



Postural organization and inter-limb coordination are altered after stroke when an isometric maximum bilateral pushing effort of the upper limbs is performed

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ARTICLE INFO

Keywords:

Stroke
Upper limbs ;Bilateral task
Coordination
Postural adjustment

ABSTRACT

Background: Postural strategies of the trunk and the lower limbs are linked to upper limb motor activities. The objective was to analyze the postural organization at the lower limbs as well as the inter-limb coordination during isometric maximal bilateral pushing of upper limbs.

Methods: Fifteen individuals after stroke and 17 healthy participants were assessed with an instrumented exerciser paired with an instrumented sitting surface while they executed isometric bilateral pushes with the upper limbs. The anteroposterior, vertical and mediolateral forces were recorded at the handles, the thighs and the feet. Force values at maximal bilateral pushing efforts at each segment and inter-limb coordination between sides were compared.

Findings: During the isometric pushes, the paretic maximal forces at the handles for stroke participants were lower than the nonparetic side and lower than both sides of the control participants ($p < 0.036$). The control and stroke participants had moderate to good coordination for the anteroposterior forces (hands and thighs). While they used similar postural strategies to the controls except for a decreased weight on the paretic foot, vertical forces were less coordinated at the handles and feet in the stroke group ($p < 0.050$). The inter-trial variability was also higher in the stroke group.

Interpretation: Bilateral pushing with gradual efforts induces impaired postural strategies and coordination between limbs in individuals after stroke. It may reveal to be a promising strategy to assess and train post-stroke individuals in a clinical setting. Also, providing feedback would help better control symmetry during efforts.

1. Introduction

Recovery of motor function of the paretic upper limb is crucial for individuals after stroke because 50% of the reduction in quality of life after stroke is due to the inability to use their arm effectively in actions of daily living (Kantak et al., 2017). It is therefore essential to identify exercises that are effective in helping to regaining upper limb function. A systematic review of upper limb interventions for persons with stroke

(Wattchow et al., 2018) highlights that only constraint-induced movement therapy and task-specific training are supported by clinical guidelines and by studies of moderate quality of evidence. These rehabilitation approaches focus on the paretic upper limb and rarely take into consideration other components of task achievement such as postural organization, the adjustments of the whole body to execute the distal movement (Bouisset et al., 2002).

It is known that upper limb movements require a postural

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<https://doi.org/10.1016/j.clinbiomech.2021.105388>

Received 28 June 2020; Accepted 18 May 2021

Available online 23 May 2021

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readjustment of all body segments (Friedli et al., 1988; Messier et al., 2005). In healthy persons, the support of the lower limbs (thighs and feet) in a sitting position contributes to improvement in reaching distance of the upper limbs (Dean et al., 1999). After a stroke, the weight-bearing strategy differed according to the direction of arm movement (Messier et al., 2005). When the paretic upper limb moved laterally toward the paretic side, the weight bearing increased on the nonparetic foot whereas when the movement was toward the nonparetic side, the weight bearing increased on both feet. Authors hypothesized that the difference observed might be a compensation for impairments of the trunk on the paretic side to ensure balance. While many daily tasks require movements of both arms against resistance (e.g., to put a heavy object on a shelf or to push a grocery basket), little is known about the postural reorganization when persons produce bilateral upper limb efforts. An increase of the vertical forces under the thighs and a decrease at the feet are reported when healthy controls executed an isometric pushing task with the upper limbs emphasizing the need to readjust the posture (Bouisset et al., 2002). Another study revealed a sequence of muscle recruitment where postural muscles precede focal muscle activations when a maximal isometric push with both upper limbs on a rigid bar was executed (Le Bozec et al., 2001). We do not know how individuals after a stroke organize their posture to push maximally with both hands against isometric resistance. Considering their predominant impairments on one side (asymmetry), they might adapt their posture differently from healthy controls which could compromise their stability and increase the risk of falls as shown for the sit-to-stand movement (Cheng et al., 1998).

Daily tasks also require good coordination between limbs to be successful and efficient and thus a decrease coordination affects the performance of daily movements during many bilateral tasks (e.g., when using a fork and a knife at the same time) (Kantak et al., 2017). A neural crosstalk exists between the right and left hemispheres to communicate and produce a coordinated movement pattern (Arya and Pandian, 2014). Consequently bilateral training after stroke, based on the premise that simultaneous movements of the nonparetic upper limb facilitate performance on the paretic side through neural coupling effects (van Delden et al., 2015), has shown greater movement amplitude and strength on the paretic side when compared to unilateral training (DeJong and Lang, 2012). Interestingly, whereas the stroke event induces motor control disorders (Son et al., 2013) and various levels of paresis at the upper limb (up to 40% according to Starosta et al., 2017), persons remain coordinated between sides when they executed bilateral hand grip (Bertrand et al., 2004). The spatiotemporal coupling of forces is similar although less grip force production on the paretic side. For the clinical practice, it would be interesting to determine whether this coordination between the paretic and nonparetic sides at the upper limbs also exist at the lower limbs, thighs and feet, during tasks performed by the upper limbs.

The objective of this study was to characterize and quantify the postural organization at the lower limbs and the inter-limb coordination (arms, thighs and feet) during isometric maximal bilateral pushing of upper limbs in post-stroke individuals and healthy controls. Our main hypothesis was that the forces between the right hemibody and the left hemibody (at each level: upper limbs, thighs, feet) were weaker on the paretic side in participants with stroke but remain coordinated between sides. Thus, the pushing task would produce a developed force correlated between the right and left sides at all segments. We also expected to observe progressive decreases in the weight bearing at the feet and increases at the thighs with the production of forces in the upper limbs in the two groups.

2. Methods

2.1. Population

Individuals with upper limb hemiparesis post-stroke were recruited

from the past clientele of a Montreal Rehabilitation Center with stroke unit (Institut de Réadaptation Gingras-Lindsay Montréal - IRGLM). Healthy participants were contacted from a list of previous study participants who agreed to be contacted and internal employee announcements at the Center.

Individuals with stroke were included if they had a first unilateral stroke more than 6 months ago, an upper limb paresis, an active wrist flexion superior to 10° and they were able to hold the handle of the exerciser (minimum score of 2/7 at the hand at the Chedoke McMaster Stroke Assessment; CMSA). Participants with upper limb pain (over 2/10 on a visual analog scale), hand anesthesia (not able to detect the 6.65 monofilament at the thenar thumb area), receptive aphasia, unstable cardiopulmonary condition and severe cognitive deficit (Mini-Mental State Examination - MMSE <25/30) were excluded. All controls had to have normal upper limb function and no present or past history of any pathologies or pain in the upper limbs to be included in this study.

The study was approved by the research ethics board of the CRIR (Centre for interdisciplinary research in rehabilitation of greater Montreal, Quebec, Canada) that conforms to the ethical standards of the Declaration of Helsinki (reference: CRIR-1202-0117). Before the experiment, all participants signed a consent form.

2.2. Clinical assessment

Physical impairments of the paretic upper limb were assessed with the CMSA (from 0 flaccid to 7 normal). For individuals with stroke, the reliability coefficients (ICC) for the total scores ranged from 0.97 to 0.99 (Gowland et al., 1993). To assess biceps and triceps muscle tone, we used the Composite Spasticity Index (Levin scale) including Ashworth test, tendinous reflex and clonus (Levin and Hui-Chan, 1992). The sensory loss at the hand was tested with Semmes-Weinstein monofilaments #6.65, #5.18, #4.31 and #4.17 (Chikai et al., 2015). If the patient detects #4.17, the sensitivity is normal and if the patient does not detect the #5.18, the deficit was considered as severe. The Box and Block test, with very high inter-rater and test-retest reliability in individuals with stroke (ICC > 0.95) was used to assess unilateral gross manual dexterity (Platz et al., 2005).

2.3. Device and pushing task

A bilateral exerciser with instrumented handles was used to execute the isometric bilateral pushing task in a seated position. This device was specifically developed for upper limb bilateral training (Fig. 1A).

The handles are attached to AMTI MC3 platforms that allow recording of forces produced by the upper limbs on the exerciser. Force signals at the thighs were obtained for dominant (or nonparetic) and nondominant (or paretic) sides from four AMTI MC3® force platforms (two on each side) installed on an instrumented chair (for details see previous article: (Nadeau et al., 2008)). The chair was positioned to have each foot on an AMTI (OR6-7-1000) force plate. The anteroposterior (AP; positive forward), vertical (V; positive upward) and mediolateral (ML, positive inside) forces were recorded at 600 Hz acquisition frequency at the handles, thighs and feet (Fig. 1A).

In the initial position (reference), participants sat with feet flat on the floor over the platforms, knees and hips were at 90° of flexion and the back was unsupported. They held the handles with mid supination/pronation of forearms and wrists were in neutral position. The forces were recorded in this position during one trial of 5 s.

The isometric maximal voluntary forces were recorded during two trials of a simultaneous bilateral pushing effort of the upper limbs on the handles with minimal compensation observed. The handles were placed at 50% of the maximal pushing distance on each side obtained without bending the trunk. The full range of the pushing task was recorded, and the controller moved and 'locked' the handles to the mid-point of this distance to assess the pushing task. The participants executed the task with the following instructions: "When you are ready, keeping your

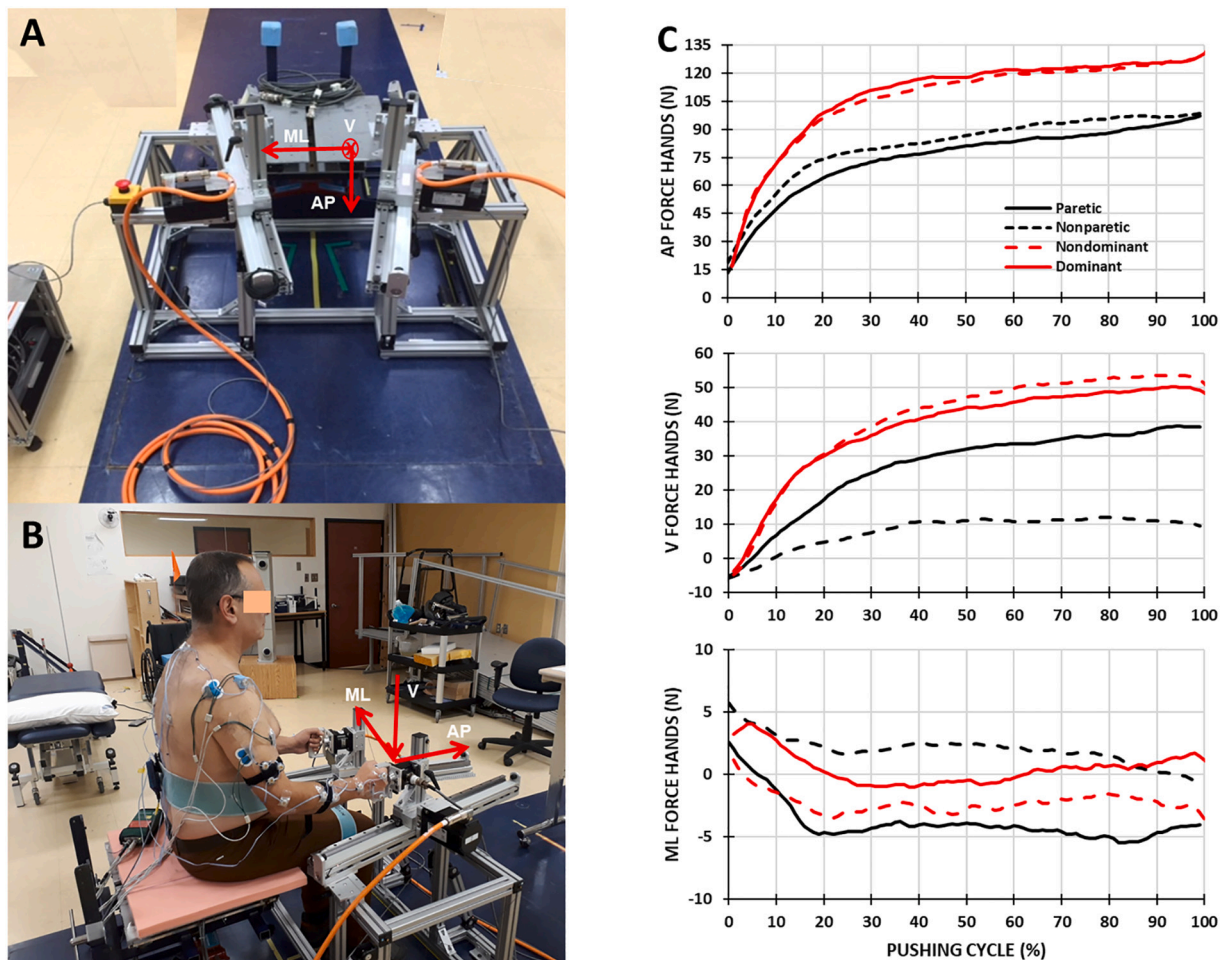


Fig. 1. A) Experimental setup for strength testing with reference for force directions. B) Photograph of a participant seated at the apparatus. C) Graphs showing the mean force progression data from both groups (control and stroke groups) in the anteroposterior (AP), vertical (V) and mediolateral (ML) directions at the handles on both sides. The pushing is time-normalized to the paretic (or nondominant) side.

trunk straight and your feet on the ground, push gradually with both arms until your reach your maximal effort then hold this maximum effort for a few seconds and relax". Thirty seconds were allowed between each trial.

2.4. Data processing

For each trial, the maximal value of the force (MVF) components (AP, V and ML) on each hemibody at the hands, thighs and feet were extracted to quantify the asymmetry of forces.

The AP time-force at the handle on the paretic side (nondominant side for control group) was used to time-normalized (t0-t100) all other forces (see Fig. 1C for the forces at the handles). The trial started when the force on the paretic handle reached 15% (t0) of the MVF in the pushing direction and ended when the highest force was observed in the same direction (t100). A value of 15% MVF was chosen to standardize the start of the task between participants. Between t0 and t100, 100 force values were extracted. For the stroke group, the data processing captured the evolution of the forces on both the paretic and nonparetic sides simultaneously during the normalization to the paretic side. For each force value as a function of time (normalized), the mean of two trials was calculated (Fig. 1B). The evolution of the time-normalized V forces at the thighs and feet allowed assessing the postural organization at the lower limbs in response to the pushing efforts at the upper limbs.

The coordination analysis included two steps. First, to reveal how the forces progressed during the bilateral pushing efforts, scatterplots of

mean forces values for 100 points between t0 and t100 were created for the stroke group (nonparetic and paretic) and the control group (dominant and nondominant) with the theoretical perfect correlation line drawn.

The aim of the second step was to assess the coordination without the influence of the difference in force (asymmetry) between sides. All absolute force values in each direction were normalized to the MVF of each force direction:

$$\left(\frac{\text{Value}}{\text{MVF}} \right) * 100$$

The difference in normalized force between sides was calculated: [dominant or nonparetic value – nondominant or paretic value] at each point. To reduce the number of points to 10 for the statistical analyses, the mean over ten-point intervals (0–9%; 10–19%; 20–29%, etc.) was calculated.

2.5. Statistical analysis

Descriptive statistics were used to characterize participants. The Mann-Whitney unpaired test (continuous variables) or χ^2 test (categorical variables) were used for comparison of demographic characteristics between groups.

As the conditions required for a parametric test were not respected, the comparisons between groups at the reference position, for MVF and at t100 were done using the nonparametric Mann-Whitney unpaired

test. A Wilcoxon paired signed rank test was used to compare the results between sides and characterize the asymmetrical behavior (nonparetic vs. paretic / nondominant vs. dominant) within each group. This nonparametric test was also used to compare the V forces (weight bearing) at the thighs and feet between the reference position and at t100 to appreciate the postural organization.

We used the ICC_{2,1} to assess the inter-limb coordination because we wanted to assess absolute agreement between sides, with identical value revealing a perfect coordination with ICC value of 1 (Koo and Li, 2016). Interpretation of ICC was as follows: values >0.75 were considered as “good coordination”, between 0.5 and 0.75 as “moderate coordination” and < 0.5 as “poor coordination” (Portney and Watkins, 2009). The coefficient variations (CVs) were calculated [(SD/Mean trial 1 and 2) *100] to assess the consistency of coordination between the two trials for a given subject.

The coordination without force asymmetry between groups (stroke vs. control) at the handles, thighs and feet were compared using Mann-Whitney unpaired tests on the 10-point interval force generation for each force direction (AP, V and ML).

Threshold value for significance was set at $p < 0.05$. Data analysis was conducted using IBM SPSS statistics V. 25 (IBM Corp 2017 Statistics for Windows, Armonk, NY).

3. Results

Fifteen individuals after stroke (mean age: 65 yrs. ± 12) and 17 healthy controls (mean age: 48 yrs. ± 14) agreed to participate. The mean duration since stroke was 3.25 years [min: 0.58 – max:10.36]. There were no significant differences between groups except for age (Table 1).

Eleven individuals had a right hemisphere stroke. The clinical characteristics of participants with stroke are described in Table 1.

The duration of the maximal push was 2.4 s (± 0.7) on the nondominant side and 2.0 s (± 0.9) on the dominant side for the control group. Corresponding values for the stroke group (paretic and nonparetic side) were 2.4 s (± 1.2) and 2.2 s (± 0.8), respectively. The position of the handle at 50% of the maximal pushing distance ranged from 0.19 m to 0.36 m for the stroke group and 0.17 m to 0.37 m for the control group with mean values of 0.26 m and 0.27 m respectively. No significant difference was found between sides or groups.

3.1. MVF at the hand and asymmetry

Hands: In individuals post-stroke, the AP MVF (paretic side: 97.9 N ± 35.7 vs. nonparetic side: 114.0 N ± 38.6 , $p = 0.006$) and V MVF (paretic side: 24.3 N ± 14.0 vs. nonparetic side: 46.9 N ± 24.8 , $p = 0.001$) differed between sides (Fig. 2). These MVF on the paretic side were lower compared to nondominant side of the control group (AP force: 133.3 N ± 36.8 , $p = 0.006$ and V forces: 58.3 N ± 41.5 , $p = 0.003$). No difference was observed between the nonparetic side in stroke group and dominant side in control group, and between sides in control group (Fig. 2)

The values for ML forces were negligible (mean values <5 N at the handles and feet and < 30 N at the thighs) without a clear pattern and are therefore not presented further.

3.2. Postural organization: reference position compared to t100

In the reference position, at the thighs, the V forces differed between sides ($p = 0.002$) in individuals after stroke with a greater support on paretic side. The V forces under both feet in the stroke group were lower compared to the control group ($p < 0.015$, Table 2). In the control group, for all segments, no significant difference between the dominant and nondominant side was observed. There was no significant difference in AP forces between groups and sides for the hands, thighs and feet.

In both groups, the maximal bilateral upper limb pushing effort

Table 1

Demographic characteristics of stroke group and control group. Description in mean (\pm SD) of the two subgroups recruited for the tests. No significant difference between stroke group and control group is indicated by « NS » ($p > 0.05$). The significant level is indicated with *p value in bold characters*.

Variables	Stroke (N = 15)		Control (N = 17)	<i>p value</i>
Age (years)	63.5 \pm 11.0		48.0 \pm 14.0	0.008
Sex (number)	8 women / 7 men		9 women / 8 men	NS
Weight (kg)	76.1 \pm 12.1		77.9 \pm 16.6	NS
Height (m)	1.64 \pm 0.10		1.71 \pm 0.10	NS
Body mass index	24.3 \pm 4.4		23.7 \pm 3.4	NS
Manual dominance (side)	2 left / 13 right		3 left / 14 right	NS
Duration since stroke (years)	3.6 \pm 3.5			
Side of stroke	11 right / 4 left			
Upper limb impairments:	Arm		Hand	
Chedoke	2: 1	5: 2	2: 1	5: 3
McMaster	(7%)	(14%)	(7%)	(21%)
Stroke Assessment (/7 pts)				
Score: number of participants (%)	4: 1 (7%)	6: 2 (14%)	3: 3 (21%)	6: 2 (14%)
		7: 9 (60%)	4: 1 (7%)	7: 5 (33%)
Manual dexterity: Box and block test (number / 150 blocks)				
Paretic side	34.1 \pm 20.8			
Nonparetic side	54.3 \pm 15.58			
Tone Upper limb: Composite Levin Scale (/16 pts)				
Biceps	5.1 \pm 3.4			
Triceps	3.5 \pm 2.8			
Hand sensibility	14 normal / 1 severe deficit			

induced significant increases for AP forces at the hands ($p < 0.001$) associated with posterior forces at the thighs ($p < 0.001$) and a significant AP force decrease at the feet ($p < 0.030$, Table 2). Compared to reference position, at t100 (maximal pushing on paretic side), the V forces increased at the hands ($p < 0.021$) and decreased at the feet ($p < 0.001$). At the thighs, the V forces increased for control group on both sides ($p < 0.001$) but was significantly increased only on the nonparetic side for the stroke group ($p = 0.001$). The V forces were less on the paretic foot resulting in an asymmetry between sides.

3.3. Coordination

3.3.1. Hands

For AP forces, time-normalized to the paretic or nondominant side, the ICC between sides were moderate in the stroke group (mean ICC \pm SD: 0.61 \pm 0.27, Fig. 3.H.a.) and good in the control group (0.88 \pm 0.12, Fig. 3.H.c.). For the V forces, the stroke group had a poor ICC (0.37 \pm 0.37) with a clear deviation toward the nonparetic side (Fig. 3.H.b.) and the control group showed a moderate ICC (0.65 \pm 0.30, Fig. 3.H.d.). The inter-trial CVs were superior in individuals with stroke.

When the amplitude effect of the forces was removed, individuals with stroke were less coordinated between sides than controls at the beginning of the effort until 30% of push cycle with a significant difference at the first interval (point 1, $p = 0.005$) for the AP forces (Fig. 3.H.e.). For the V forces, in accordance with the poor ICC mentioned

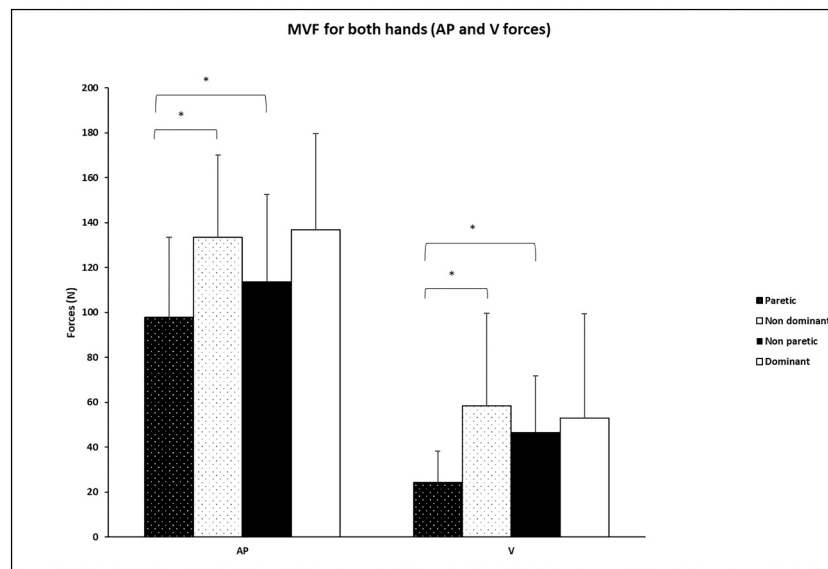


Fig. 2. Maximal values (MVF) of anteroposterior (AP) and vertical (V) forces during isometric maximum bilateral pushing effort of the upper limbs in the stroke group (black) and the control group (white). A significant p value ($p < 0.05$) is represented by “*”.

Table 2

Comparison of the forces between the reference position and when voluntary maximal force was obtained on the paretic (nondominant) side (t100) during the bilateral pushing effort in the two groups.

			Paretic / Nondominant side			Nonparetic / Dominant side		
			Stroke (N = 15)	Control (N = 17)	p value (stroke vs. control)	Stroke (N = 15)	Control (N = 17)	p value (stroke vs. control)
Hands	AP forces	Reference	-3.1 ± 5.3	-1.3 ± 4.4	NS (0.165)	-2.4 ± 5.7	-1.8 ± 4.5	NS (0.303)
		t100	97.9 ± 35.7	133.3 ± 36.8	0.006	98.8 ± 42.7	136.9 ± 42.8	0.027
	V forces	Reference	-6.4 ± 2.5	-7.0 ± 2.7	NS (0.276)	-6.9 ± 4.5	-5.1 ± 3.4	NS (0.128)
		t100	9.3 ± 22.6	49.6 ± 40.3	0.001	$38.3 \pm 34.3^*$	44.9 ± 39.6	NS (0.435)
Thighs	AP forces	Reference	-6.8 ± 8.2	-5.5 ± 8.5	NS (0.478)	-3.2 ± 10.4	-9.5 ± 8.4	NS (0.060)
		t100	-91.4 ± 38.5	-113.9 ± 49.1	NS (0.061)	-99.4 ± 47.1	-129.9 ± 46.1	0.041
	V forces	Reference	-355.5 ± 71.6	-302.1 ± 66.4	0.014	$-311.3 \pm 56.4^*$	-297 ± 69.3	NS (0.145)
		t100	-392.5 ± 91.0	-386.3 ± 102.2	NS (0.455)	-417.3 ± 115.1	-412.9 ± 108.5	NS (0.381)
Feet	AP forces	Reference	5.4 ± 6.2	4.8 ± 3.3	NS (0.240)	11.7 ± 21.3	5.0 ± 3.7	NS (0.163)
		t100	0.2 ± 4.6	-1.1 ± 6.4	NS (0.493)	2.4 ± 12.2	-1.7 ± 4.3	NS (0.071)
	V forces	Reference	-49.0 ± 13.8	-60.5 ± 13.7	0.013	-46.3 ± 18.3	-57.9 ± 13.5	0.015
		t100	-6.5 ± 6.7	-13.3 ± 11.4	0.023	$-14.8 \pm 8.8^*$	-10.9 ± 8.3	NS (0.075)

The sign “*” represents a significant difference between sides ($p < 0.05$). Bold characters represent significant differences ($p < 0.05$) between “reference position” and t100 and between groups.

above, the difference between groups is presented in Fig. 3.H.f. with negative values at the beginning (0–20%, points 1 and 2) and positive values after (from 40 to 100%; points 4 to 9; $p \leq 0.040$). This revealed greater (negative values) and then lower values on the paretic side compared to the nonparetic side.

3.3.2. Thighs

In both groups, the mean ICC values for the AP forces were moderate (0.56 for stroke and 0.51 for control) and they were poor for the V forces (Fig. 3.T.a.b.c.d.). Fig. 3.T.b. and d. show clear asymmetry starting at 50% of the push cycle and greater values on the nonparetic and dominant sides respectively for the stroke and control groups. The inter-trial variability of the ICC for the vertical forces was twice as wide than for the AP forces in both groups.

When the amplitude of the force effect was removed, no significant difference was observed for the coordination for both AP and V forces

between groups (Fig. 3.T.e. and f.). At the beginning of the pushing (0–60%), the negative values indicated that both groups had lower values for V forces on the paretic or nondominant side.

3.3.3. Feet

The ICC between sides revealed poor and moderate coordination in the AP and V directions, respectively for stroke and controls (Fig. 3.F.a. b.c.d.). At the beginning of the pushing effort up to approximately 50% of the push cycle, the stroke group had greater positive (anterior) forces on the nonparetic side while, starting at approximately 30% of the push cycle they decreased their support under the paretic foot to a greater extent than on the nonparetic foot (Fig. 3.F.b.). The inter-trial CVs were similar between groups.

When the amplitude effect of the forces was removed, we found similar coordination for the AP forces between groups. For the V forces, the stroke group was less coordinated than control group starting at 30%

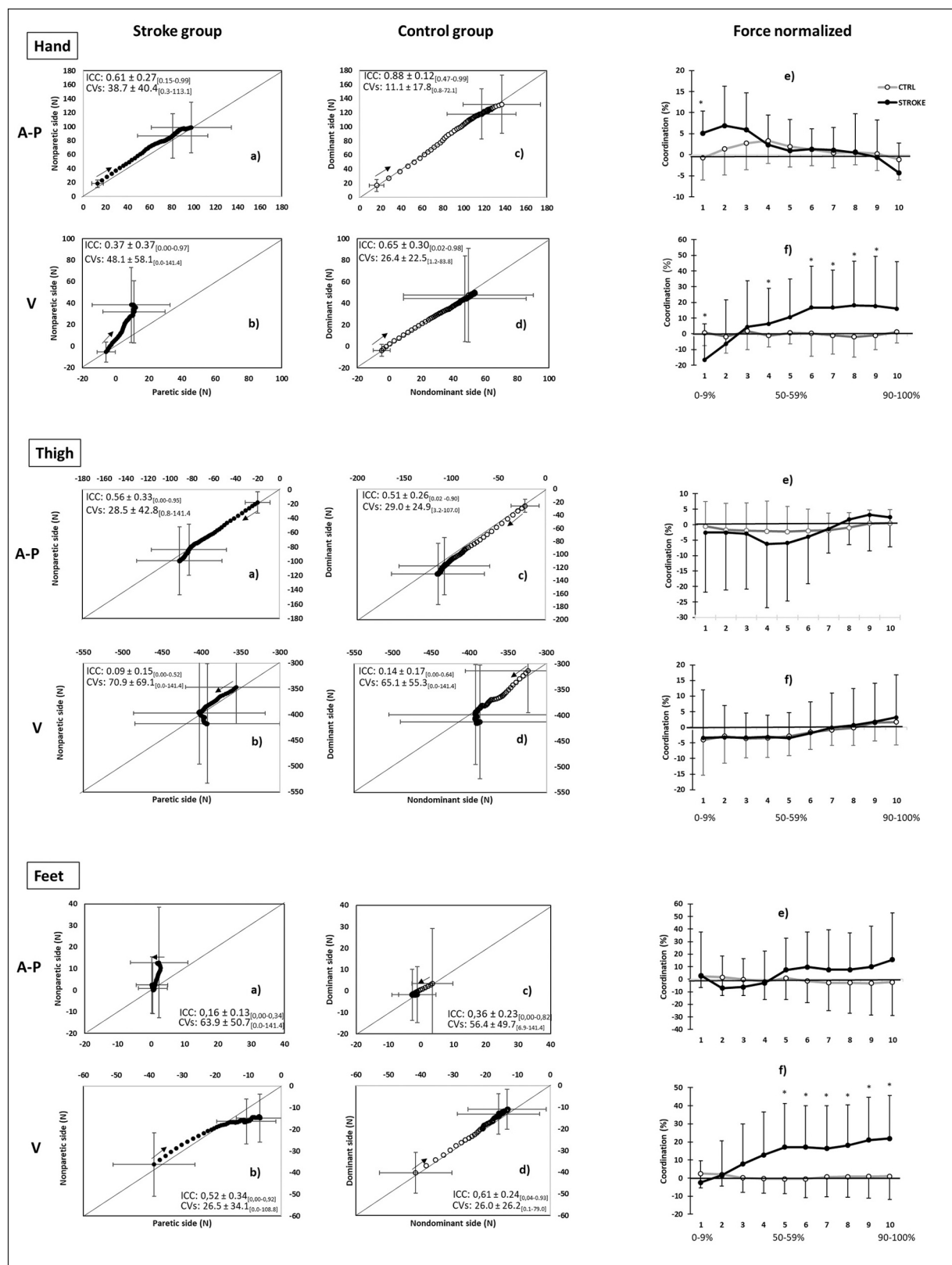


Fig. 3. Force evolutions (a, b, c, d) for AP and V components for handles (H), thighs (T) and feet (F) in both groups (stroke circles in black, control in white). The standard deviation values (SD) are represented for initial 0%, 50% and 100% of the pushing cycle values. The mean intra-class correlation (ICC) coefficients and the mean inter-trial coefficient of variation (CVs) are indicated with ranges for each level (hands, thighs, feet) and groups (stroke, control). The arrow represents the beginning and the direction of the pushing effort. The e. and f. represent the comparison between both groups for the coordination at each 10%. A significant p value between groups ($p < 0.05$) is represented by “*”.

of the cycle to the end with many points showing a difference from the control group (points 5 to 10, $p < 0.05$) (Fig. 3.F.f.). This indicates differences in the V support pattern at the feet in stroke individuals. Fig. 4 summarizes the results at each segment for the individuals with stroke and the controls.

4. Discussion

When individuals executed the isometric upper limb maximal pushing, the effort induced forward and upward forces on the handles, backward and downward forces on the seat produced by the thighs, with less variation of support on the paretic thigh in the stroke group. At the feet, the maximal pushing effort resulted in an asymmetry in feet support; the paretic foot supported less weight. The best coordination was observed for the AP forces produced at the handles in both groups with some difficulties at the beginning of the effort in individuals post-stroke. As expected, the MVF at the handles (AP and V) produced by the paretic side were less than the nonparetic side. These results partially confirm the main hypothesis.

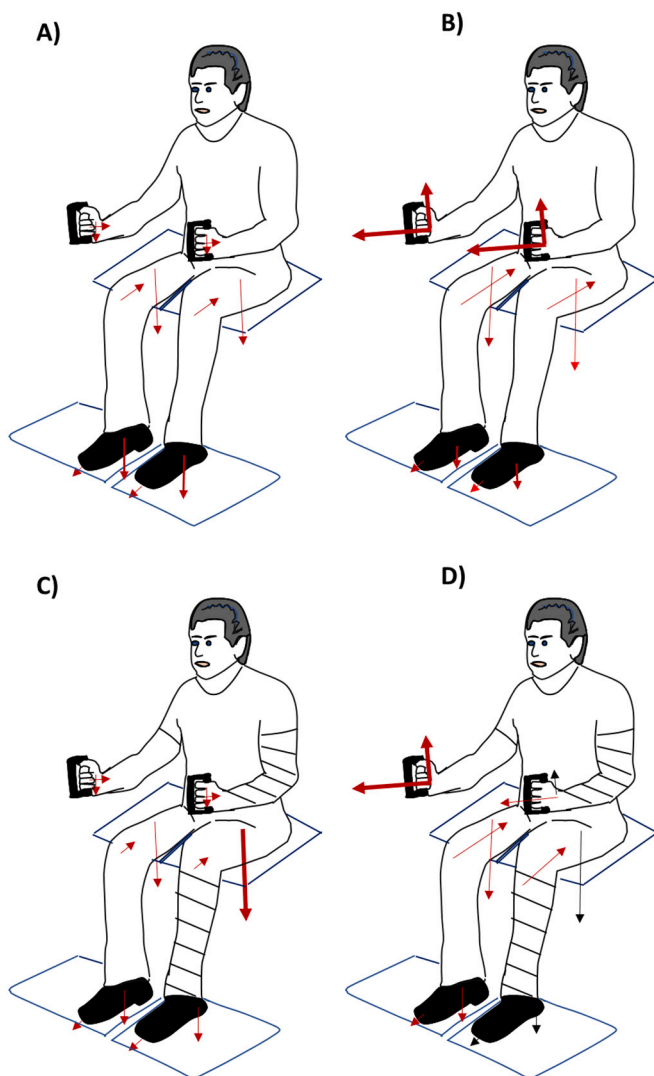


Fig. 4. Summary of the findings in the control group (A and B) and stroke group (C and D). A/C and B/D, reference position and results for the isometric pushing task, respectively. An arrow of a different size between sides indicates asymmetry with a thick arrow illustrating where the greater force is. For B and D), arrows of the same colour represent a coordinated development of force between limbs. The paretic side is hatched on the figure.

4.1. Maximal pushing efforts: the stroke group is asymmetric

Regardless of the force components analyzed, the MVF showed no difference between sides for the control group at the hands. Individuals with stroke consistently showed asymmetries for AP and V forces at the handles. In comparison to a unilateral effort such as hand grip (−23% for paretic side) (DeJong and Lang, 2012) and a wrist/finger extension task at 50% of MVF (−20%) (Lodha et al., 2012), the asymmetry between sides in our pushing exercise in AP seems less important (−9%). This can be explained by the bilateral and simultaneous effort. DeJong and Lang (2012) previously showed, in a bilateral task, a decrease in maximal grip force for the nonparetic side and an increase for the paretic side with less asymmetry than for the unilateral task. Bilateral tasks, with simultaneous dependent performance of both hands together, activate balanced interhemispheric interactions, thus improving coupling and motor regulation between sides (Arya and Pandian, 2014). In addition, the bilateral condition seems to facilitate performance of the paretic side only for a high level of force (DeJong and Lang, 2012; Kang and Cauraug, 2014), which was the case with our task. One cannot exclude that the reduced forces produced at the handles on the paretic side is partly associated with weakness of the trunk muscles (Karthikbabu et al., 2012) that reduced the ability to stabilize the trunk and thus the capacity of the paretic upper limb to produce force (Gagnon et al., 2016).

4.2. Reference position: asymmetry under the thighs in the stroke group

The control group had V forces similar between sides with ~83% of the weight on the thighs. The individuals post-stroke had more V forces on the thighs (86–87%) with difference between sides at the thighs (paretic greater) (Fig. 4). This asymmetry at the thighs could be explained by the weakness of the ipsilateral trunk muscles which could induce a tilt on this side (Karthikbabu et al., 2016). Holding the handles could have helped to control the trunk and reduce the postural asymmetry in sitting position.

4.3. Postural strategies during maximum bilateral pushing effort

The movements produced in the upper limbs depend on the ability of the rest of the body to adjust the posture (Bouisset et al., 2002). Changes in V reaction force under the thighs and feet actively contribute to the upper limb movements in healthy (Dean et al., 1999) and individuals with hemiparesis (Messier et al., 2005). When individuals performed an isometric maximum upper limb pushing, AP and V forces changed in the same direction on the thighs and feet for the stroke and control groups and this confirms the similar postural adaptations for both groups (Dean et al., 1999; Likhi et al., 2013; Messier et al., 2005). In the stroke group, the asymmetrical support at the thighs observed in the reference position was not seen at t100 while an asymmetry appeared at the feet with less support by the paretic foot. The reduced support by the feet can be explained by the strategy to produce a maximal pushing effort (Huang and Ferris, 2009). The more important decrease of support on the paretic foot might be the result of associated movements (synkinesis) in a flexion scheme at the level of the paretic lower limb (Boissy et al., 2000). It could be that, the production of greater positive AP force by the nonparetic hand came with an increase in the V component that might be equilibrated by an increase V force in the opposite direction and so more support on the thigh and less removal of support at the foot. This confirms that the maximum effort of force on a distal limb induces postural reactions on the other limbs and the presence of a strong link between the upper and lower limbs (Boissy et al., 2000; Bouisset et al., 2002).

4.4. Coordination during isometric upper limb pushing efforts

During the bilateral task, the stroke group had decreased inter-limb coordination compared to control group. The AP forces produced by the

hands on the handles showed better coordination with the effort. Using a bimanual maximal grip task, Bertrand et al. (2004) observed a similar force development on both sides despite the strength difference. In contrast, Lodha et al. (2012) showed that bimanual motor impairments after stroke are characterized by an increase of asymmetry and a reduced coordination compared to control group during isometric wrist/finger extension tested at 5%, 25% and 50% of MVF (Lodha et al., 2012). They found that individuals with stroke had a constant pattern of coordination, assessed with the time lag between force of both hands, regardless of the force levels while control participants improved their coordination. Our isometric pushing task was 100% of the MVF while Lodha et al. (2012) used 50% of the MVF which could explain the better synchronization observed at the end of the push cycle. The reduced asymmetry observed for high level effort in individuals with stroke (Kang and Cauraugh, 2014) could induce a better coordination between side. In our study, the ability to develop coordinated V forces is altered in the stroke group even when the level asymmetry of V force between sides is removed. The difference between sides increases with the force development. Thus, individuals with stroke seem to be unable to coordinate the forces in both direction and prioritize the AP direction that matches the task requested.

The coordination patterns between paretic (nondominant) and nonparetic (dominant) were moderate for both groups at the thighs in AP direction. For V forces, the comparison between groups highlighted a similar pattern, but a poor ICC was found. This difference could be explained by the small amplitude variations in V forces (a large portion being associated to the weight of the subject) that makes the use of ICC less sensitive. For the feet, the asymmetric V coordination forces during the force development confirms the individuals' asymmetric foot strategies for stroke group during upper limb motor activity (Messier et al., 2005). Similarly, to Messier et al. (2005) during a bilateral upper limb forward movement, we observed less weight support under the paretic foot than nonparetic but only starting at 30% of the isometric push cycle.

Individuals with stroke are more variable in their upper-limb unilateral and bilateral movements than controls (Thies et al., 2009). The increase of CVs in the stroke group has already been shown for inter-limb coordination during grip measurement indicating unstable coordination control (Lai et al., 2019). Lack of stable coordination could be associated with delayed reaction to start force production on the paretic side, especially since asymmetry seems to be mainly present at the beginning of the pushing effort. In addition, the muscle weakness and brain injury area associated with bimanual coordination could affect the stability of the strategies (Donchin et al., 1998). For thighs and feet, the CVs were more similar between groups.

4.5. Clinical implications

As in healthy participants (Bouisset et al., 2002), the isometric pushing task highlights postural adjustments in stroke context. Therefore, analysis of this task could be a relevant test to assess the impact of hemiparesis on asymmetry, postural organization and coordination.

4.6. Study limitations

The mean age of participants in the control group was lower than those in the stroke group. However, a study on healthy participants did not show a difference in upper limb strength between individuals aged 40–49 and 60–69 years (Ditroilo et al., 2010). Moreover, all other demographic characteristics were similar between the groups. The sample size was not calculated due to the difficulties related to the use of relevant variables for an original testing method. Nevertheless, despite the small number of participants and the rather good motor recovery in our subjects with stroke, we observed significant differences between sides and groups. It could have been judicious to place the healthy controls in a situation of asymmetric pushing with less force on the dominant and nondominant sides in order to assess whether they remained

coordinated in the same manner. However, this would have changed their level of pushing effort relatively to their maximum forces. Lastly, an electromyographic analysis would have helped understand motor strategies used during pushing tasks and should be included in future studies.

5. Conclusion

This original study showed the relevance of posture analysis (thighs and feet) and coordination when producing maximum isometric upper limb pushing efforts. Despite evidence of force asymmetries, individuals with stroke adapted their postural organization similarly to healthy controls. During the development of the maximum pushing efforts, the coordination was moderate in the AP direction for both the forces exerted by the hands and thighs. Stroke participants were not coordinated for the V forces at any level while healthy controls showed some coordinated forces at the feet and hands. In future studies, using these bilateral pushing exercises in a training protocol will allow to judge their superiority in comparison to other approaches targeted at the paretic upper limb.

Authors' contributions

AVB: Statistics, Data analysis, Formal Analysis, Original Draft Preparation, Writing (VB was a major contributor in writing the manuscript).

JH: Conceptualization, Funding Acquisition, Methodology, Supervision Writing -Review & Editing

HA: Methodology, Investigation, Writing - Review & Editing

RA: Methodology, Design of the exerciser

SN: Conceptualization, Funding Acquisition, Methodology, Project Supervision, Administration Writing, Review & Editing.

Funding

The project was supported by Interactive technologies of engineering in rehabilitation (INTER-FRQNT), the Foundation LRH and Mission universitaire de Tunisie de Montréal, doctoral awards from university of Montreal (H. Akremi) and School of Health Sciences, HES-SO//University of Applied Sciences and Arts Western Switzerland.

Declaration of Competing Interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the article.

Acknowledgments

We would like to acknowledge the participants of our study and thank Philippe Gourdou, Michel Goyette, Amine Guediri and Daniel Marineau for their technical support.

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