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RESEARCH ARTICLE

Dynamic bimanual force control in chronic stroke: contribution of non-paretic and paretic hands

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Abstract
Dynamic force modulation is critical for performing skilled bimanual tasks. Unilateral motor impairments after stroke contribute to asymmetric hand function. Here, we investigate the impact of stroke on dynamic bimanual force control and compare the contribution of each hand to a bimanual task. Thirteen chronic stroke and thirteen healthy control participants performed bimanual, isometric finger flexion during visually guided, force tracking of a trapezoidal trajectory with force increment and decrement phases. We quantified the accuracy and variability of total force from both hands. Individual hand contribution was quantified with the proportion of force contributed to total force and force variability of each hand. The total force output was 53.10% less accurate and 56% more variable in the stroke compared with the control group. The variability of total force was 91.10% greater in force decrement than increment phase. In stroke group, the proportion of force and force variability contributed by each hand differed across the two phases. During force decrement, the proportion of force contributed by the non-paretic hand reduced and force variability of the non-paretic hand increased, compared with the increment phase. The control group showed no differences in each hand's contribution across the two force phases. In conclusion, dynamic bimanual force modulation is impaired after stroke, with greater deficits in force decrement than force increment. The non-paretic and paretic hands adapt differentially to dynamic bimanual task constraints. During force decrement, the non-paretic hand preferentially assumes force modulation, while the paretic hand produces steady force to meet the force requirements.

Keywords Hemiparesis · Force modulation · Force variability · Task constraint · Motor control

Introduction

Skilled bimanual tasks require dynamic modulation of forces with both hands to achieve a common goal (Gorniak and Alberts 2013; Gorniak et al. 2010). For example, tasks such as buttoning a shirt and tying a shoelace rely on the ability to scale forces with both hands to meet the task goal. Despite this, the effect of stroke on a bimanual task requiring dynamic force control is not well understood. Furthermore, unilateral motor impairments following stroke contribute to limb asymmetries and affect bimanual function (Gebruers et al. 2010; Jorgensen et al. 1995; Michielsen et al. 2012). However, the contribution of non-paretic and paretic hands to a dynamic bimanual force task has not been examined before. The goal of the current study was to determine the impact of stroke on dynamic bimanual force control and compare the contribution of each hand to the bimanual task.

The previous research on bimanual force control after stroke has focused on the modulation of constant forces. Evidence suggests that individuals with stroke demonstrate increased force asymmetry and reduced coordination during modulation of constant bimanual forces (Lodha et al. 2012a). Furthermore, force variability while modulating constant bimanual forces increased following stroke (Kang and Cauraugh 2014, 2015; Lodha et al. 2012b). However, several skilled bimanual tasks require dynamic modulation of forces to manipulate objects. Object manipulation is achieved by systematic increase in force to grasp and lift an object, and controlled decrease in force to release an object. Given the complexity of task involved in scaling forces, dynamic force modulation is intrinsically more challenging than constant force modulation (Newell et al. 2003). Sosnoff and Voudrie

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(2009) reported that healthy adults demonstrate increased magnitude of force variability and reduced structure of force variability during dynamic force modulation compared with constant force modulation (Sosnoff and Voudrie 2009). Here, we investigate the impact of stroke on a bimanual force control task requiring systematic force increment and decrement.

Collaborative interaction between both hands is critical for achieving a common bimanual goal. Consequently, how each hand contributes to a bimanual task is important for understanding limb-specific impairments following stroke. Prior evidence suggests that individual hand contribution in a bimanual task was influenced by specific muscle groups involved (Bertrand et al. 2015; Lodha et al. 2012b). For example, Lodha et al. (2012b) demonstrated that the paretic hand contributed less magnitude of force than non-paretic hand in bimanual finger extension, but this relationship was reversed for bimanual power grip, suggesting that the nature of the muscle contraction influenced hand contribution in bimanual constant force task. Furthermore, Kang and Cauraugh (2014) demonstrated that increased force variability of the paretic hand relative to the non-paretic hand in a bimanual constant force task contributed to impaired bimanual force variability. The evidence regarding individual hand contribution to dynamic force modulation in bimanual task is lacking. Therefore, the second goal of the current study was to examine the contribution of non-paretic and paretic hands to dynamic bimanual force modulation.

The twofold aim of our study was (1) to investigate the impact of stroke on dynamic bimanual force control and (2) to compare the contribution of each hand to the bimanual force increment and decrement in individuals with stroke and age-matched healthy controls. Dynamic bimanual force control was examined using a visually guided, force tracking of a trapezoidal trajectory that required controlled force increment and decrement. We determined the contribution of each of hand to bimanual task by examining (a) proportion of force contributed by each hand to the total force and (b) force variability of each hand. We hypothesized that the stroke group would demonstrate impaired dynamic bimanual force control compared with the healthy controls. Considering that unilateral motor deficits result in asymmetric hand function after stroke, we expected that the contribution of each hand to bimanual task will be altered between the two force phases in the stroke but not in the control group.

Methods

Participants

Thirteen chronic stroke survivors (age = 68.04 ± 12.17 years; time post-stroke = 5.46 ± 3.78 years) and 13 age-matched healthy controls (age = 69.79 ± 7.94 years) participated in the study. Participant characteristics are presented in Table 1. The inclusion criteria for the stroke group were: (1) diagnosis of cerebrovascular accident at least 6 months prior to participation, (2) ability to maintain a neutral wrist, metacarpophalangeal, and interphalangeal joint position with or without assistance, (3) ability to voluntarily press down with the index finger, (4) ability to follow a three-step command, (5) not taking Botox treatment. For both groups, the exclusion criteria were presence of musculoskeletal injuries or any other neurological condition, history of surgery or pain affecting upper limbs, and uncorrected vision and hearing impairments. The Institutional Review Board of Colorado State University approved the experimental procedures. All participants provided a written informed consent prior to the study participation.

Table 1 Participant characteristics

	Stroke (*N* = 13)	Control (*N* = 13)
Age (years)	68.04 ± 12.17	69.79 ± 7.94
Gender (female), *N*	7	6
Pre-stroke hand dominance (right), *N*	10	12
Montreal cognitive assessment (/30)	27.69 ± 2.13	28.00 ± 1.41
Hemiparetic side (left/right), *N*	9/4	n/a
Time since stroke (years)	5.46 ± 3.78	n/a
Fugl-Meyer assessment upper extremity		
Motor score (/66)	49.46 15.14	n/a
Sensation score (/12)	9.91 ± 3.57	n/a
Modified Ashworth score (/4)	0.47 ± 0.37	n/a
Bimanual MVC (N)	13.91 ± 5.56	21.84 ± 9.12
Non-paretic/dominant hand force in bimanual MVC (N)	8.72 ± 4.28	11.86 ± 5.50
Paretic/non-dominant hand force in bimanual MVC (N)	5.31 ± 2.14	10.02 ± 3.97

All scores are mean ± standard deviation

MVC maximum voluntary contraction, *n/a* not applicable

Clinical evaluation

For the stroke group, the degree of sensorimotor impairment was evaluated using the upper extremity component of the Fugl-Meyer Assessment of sensory and motor function (Fugl-Meyer et al. 1975). The sensory examination included assessment for light touch on the palmar surface of the index finger. The extent of spasticity was measured by the Modified Ashworth Scale (Bohannon and Smith 1987). For both groups, the cognitive status was assessed by the Montreal Cognitive Assessment (Nasreddine et al. 2005) and the hand dominance was determined using the Edinburgh Handedness Inventory (Oldfield 1971).

Experimental set-up

Participants sat in an upright chair in front of a 32 inch monitor placed ~ 3.5 feet away from the chair. The arms rested on the table with shoulders in ~ 20° abduction and 30° flexion, and elbows at 90° flexion. The forearms were positioned in full pronation. The forearm, wrist, and hand were stabilized on a wooden platform with a velcro strap to prevent any extraneous movements during task performance. Figure 1a shows the position of the forearm and fingers in customized platforms during the bimanual task. Participants performed the following tasks involving bimanual isometric index finger flexion: (1) maximum voluntary contractions (MVC) and (2) visually guided, force tracking of a trapezoidal trajectory involving force increment and decrement phases (Fig. 1b).

Maximum voluntary contraction

Participants were instructed to push down with both hands' index fingers simultaneously on a small button force transducer by pressing as hard as possible for 3 s. Three trials were performed with a rest period of 60 s between the trials. The MVC for each trial was computed as the maximum total force (sum of forces from two hands) produced during simultaneous isometric finger flexion of both hands. Within each trial, the maximum force was calculated as the average of ten samples around the peak total force produced. Each participant's bimanual MVC was determined as the maximum total force obtained in the three MVC trials.

Dynamic bimanual task

The dynamic bimanual force tracking task involved controlled increment (force increase) and decrement (force release) of submaximal finger forces with both hands while tracking a trapezoidal trajectory presented on the computer screen (Fig. 1a). Submaximal forces were determined as a percentage of each participant's bimanual MVC force. The tracking task included two force phases: (1) force increment phase which involved gradual increase in isometric finger flexion force from 0 to 20% MVC at the rise rate of 3% MVC per second and (2) force decrement phase which involved gradual decrease in force from 20 to 0% MVC at the fall rate of 3% MVC per second. Both force increment and force decrement phases lasted for 6.5 s each. The complete trial duration was 17 s.

The participants were instructed to execute isometric finger flexion with both hands simultaneously to track the target trajectory as accurately as possible. Participants received a real-time feedback of their total force output relative to the target force. Total force output was the sum of forces produced by both hands. Figure 1b shows a representative trial of bimanual dynamic force tracking from a participant. Before the experimental session, each participant performed

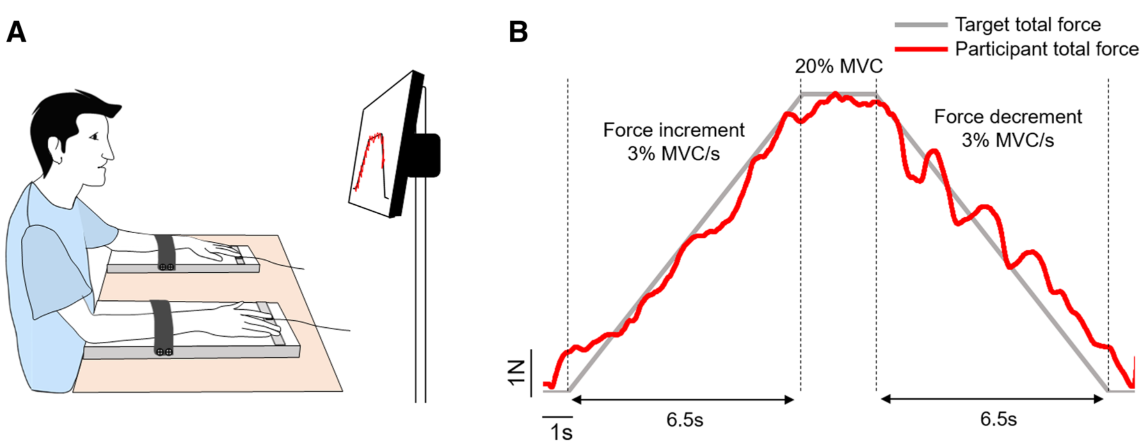

Fig. 1 **a** Experimental set-up for performing isometric bimanual finger force tracking. Participants were seated upright in front of a computer with their arms resting on a platform. Participants performed isometric finger flexion with right and left index fingers simultaneously to match a trapezoidal trajectory that included force increment and force decrement phases. **b** A representative trial of a control participant illustrating the target force (gray line) and participant force (red line)

2–3 practice trials. Following familiarization, participants performed a block of five experimental trials. We provided a 20 s rest period between successive trials to avoid fatigue. The experimental protocol was adapted from previous studies examining force control in individuals with stroke (Blennerhassett et al. 2006; Chow and Stokic 2011; Li 2013; Lodha et al. 2012a; Naik et al. 2011).

Data acquisition

Data acquisition was performed using a custom-written program in Matlab, 2015b (MathWorks, Natick, MA, USA). The force data were collected using two small button force transducers (SLB-25, Transducer Techniques, diameter 0.09 × height 0.25 inches, R.O. 2 mV/V nominal). The force signal from each transducer was amplified by a gain of 100 using the Bridge8 Transducer Amplifier Module (World Precision Instruments, Sarasota, FL, USA). Force data were sampled at a rate of 1000 Hz on a 16-bit Analog-to-digital converter (A/D; NI DAQ, National instruments). The raw force data were filtered using fourth-order Butterworth filter with a cut-off frequency of 10 Hz. Force data were digitally summed and displayed on the computer screen with a visual gain of 210 pixels per newton. Force data were saved for offline analysis.

Data analysis

The first 0.5 s and the final 0.5 s from each phase were removed from all analysis to account for the initial and terminal trial adjustments. We calculated each outcome measure independently for force increment and force decrement phases.

Bimanual task performance

To evaluate the task performance, we measured the accuracy and variability of the total force output.

Force accuracy We calculated the root-mean-squared error (RMSE) to measure the deviation of participant's total force output from the target force (Lodha et al. 2010). We normalized the absolute RMSE by the mean force to allow comparison between individuals with varying finger flexion strength. Higher values for relative RMSE indicate less accuracy of total force output.

Force variability We computed the coefficient of variation (CV) on the detrended force data to determine the variability of total force output relative to the mean force output (Christou 2011). Higher values for CV indicate reduced steadiness of force output.

Contribution of each hand to dynamic bimanual task

To determine the contribution of each hand to the bimanual task, we measured the proportion of force contributed by each hand to the total force and the variability of force produced by each hand.

Proportion of force The proportion of force produced by each hand was expressed as a percentage of total force output produced by both hands together. The formula for the calculation of proportion of force produced by the non-paretic hand is shown in Eq. 1. Similarly, we measured the proportion of force produced by the paretic hand for the stroke group, and the non-dominant and dominant hands for the control group:

$$\text{Proportion of force non-paretic hand (\%)} = \frac{\text{Amplitude of force by non-paretic hand}}{\text{Amplitude of total force by both hands}} \times 100. \quad (1)$$

Force variability We measured the coefficient of variation of the force produced by each hand. The force data were detrended prior to calculating CV. The formula for CV of the non-paretic hand is shown in Eq. 2. Similarly, we measured CV of the paretic hand for the stroke group, and the non-dominant and dominant hands for the control group:

$$\text{CV of non-paretic hand (\%)} = \frac{\text{Standard deviation of force output by non-paretic hand}}{\text{Mean force output by non-paretic hand}} \times 100. \quad (2)$$

Statistical analysis

We examined the distribution of the data with Shapiro–Wilk test. We analyzed the accuracy and variability of total force with a 2 × 2 (group: stroke and control; force phase: increment and decrement) mixed model analysis of variance (ANOVA) with repeated measures on force phase. To examine the contribution of each hand to the bimanual task, we analyzed the proportion of force and variability of force output by each hand in increment and decrement phases. We conducted separate repeated-measures ANOVA for each group. We performed 2 × 2 (hand: non-paretic and paretic for stroke group; hand: non-dominant and dominant for control group; force phase: increment and decrement) repeated-measures ANOVA on the proportion of force and force variability. To further examine the changes in force variability, we conducted a separate 2 × 2 repeated-measures ANOVA on standard deviation (SD) and mean force for each group. We performed Mauchly's test to examine sphericity of the data. If the assumption of sphericity was violated, we used Greenhouse–Geisser's degrees of freedom adjustment. Any significant interactions were followed-up with Bonferroni's post hoc comparisons. All statistical tests were performed with the alpha level set at $p < 0.05$ using SPSS 25.0. Only statistically significant findings are reported in the "Results" section.

Results

Bimanual maximum voluntary contraction and force rate

The bimanual isometric finger flexion MVC for the stroke group was 13.91 ± 5.59 N (39.66% from paretic hand) and for the control group was 21.84 ± 9.12 N (46.51% from non-dominant hand). The bimanual MVC was significantly reduced in stroke relative to the control group, ($|t_{12}| = -2.34$; $p < 0.05$). The target rate of force change was lower in the stroke group (0.44 ± 0.17 N/s) compared with the control group (0.87 ± 0.35 N/s), ($|t_{24}| = -3.90$; $p < 0.01$)

Bimanual task performance

Pearson's bivariate correlation confirmed a significant positive correlation between mean force and absolute RMSE in both groups (Fig. 2a). Similarly, mean force was positively correlated with standard deviation (SD) of force in both groups (Fig. 2b). Therefore, we normalized the absolute RMSE and SD of force with mean force to allow comparison between individuals with varying finger flexion strength. These results are presented as relative RMSE and CV of force below.

Force accuracy

The relative RMSE of total force output for both groups is shown in Fig. 3a. We found a significant main effect of group, [F (1, 24) = 5.11, $p < 0.05$, partial $\eta^2 = 0.17$],

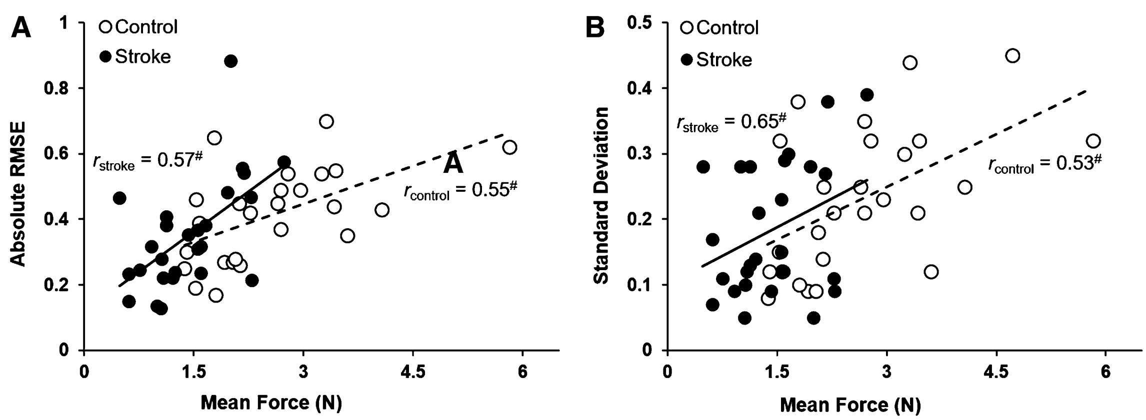

Fig. 2 Relationship between mean force and **a** absolute RMSE and **b** SD of force. The data for force increment and decrement phases were combined. Mean force was positively correlated with absolute RMSE and SD of force in both groups. Significant correlations are indicated by $^{\#}p < 0.01$

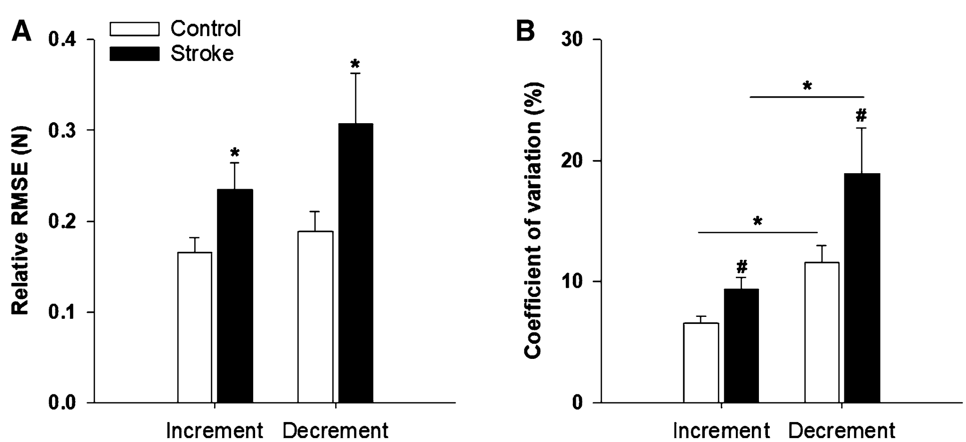

Fig. 3 Differences in bimanual task performance between the two groups across force increment and decrement phases. The error bars represent standard error. **a** The relative RMSE increased in the stroke compared with control group. **b** The variability of total force (CV) increased in the stroke compared with control group, and was higher in the decrement phase than increment phase for both groups. Significant differences are indicated by $^{\#}p < 0.01$ and $^{*}p < 0.05$

suggesting that the stroke group produced greater error (less accurate) in total force compared with the control group.

Force variability

The coefficient of variation (CV) of total force output is shown in Fig. 3b. We found a significant main effect of group, [F (1, 24) = 4.39, $p < 0.05$, partial $\eta^2 = 0.15$], indicating that the stroke group produced more variable total force compared with the control group. Furthermore, we found a significant main effect of force phase, [F (1, 24) = 18.75, $p < 0.01$, partial $\eta^2 = 0.43$], confirming that the variability of total force output was greater in decrement compared with increment phase.

Contribution of each hand to dynamic bimanual task

The group data for contribution of each hand are shown in Fig. 4. Figure 4a, c shows the dominant and non-dominant hand's data for the control group. Figure 4b, d shows the non-paretic and paretic hand contribution for the stroke group.

Proportion of force

We compared the proportion of force contributed by each hand to total force across the force increment and decrement phases. For stroke group, we found a significant main effect of force phase, [F (1, 12) = 5.13, $p < 0.05$, partial $\eta^2 = 0.30$]. We also found a significant hand × force phase interaction, [F (1, 12) = 5.64, $p < 0.05$, partial $\eta^2 = 0.32$; Fig. 4b]. Post hoc analysis showed that the proportion of force produced by the non-paretic hand was significantly reduced in the force decrement than the increment phase ($p < 0.05$). Furthermore, the proportion of force produced by the paretic hand appeared to be greater in force decrement than force increment phase, however, did not reach the significance level ($p = 0.056$). In the control group, a significant main effect of hand, [F (1, 12) = 8.03, $p < 0.05$, partial $\eta^2 = 0.40$] confirmed that the dominant hand contributed greater proportion to the total force compared with the non-dominant hand (Fig. 4a).

Force variability of each hand

For the stroke group, we examined whether the variability of non-paretic and paretic hands differed across the force phases (Fig. 4d). A reliable main effect of force phase [F (1, 12) = 10.69, $p < 0.01$, partial $\eta^2 = 0.49$] revealed that the variability of force output was greater in force decrement

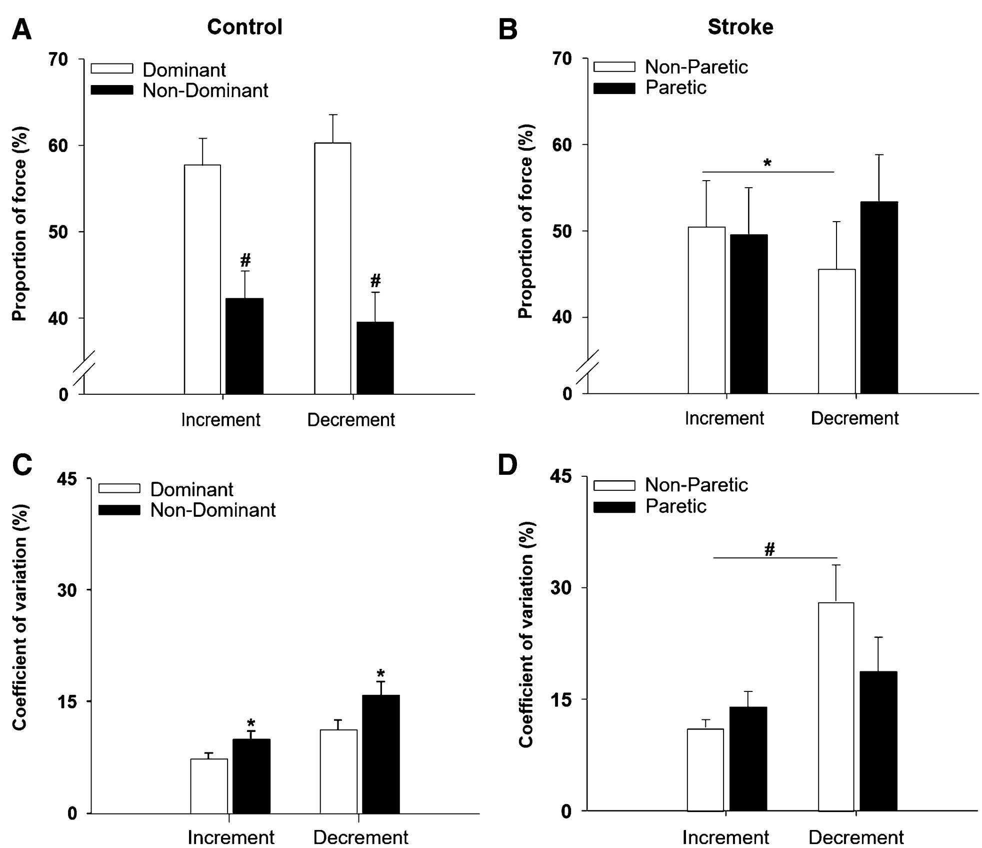

Fig. 4 Contribution of each hand to bimanual task performance during force increment and decrement. **a** In the control group, each hand's contribution to total force did not vary across phases. The dominant hand contributed greater proportion of force than the non-dominant hand in both phases. **b** In the stroke group, the proportion of force contributed by the non-paretic hand reduced in the force decrement than increment phase. **c** In the control group, force variability of the non-dominant hand was increased compared with dominant hand for both phases. **d** In the stroke group, force variability of non-paretic hand increased in decrement than increment phase. The error bars represent standard error. Significant differences are indicated by $^{\#}p < 0.01$ and $^{*}p < 0.05$

than force increment. Furthermore, we found a significant hand × force phase interaction, [F (1, 12) = 5.64, $p < 0.05$, partial $\eta^2 = 0.33$]. The post hoc comparisons revealed that force variability of the non-paretic hand increased significantly in force decrement compared with the increment phase ($p < 0.01$). For the control group, a significant main effect of force phase, [F (1, 12) = 14.68, $p < 0.01$, partial $\eta^2 = 0.55$] indicated greater force variability in force decrement than force increment (Fig. 4c). We also found a significant main effect of hand, [F (1, 12) = 18.15, $p < 0.01$, partial $\eta^2 = 0.60$], demonstrating that the force variability of the non-dominant hand was greater than the dominant hand.

Finally, considering the difference in CV of each hand across the force phases for both groups, we conducted an additional ad-hoc analysis. Here, we examined each hand's SD of force output and mean force—the two components of CV that influence the overall force variability (CV) of each hand. The results for SD of force output and mean force are presented in Table 2. For both the groups, we found that SD of force output increased in force decrement compared with the increment phase. For the stroke group, we found no difference in mean force between the two force phases for both paretic and non-paretic hands.

Table 2 Standard deviation and mean force of each hand in force increment and decrement phase for stroke and control groups

Group	Standard deviation		Mean force (N)	
	Increment	Decrement	Increment	Decrement
Stroke				
Non-paretic	0.08 ± 0.01	0.15 ± 0.02	0.70 ± 0.11	0.69 ± 0.13
Paretic	0.08 ± 0.01	0.11 ± 0.01	0.69 ± 0.09	0.76 ± 0.09
P_{Phase}	**< 0.01**		> 0.05	
P_{Hand}	> 0.05		> 0.05	
$P_{Phase \times Hand}$	> 0.05		> 0.05	
Control				
Dominant	0.09 ± 0.01	0.17 ± 0.01	1.42 ± 0.16[ab]	1.68 ± 0.19[a]
Non-dominant	0.094 ± 0.01	0.15 ± 0.01	1.04 ± 0.12	1.12 ± 0.16
P_{Phase}	**< 0.001**		**< 0.01**	
P_{Hand}	> 0.05		**< 0.01**	
$P_{Phase \times Hand}$	> 0.05		**< 0.05**	

Standard deviation and mean force analyzed in separate two-way repeated-measures analysis of variance for each group. Scores represent mean ± standard error. P_{Phase} indicates main effect of phase. P_{Hand} indicates main effect of hand. $P_{Phase \times Hand}$ indicates phase × hand interaction. Significance level was set at $p < 0.05$. Bolded p values indicate statistical significance

[a]Significant difference between dominant and non-dominant hands in each force phase

[b]Significant difference between force phases for dominant hand

Finally, for the control group, the mean force differed between the two force phases and for both hands.

Discussion

The purpose of the current study was to determine the impact of stroke on dynamic bimanual force control and to compare the contribution of each hand to bimanual force increment and decrement. Our results demonstrate that stroke impairs the ability to produce accurate and steady forces during bimanual dynamic force modulation. The bimanual force variability was higher in force decrement than increment, suggesting that force control deficits are exaggerated when releasing than increasing forces. Furthermore, the individual hand contribution to bimanual task is altered between force increment and decrement. Specifically, the proportion of force contributed by the non-paretic hand was lesser and more variable in the decrement than increment phase. In contrast, in the control group, the proportion of force contributed by both hands was consistent across the two phases. Our study provides novel evidence that stroke impairs dynamic bimanual force modulation with greater deficits in force decrement than force increment. Furthermore, the differences in individual hand contribution across force increment and decrement highlight the functional dissociation between paretic and non-paretic hands with altered demands of a dynamic bimanual task.

Dynamic bimanual force control is impaired after stroke

Dynamic force modulation requires continuous alteration of the force output to meet the changing task requirements (Johansson 2002; Witney et al. 2004). Performing such a task bimanually demands force outputs from both hands to be mutually collaborative to achieve a shared task goal. Reduced bimanual force control after stroke has been demonstrated previously for constant force tasks (Kang and Cauraugh 2015; Lodha et al. 2010, 2012b). Our findings extend the previous work by showing inadequate force regulation following stroke while scaling dynamic bimanual forces.

The relative force error and variability quantified bimanual task performance in our study. We normalized the RMSE and SD by the mean force, because the absolute force error (RMSE) and variability (SD) are shown to increase with the increase in the magnitude of force (Fig. 2) (Lindberg et al. 2009; Morrison and Newell 1998; Vaillancourt et al. 2002). The direct comparison of absolute SD revealed comparable scores between the two groups (Table 2). One reason is, perhaps, the effect of disease-related amplification in motor fluctuations (SD) (Lodha and Christou 2017) was canceled by reduction in SD because of less mean force in stroke. In addition, force accuracy reduces with increase in the rate of force change (Lindberg et al. 2009; Naik et al. 2011). In our study, the rate of force change was lower in the stroke compared with the control group. Despite this, the bimanual task performance was compromised in the stroke group as indicated by reduced accuracy (increased relative error). These results suggest that dynamic force control is inherently more challenging in stroke, resulting in inadequate bimanual task performance.

Controlling dynamic forces challenges the neuromuscular system to match the force output to the continuously changing force demands. Stroke increases the reliance on visual information processing for altering the motor output (Bonan et al. 2004). The previous studies have shown that appropriate integration of visual feedback improved motor performance in stroke by reducing the error and variability of force (Archer et al. 2016, 2018). Furthermore, individuals with stroke show impaired reactive grip force control when responding to a sudden change in grip load (Dispa et al. 2014; Grichting et al. 2000). Our study extends prior findings by showing that stroke impairs visuomotor control of dynamic forces. The decline in dynamic force control may be linked to reduced sensorimotor capacity and impaired voluntary muscle recruitment in stroke survivors (Allgower and Hermsdorfer 2017; Blennerhassett et al. 2008; Hermsdorfer et al. 2003). Furthermore, stroke-related deficits in force modulation during controlled force increase and release have been attributed to stair-stepping phenomenon (Naik et al. 2011). The stair-stepping is characterized by a step-like pattern in force output with large periods of constant force while tracking a dynamic force target (Kurillo et al. 2004; Lindberg et al. 2009; Naik et al. 2011). Specifically, stroke survivors demonstrated longer periods of constant forces (large step duration) and fewer number of steps relative to controls during dynamic force tracking with the paretic hand. Furthermore, stair-stepping appeared to increase error and variability of force output (Naik et al. 2011). These studies provide insights into the potential mechanisms that could contribute to impaired dynamic force modulation after stroke.

Bimanual force control is altered in force increment versus force decrement

Our results suggest that the bimanual force modulation is altered with dynamic task constraints. We manipulated the task constraints by including systematic force increment and decrement phases in the bimanual task. We found that total force variability in the stroke group is significantly increased in force decrement than increment phase. These results suggest that bimanual force release is less steady than bimanual force generation. Our findings are in line with the previous work, suggesting that voluntary force release is impaired in unimanual tasks (Cruz et al. 2005; Ohtaka and Fujiwara 2016). For example, Park et al. (2016) reported that healthy young and older adults demonstrate increased force variability during force release as compared with force generation in unilateral ankle dorsiflexion. Similarly, unimanual grip force release was more variable and contributed to diminished hand dexterity in older adults (Voelcker-Rehage and Alberts 2005). Our study extends these findings to bimanual tasks by showing that force control is inadequate while releasing forces than increasing forces with both hands.

The differences in bimanual force modulation during force increment and decrement may be potentially related to stroke-related changes in muscle activation and motor-unit modulation pattern. For example, stroke survivors demonstrate increased delay in terminating forearm flexor activity to release grip force compared with initiating muscle activity to generate force (Seo et al. 2009). Other possible neuromuscular mechanisms for increased variability during force release have been identified in older adults. Park et al. (2016) showed that greater variability during force release related to reduced modulation of multiple motor-unit discharge rate in 35–60 Hz. While impaired motor-unit recruitment after stroke is well documented (Mottram et al. 2014; Hu et al. 2015), whether motor unit discharge rate could contribute to increased force variability in force decrement needs further investigation. Furthermore, stroke survivors show differential motor impairments in finger flexors and extensors (Kamper et al. 2003; Lodha et al. 2012a). The current study focused on isometric contraction (increasing force) and controlled relaxation (decreasing force) of finger flexors. The task did not involve isometric finger extension to release force in the decrement phase. Thus, our findings suggest impaired force regulation during force decrement in a flexion task, demonstrating reduced steadiness in force decrement that may interfere with both hand use following stroke.

Asymmetric hand contributions in bimanual increment vs decrement in stroke

A key finding in our study is that the individual hand contribution in stroke differs with the bimanual task constraints. Given that the bimanual task involved collaborative use of hands to achieve a mutual goal, contribution from each hand influenced final goal attainment. Two key factors affecting the total force were distribution of the amount of forces (proportion of force) contributed by each hand and the modulation of force (force variability) by each hand. Our findings suggest that these factors—proportion and variability of force from each hand—were altered with the force phase.

Proportion of force

In the stroke group, proportion of force contributed by the non-paretic hand was reduced in the decrement compared with increment phase. Conversely, the proportion of force contributed by the paretic hand trended to be higher during force decrement than increment. In contrast, the pattern of force asymmetry was consistent across the two phases in the control group. The previous studies have shown that healthy adults, in the absence of apparent motor deficits, produce relatively symmetric forces during constant bimanual force tracking (Bertrand et al. 2004; Lodha et al. 2012a). However, our study focused on dynamic modulation of forces which is intrinsically more challenging than controlling constant forces (Sosnoff and Voudrie 2009). In a dynamic force task involving both hands, the force contribution from the dominant hand superseded the non-dominant hand. Together, these results point towards task-related reorganization of force output from the two hands.

Force variability

An important but unaddressed question relates to the force modulation strategy adopted by two hands while sharing a common goal. Our findings indicate an implicit dissociation between non-paretic and paretic hand function, especially in force decrement phase. The non-paretic hand had higher CV of force and reduced proportion of force contribution in increment phase compared with decrement phase. Perhaps, the non-paretic hand preferentially assumed the role of modulating force to meet the dynamic force target, while the paretic hand produced stable and less variable force output. The non-paretic hand's increased role in force control was concomitant with reduced role in force production, consequently, equalizing force contributions from paretic and non-paretic hands. Clearly, each hand in the stroke group adopted distinct strategies for task completion to meet the specific demands of the force phase. Prior research demonstrates that force control during decrement is less accurate and more variable than increment, highlighting the inherent challenge in executing controlled force release (Li 2013; Naik et al. 2011). Performing relatively demanding bimanual force decrement likely compels the non-paretic hand to take charge of modulating forces to meet the dynamic target. Self-adopted assignment of specific roles by each hand in stroke may improve task efficiency while tracking a dynamic bimanual target. To our knowledge, the current study is the first one to show that dynamic bimanual force tracking facilitates equal proportion of force sharing between hands in stroke survivors.

Our results support a robust and sustained increase in non-paretic hand force variability in force decrement phase. Notably, in the stroke group, the mean force did not differ between phases, while the standard deviation increased in the decrement phase (Table 2). Thus, higher force variability (CV) of the non-paretic hand in force decrement was influenced by increased standard deviation rather than reduced mean force. Clearly, the dynamic bimanual task revealed that the force variability of individual hands differs with the constraints of the dynamic bimanual task. Future studies are needed to investigate the possible mechanisms underlying dynamic force regulation in bimanual tasks and relationship to functional activities involving both hands.

Considerations

The relative contribution of the paretic hand in a bimanual force control task could be affected by the severity of motor impairments after stroke (Lodha et al. 2012b). Considering that majority of the individuals with stroke in our study demonstrated mild-to-moderate motor impairment (FMA score = 44–62), we could not determine the influence of the severity of motor impairment on dynamic bimanual task. Future studies that systematically investigate the effect of the side of stroke, hand dominance, and severity of motor impairment could provide insights into pathological-feature specific differences in bimanual force sharing strategy after stroke.

Clinical implications

Our findings highlight the need for re-educating dynamic force modulation during bimanual activities after stroke. Unilateral motor deficits after stroke contribute to the difficulty in performing bimanual tasks that rely on dynamic bimanual modulation such as lifting or lowering a heavy box or a tray of glasses, tying shoelaces, and car steering, (Basilio et al. 2016). Upper limb rehabilitation approaches have been focused on addressing deficits of the paretic hand (e.g., strengthening, forced use, and mirror therapy) to improve motor function (Hatem et al. 2016; Stein et al. 2004; van Delden et al. 2013; Wu et al. 2013). However, recent research has shown that rehabilitation of the paretic hand alone does not necessarily transfer to spontaneous improvement of bilateral use of hands (Waddell et al. 2017). Considering lack of effective strategies to remediate performance in bimanual activities, evaluating bimanual force modulation with varied task constraints may provide insights into potential strategies for improving bimanual function following stroke. Retraining the paretic hand to adequately modulate forces in bimanual tasks may facilitate arm use in daily activities that require collaborative hand function.

Summary

Understanding how stroke affects the control of bimanual forces is critical to improve bimanual function after stroke (Rose and Winstein 2004). The previous work focused on bimanual control in constant force tasks. However, several bimanual activities require dynamic force modulation. We identified deficits in dynamic bimanual force modulation in force increment versus decrement after stroke. The current study provides novel evidence that dynamic bimanual force modulation is impaired after stroke with greater deficits in force decrement relative to force increment during finger flexion. Another noteworthy finding is that bimanual task constraints influence force control strategies of the paretic and non-paretic hands to achieve a common goal. With significant demand for precise control during force release, the non-paretic hand preferentially modulates the force, while the paretic hand produces steady force output to meet the task goal. These findings highlight the functional dissociation between the paretic and non-paretic hand in a dynamic bimanual task.

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interests.

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