = 2.84$, $P < 0.05$], but no significant effect of FINGER [$F(3,117) = 2.41$, $P = 0.07$]. Further analysis of multiple comparisons (post hoc tests) with statistical adjustments showed that MOM values during index and middle finger tasks were different between flexion and extension ($P < 0.05$), but the values were not different between flexion and extension for ring and little finger tasks.

Motor overflow direction (MOD) values were also calculated to quantify the similarity between the non-task finger forces and the task hand finger forces in terms of directions of the forces in multi-finger force vector space (Fig. 4d). MOD values were not different between flexion and extension tasks, while the values were different between different single-finger tasks ($I > R > M > L$). These findings were supported by significant effects of FINGER [$F(3,117) = 9.45$, $P < 0.001$], but no significant effects of DIRECTION [$F(1,39) = 0.00$, $P = 0.98$] or DIRECTION x FINGER [$F(3,117) = 0.74$, $P = 0.53$].

MOM, MOD, and MOS for four-finger MVF tasks were calculated from the individual finger force values (Table 2) at the time of four-finger MVF. MOM and MOD values during four-finger MVF tasks were not statistically different between flexion and extension tasks although the average value of MOM for flexion was 64% of the average value of MOM for extension and the averaged value of MOD for extension was 74% of the average value of MOD for flexion (Fig. 5). Thus, motor overflow was not specific to finger force directions (i.e., flexion and extension) for the four-finger tasks. This finding was supported by One-Way repeated-measures ANOVA with the factor of DIRECTION which revealed no significant difference between flexion and extension tasks in MOM [$F(1,44) = 1.533$, $P = 0.222$] or MOD [$F(1,44) = 0.398$, $P = 0.531$].

Relationship between motor overflow and children's age

Linear regression analysis on MOM and MOD during single-finger tasks with children's age was performed to investigate whether MOM and MOD change with children's chronological age (Fig. 6). The regression analysis showed that the children's age was not significantly related with the MOM or MOD changes. This finding was supported by relatively low and no significant coefficients of correlation for MOM [flexion: I ($r = 0.094$), M ($r = -0.077$), R ($r = -0.026$), and L ($r = -0.066$); extension: I ($r = 0.014$), M ($r = 0.082$), R ($r = 0.000$), and L ($r = 0.152$)] and MOD [flexion: I ($r = -0.123$), M ($r = -0.274$), R ($r = -0.032$), and L ($r = 0.032$); extension: I ($r = -0.138$), M ($r = 0.161$), R ($r = 0.062$), and L ($r = 0.118$)]. Regression analysis performed on four-finger tasks also showed that overflow variables showed no significant coefficients of correlation with children's age

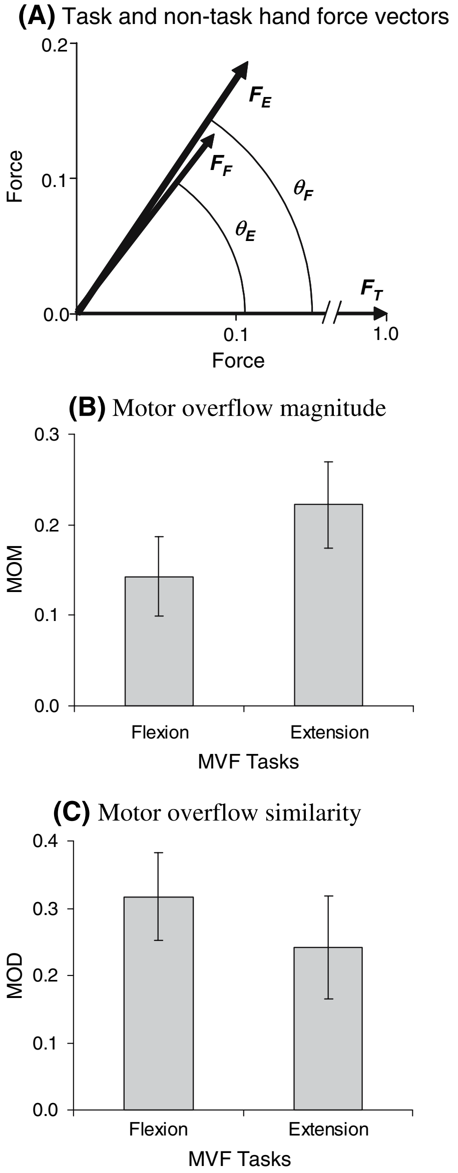


Fig. 5 **a** The non-task hand finger forces for flexion and extension tasks (F_F and F_E) normalized by the task hand finger force (F_T) magnitude. The task hand force direction is parallel to the horizontal axis and the angles between the task hand force and the non-task hand force are shown for flexion and extension tasks (θ_F and θ_E). The non-task finger forces in the plane composed by task and non-task hand forces are shown. The length and the width of the force vectors represent the mean and the SE values across all subjects respectively. **b** The MOM and **c** MOD during four-finger MVF tasks. Means and SE's across all subjects are shown

[MOM: flexion ($r = -0.141$) and extension ($r = 0.125$); MOD: flexion ($r = -0.010$) and extension ($r = -0.017$)].

Motor overflow surplus

In order to investigate whether the summed motor overflow from each single-finger task was the same as the motor overflow from a four-finger task, the MOM values in Newton (N) (Fig. 7a) for single-finger tasks were summed and compared to MOM values in N for four-finger tasks. The sum of MOM values of single-finger tasks were greater than the MOM values of four-finger tasks, which was reflected in the negative MOS values in N for both flexion and extension (Fig. 7b). These findings were supported by two-way repeated-measures ANOVA performed on MOM values with the factors of DIRECTION and TASK which showed the significant effect of TASK [$F(1,44) = 4.78$, $P < 0.05$], but no significant effects of DIRECTION [$F(1,44) = 2.68$, $P = 0.11$] or DIRECTION × TASK [$F(1,44) = 0.27$, $P = 0.61$].

We also calculated the MOM and MOS values normalized by the corresponding task finger maximum forces (Fig. 7c). The MOM values calculated from the single-finger tasks were smaller than the MOM values calculated from the four-finger task. This was reflected in the positive MOS values for both flexion and extension (Fig. 7d). The MOM values were greater in extension than flexion. These findings were supported by two-way repeated-measures ANOVA with the factors of DIRECTION and TASK which showed significant effects of DIRECTION [$F(1,44) = 6.35$, $P < 0.05$] and TASK [$F(1,44) = 4.15$, $P < 0.05$], but no significant effect of DIRECTION × TASK [$F(1,44) = 0.02$, $P = 0.89$].

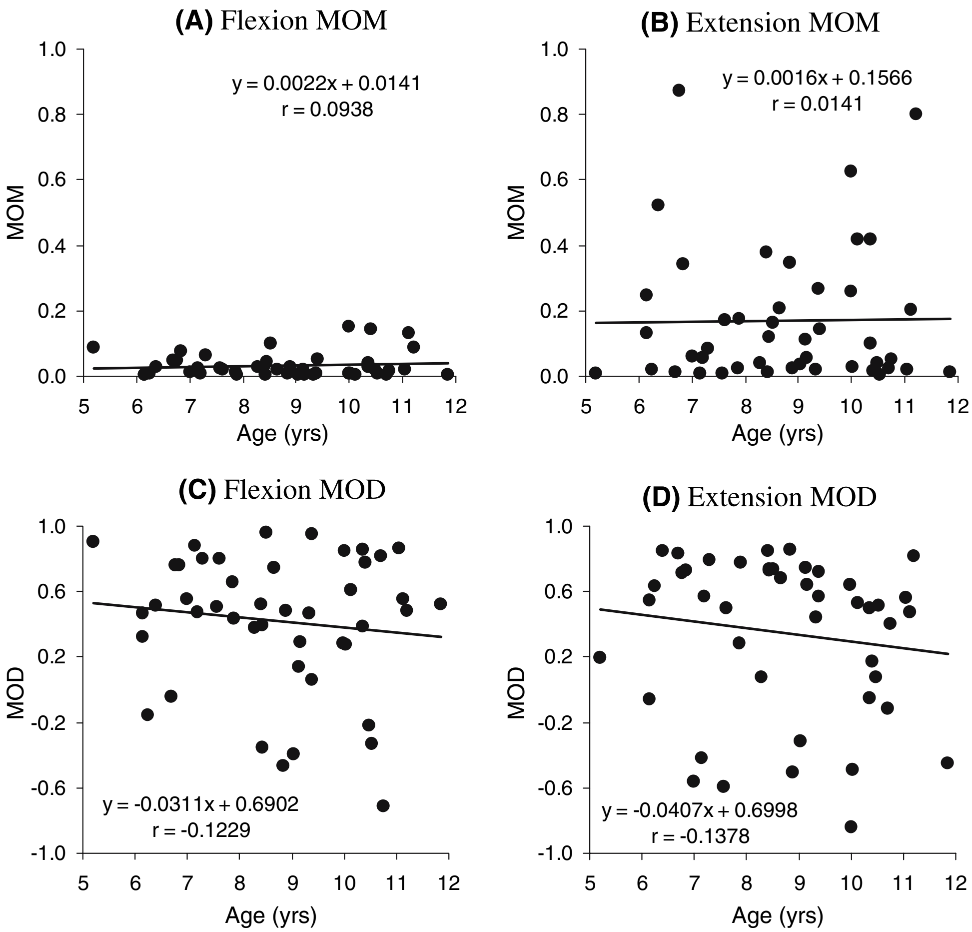
Discussion

In summary, the results showed that increases in task (right) hand finger forces were linearly associated with non-task (left) hand finger forces. The motor overflow magnitude was greater in extension than flexion, and the index finger flexion task showed the smallest motor overflow magnitude values. The motor overflow directional similarity in multi-finger force vector space was the greatest for index and smallest little finger tasks. MOM of a four-finger task was greater than the sum of MOMs of single-finger tasks. Contrary to previous studies, our finger force production tasks showed no significant changes of motor overflow variables with children's age.

A simple illustration (Fig. 8) is used to explain the general phenomenon of contralateral motor overflow (e.g., motor overflow between two hands during a one-hand task) and ipsilateral motor overflow (e.g., motor overflow between the fingers in the same hand during a single-finger task) during single-finger and multi-finger force production tasks.

For a right index finger force production in flexion, for example, cortical and subcortical neurons are activated to carry out the "command" for index finger force production (A in Fig. 8). However, the command to activate only the

Fig. 6 Relationship of MOM (**a**, **b**) and MOD (**c**, **d**) with the children's age for a representative single-finger (index-finger) MVF tasks during flexion (**a**, **c**) and extension (**b**, **d**). Each *closed circle* represents an individual child and all 45 children are shown in each panel.



index finger flexor muscles is usually interfered by the CNS constraints (B in Fig. 8; reviewed by Schieber and Santello 2004), which may include cortical outputs diverging and innervating the spinal cord motor neuron pools of different finger muscles in the same (i.e., ipsilateral) hand (Shinoda et al. 1979; Fetz and Cheney 1980; Buys et al. 1986). The neuronal activities originated from the right hemisphere "flow" to the other hemisphere (i.e., facilitations) (Cernacek 1961; Ugawa et al. 1993; Mayston et al. 1999; Hanajima et al. 2001) and are also inhibited (i.e., inhibitions) through interhemispheric connections (Ferbert et al. 1992; Leocani et al. 2000; Aranyi and Rosler 2002; Sohn et al. 2003) (C in Fig. 8). The upper two boxes in the illustration represent complex neuronal connections on each side.

The neural signals arriving at the muscles are also interrupted by the peripheral constraints (D in Fig. 8), which may include interconnections of finger tendons (von Schroeder et al. 1990; von Schroeder and Botte 2001) and insertions of one muscle to multiple fingers such as the flexor digitorum profundus (Leijnse et al. 1997; Kilbreath et al. 2002). Each black box at the peripheral level represents complex musculotendinous connections. The horizontal arrows between two boxes represent the mechanical interactions between two limbs (E in Fig. 8), such as force transfer through kinetic linkages (Zatsiorsky 2002). The contralateral motor overflow between task and non-task hands mostly attributes to the central constraints (reviewed by Hoy et al. 2004) because the kinetic interactions between two limbs due to biomechanical connections are minimal in the fingers between two hands, especially when the motor task is isometric. Sensory feedback (G in Fig. 8) is also included in the illustration. Although different modalities of sensory feedback play critical roles in controlling the fingers (Edin et al. 1992; Forssberg et al. 1995; Johansson 1998; Monzee et al. 2003; Nowak et al. 2003), possible effects of sensory feedback on ipsilateral or contralateral motor overflow have been understudied and require more attention. The present study is limited in addressing the issues of the relative contributions of central and peripheral constraints or sensory feedback contributions to motor overflow in children.

Linearity of motor overflow

Our current and previous studies showed linear increases in both ipsilateral and contralateral non-task finger forces with

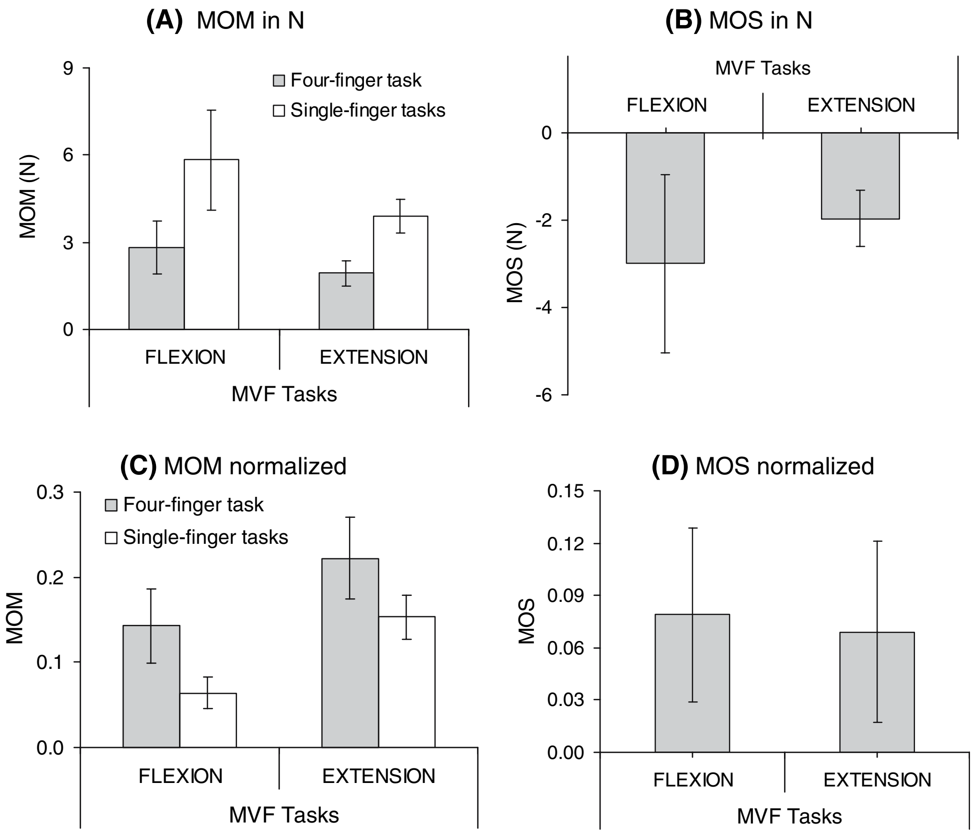


Fig. 7 MOM in N (**a**) and in a normalized form (**c**) calculated from four-task and single-finger tasks during flexion and extension MVF tasks. MOS values in N (**b**) and in a normalized form (**d**). Means and SE’s across subjects are shown

task finger forces. Thus, despite the extreme nonlinearity of the biological system even from the cellular level, the connections between the two black boxes (C in Fig. 8) at the CNS may be modeled as linear systems at the behavior level. The increase in non-task hand finger forces with task hand finger forces found in the current study support other previous findings in children (Armatas et al. 1996b; Georgiou-Karistianis et al. 2004). Armatas et al. (1996b) used 25, 50, and 75% MVF for constant target forces and found that the involuntary forces of non-task index and little fingers increased with target force magnitudes. Although both neural and biomechanical connections between the muscles for individual fingers in an ipsilateral hand are extremely complex (black boxes at the CNS level in Fig. 8), previous studies on ipsilateral motor overflow in children and adults also showed linear increases in non-task finger outputs with task finger motor outputs during slowly increasing maximum force production tasks (Hager-Ross and Schieber 2000; Zatsiorsky et al. 2000; Shim et al. 2006).

Finger and finger force direction dependent motor overflow

The single-finger MVF tasks induced greater motor overflow magnitude (e.g., MOM) in extension tasks than flexion tasks. These results are similar to the findings from our recent study on ipsilateral motor overflow during single-finger tasks in children (Shim et al. 2006), which also showed greater force enslaving (i.e., ipsilateral motor overflow) in extension than flexion. The study suggested that the dexterous finger actions in everyday activities largely rely on finger flexion than extension, and more experience with finger flexion tasks may contribute to lessening ipsilateral motor overflow for flexion. Given this suggestion and no changes of contralateral motor overflow with children’s age found in our experiments, one can suggest that the smaller contralateral motor overflow in flexion may be due to the greater increase in interhemispheric inhibition or decrease in interhemispheric facilitation in flexion than extension. The inhibition and facilitation may be attributed by everyday grasping experiences before the age of five or inborn characteristic differences between flexion and extension muscle controls.

In general, the index finger tasks showed smaller motor overflow magnitude as compared to little finger tasks in children, particularly for flexion. This finding is consistent with previous studies which demonstrated smaller contralateral motor overflow during index finger tasks as compared to little finger tasks (Armatas et al. 1996a; Georgiou-Karistianis et al. 2004). The finding is also similar to the finding from previous studies on ipsilateral

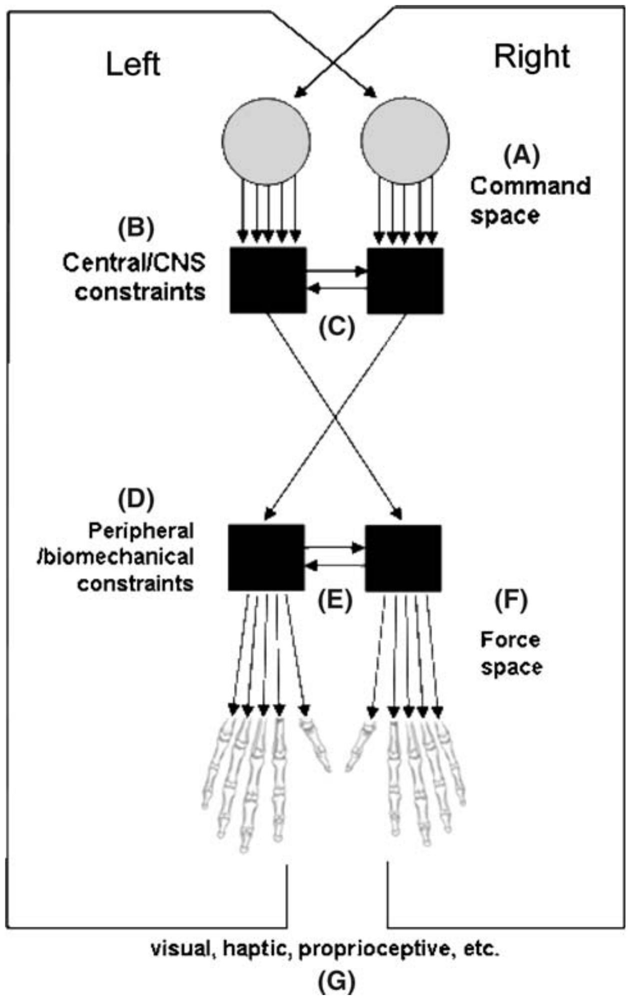


Fig. 8 Schematic representations of finger control in two hands for ipsilateral and contralateral overflow

motor overflow, which showed small force enslaving during index finger tasks as compared to the other fingers (Hager-Ross and Schieber 2000; Reilly and Hammond 2000; Zatsiorsky et al. 2000; Shinohara et al. 2003b; Lang and Schieber 2004). The small contralateral motor overflow in the index finger can be interpreted as the large independency of the index finger, which may contribute to the index finger dexterity.

No age-related changes in motor overflow in children

It has been thought that the decrease in motor overflow is associated with the cortical development for contralateral hemispheric inhibition in children (Cohen et al. 1967; Wolff et al. 1983; Lazarus and Todor 1987; Taylor et al. 1988). The underdeveloped myelination and immature corpus callosum in children have been considered to be responsible for the noticeable motor overflow in children especially under the age of 10 years (Cohen et al. 1967; Nass 1985; Mayston et al. 1997, 1999). Contrary to previous findings, our study showed no significant relationship between *contralateral motor overflow* variables and children's age although significant decrease in *ipsilateral motor overflow* with children's age was found in our previous study (Shim et al. 2006). Thus, our data may not completely support the hypothesis of increasing hemispheric inhibition in children. Although most previous studies used submaximal motor exertion levels and our study used the maximal level, the difference between age-related changes in motor overflow do not seem to arise from the differences in finger force magnitudes employed in experiments. A study by Lazarus and Todor (1987) used MVF for thumb-index gripping to quantify motor overflow and reported decrease in motor overflow from 6- to 7-year-old children. The difference between our study and Lazarus and Todor (1987) may be due to the different tasks. Our study employed an isometric pressing task while the other study used a precision grip

Greater motor overflow during multi-finger tasks

Another interesting result found in our experiments was the motor overflow surplus. The exact mechanism of the positive motor overflow surplus is currently unknown and requires further investigation. One, however, can speculate that the positive motor overflow surplus during four-finger tasks may be due to a decrease in interhemispheric inhibitions (Ferbert et al. 1992; Leocani et al. 2000; Aranyi and Rosler 2002; Sohn et al. 2003) or increase in interhemispheric facilitations (Cernacek 1961; Ugawa et al. 1993; Mayston et al. 1999; Hanajima et al. 2001) during four-finger tasks. Another possible explanation may include interhemispheric "flow" during four-finger tasks to ipsilateral cortical neurons with more diverging outputs to spinal motor neuron pools for finger muscles as compared to single-finger tasks.

Hand dominance effects on Motor Overflow

Previous studies on hand dominance effects on motor performance and control strategies during reaching movements showed that the dominant arm is largely controlled through planning while the non-dominant arm is controlled through feedback mechanisms. This led to the Dynamic-dominance hypothesis (Sainburg and Kalakanis 2000; Sainburg 2002). Based on the studies, one can argue that our results for finger force overflow from the dominant hand tasks may not be generalized to the non-dominant hand. This is debatable considering another study which showed that the Dynamic-dominance hypothesis may not be generalized for isometric finger force production tasks similar to our experimental tasks (Zhang et al. 2006). Our future study will address the issue of the effects of hand dominance in motor overflow by investigating dominant and non-dominant hand finger force production tasks.

We conclude that the motor overflow in children during finger MVF tasks is dependent upon the task fingers, task finger force magnitude, and task finger force direction. The method developed to study motor overflow in multi-finger force vector space may also be used for other motor overflow studies involving other types of multiple effectors such as electromyography studies of multi-muscle activations, kinematic studies of multi-joint angles, and kinetic studies of multi-joint torques.

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