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Influence of target uncertainty on reaching movements while standing in stroke

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A R T I C L E I N F O

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A B S T R A C T

Stroke individuals frequently have balance problems and impaired arm movements that affect their daily activities. We investigated the influence of target uncertainty and the side of the brain lesion on the performance of arm movements and postural adjustments during reaching in a standing position by stroke individuals. Participants stood on force plates and reached a target displayed on the center of a monitor screen under conditions differentiated by the prior knowledge of the target location at the beginning of the movement. Individuals who had a stroke in the right side of the brain performed the tasks with the ipsilesional, right upper limb while the individuals with a left stroke performed with the ipsilesional, left upper limb. Healthy individuals performed with right and left limbs, which data were later averaged for statistical analysis. Kinematic analysis of the arm and lower limb joints and displacements of the center of pressure of each lower limb were compared between target conditions and groups. Stroke individuals showed larger center of pressure displacements of the contralesional compared to the ipsilesional limb while these displacements were symmetrical between lower limbs for the healthy individuals, regardless of the target condition. The target uncertainty affected both the characteristics of the arm movements and postural adjustments before movement onset. Right stroke individuals used more ankle joint movements under the uncertain compared to the certain condition. The uncertainty in target location affects the arm reaching in upright standing, but the effects depend on the side of the brain lesion.

1. Introduction

Individuals who have suffered a cerebrovascular accident (CVA) have alterations in the postural control during quiet, upright standing (Corriveau, Hebert, Raiche, & Prince, 2004; Cunha, Alouche, Araujo, & Freitas, 2012; Duclos, Maynard, Abbas, & Mesure, 2015; Fernandes, Coelho, Martinelli, & Teixeira, 2018). Overall, they are more unstable and show increased postural sway observed

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by large displacements of the center of pressure (COP). These changes have been attributed to, at least in part, their weight-bearing asymmetry and the inability of the lower limb contralateral to the brain lesion (referred to as the contralesional limb in the current study) to control the upright stance. Therefore, many activities of daily living performed in standing are limited, such as reaching an object on a high shelf, as the arm movements could disturb the balance and lead to a fall.

It is well-known that the performance of an arm movement (called as focal action) in upright standing is always preceded by anticipatory postural adjustments (APAs) that could be observed by changes in the muscle activation or the COP trajectory prior to movement onset (Aruin, 2002). The effects of this internal perturbation on the APAs of stroke individuals were previously investigated when they raised their arms or released a load held in their hands (Garland, Stevenson, & Ivanova, 1997; Hedman, Rogers, Pai, & Hanke, 1997; Horak, Esselman, Anderson, & Lynch, 1984; Lamontagne, Paquet, & Fung, 2003; Slijper, Latash, Rao, & Aruin, 2002; Ustinova, Goussev, Balasubramaniam, & Leven, 2004). Stroke individuals showed the same sequence of postural muscle activation before raising their arms compared to healthy participants (Horak et al., 1984). In another study using similar task, longer latency and reduced muscle activities of the contralesional lower limb were accompanied by higher COP velocity (Garland et al., 1997). Such changes are impressive considering that their self-initiated arm movements are usually slower than healthy individuals inducing only small postural perturbations.

Reduced and asymmetrical activation of muscles of the lower limbs were also observed when stroke individuals released a load held in their ipsilesional hand (Slijper et al., 2002). However, in this task, the COP displacements of stroke individuals were like those of healthy, control participants. Recently, it was documented that stroke individuals have impairments in the preparation of both APAs and focal movements in a simple reaction time reaching task (McCombe Waller et al., 2016). In their study, the target to be reached was always known in advance while a loud acoustic stimulus was applied in 67% of the trials. In addition to the absence of response to the acoustic stimulus, individuals with stroke showed reduced APAs revealed by only small COP displacements. Altogether, these findings suggested that individuals who have suffered a CVA may use different motor strategies to deal with the internal perturbations associated with varying effects on the COP displacements. In the studies mentioned above, the motor actions to be performed were well-known in advance and individuals did not need to be prepared to make further corrections after the movement onset. Recent studies on arm movements in upright position performed by healthy individuals have suggested that the uncertainty in the target position to be reached (i.e. after the beginning of the movement the target position could change) influences the focal action or postural balance (Leonard, Gritsenko, Ouckama, & Stapley, 2011; Loureiro-Junior, Freitas, & Freitas, 2012; Martin, Teasdale, Simoneau, Corbeil, & Bourdin, 2000). In a context of target uncertainty, individuals need to reorganize the movements of the joints responsible for the focal action to make corrections, if necessary, of the hand trajectories to accurately reach the target. Leonard et al. (2011) observed that when performing reaching movements, healthy individuals presented earlier APAs in the lower limb contralateral to the moving arm when online corrections were needed. Based on these findings on healthy, young individuals, it has been assumed that the motions of the postural joints are not responsible only for the APAs, but they also contribute to the execution of the focal movement (Leonard et al., 2011). However, it is unknown whether stroke survivors who have several impairments in postural control also use a similar strategy to perform the arm movements under conditions of target uncertainty during upright standing.

Therefore, the current study is, to our knowledge, the first to examine the influence of target uncertainty on the performance of arm (focal) movement and APAs during reaching in the upright standing position by stroke individuals. Also, we aimed to investigate whether the effects of the target position uncertainty differed with the side of the brain lesion. It has been reported that right CVA individuals (RCVA) present more balance deficits compared to individuals who suffered a left CVA (LCVA). After a right CVA, individuals usually show large postural sway, more asymmetry in the weight-bearing, poor responses to external perturbations and reduced limits of postural stability (Duclos et al., 2015; Fernandes et al., 2018; Geurts, de Haart, van Nes, & Duysens, 2005; Laufer, 2003; Manor et al., 2010). Based on these findings, we expected to observe more changes in the postural adjustments for the RCVA individuals mainly when the target position was uncertain (i.e., decreased amplitude of the COP and increased angular amplitude of the lower limb joints, in particular, the hip). Hence, we also examined whether the RCVA participants had more balance deficits by assessing their postural sway during quiet standing that could influence their postural adjustments and, consequently, the performance in the arm reaching trials.

Regarding the movement performance, we hypothesized that the healthy and stroke individuals should need more time to start the arm reaching movements when the target position was uncertain, mainly for the RCVA individuals. Such hypothesis of target uncertainty was based on a previous study that investigated healthy individuals reaching toward uncertain targets in sitting position (Freitas & Scholz, 2009). On the other hand, the other temporal variables and spatial accuracy should be similar as, in the current study, movements toward the same target location (i.e., center target) but with or not uncertainty were compared. However, it was expected that the hand trajectories should be more affected by the uncertainty due to possible necessary online corrections and those should be related to hemispheric specialization. Hence, it was expected that the LCVA individuals should present more deficits in the movement trajectory (i.e., greater hand trajectory) compared to RCVA or healthy individuals. The hypotheses in function of the side of the brain lesion on the temporal and spatial characteristics of the movements are related to a specialization of the right hemisphere in movement planning, and the left hemisphere in movement execution (de Paiva Silva, Freitas, Silva, Banjai, & Alouche, 2014; Freitas, Gera, & Scholz, 2011; Schaefer, Haaland, & Sainburg, 2009). Note that the findings from previous studies about the specific role of each brain hemisphere on the control of arm movements were based on the performance of the alterations of the ipsilesional arm movements of stroke individuals in sitting position. We expected that these alterations of the arm movements after the occurrence of a CVA should be more evident in standing position mainly under uncertain condition.

Table 1
Characteristics of stroke participants and their healthy, matched controls.

	RCVA (n = 7)	LCVA (n = 8)	CG (n = 8)
Age (years)	57.1 ± 7.6	53.7 ± 7.3	57.2 ± 5.9
Sex	5 M/2 F	5 M/3 F	4 M/4 F
Body mass (kg)	72.8 ± 10.4	78.9 ± 11.4	73.5 ± 8.4
Height (cm)	162.7 ± 7.2	165.9 ± 7.7	167.1 ± 6.5
MMSE (score)	27 ± 3	27 ± 4	30 ± 0
Months since stroke	68.7 ± 55.1	50.1 ± 32.6	n/a
FMA-UE (score)	43.1 ± 14	43.4 ± 19	n/a

Note: Except for sex, the values repreent means and standard deviations.
Abbreviations: RCVA = Right Cerebrovascular Accident; LCVA = Left Cerebrovascular Accident; CG = Control Group; M = Male; F = Female; MMSE = Mini-Mental State Exam; FMA-UE = Fugl-Meyer Motor Assessment scale of the Upper Extremity; n/a = not applied.

2. Methods

2.1. Participants

Fifteen individuals with hemiparesis following a single stroke (CVA was confirmed by computerized tomography or magnetic resonance imaging), in the anterior and middle cerebral arteries territory [divided into two groups: 8 with LCVA (aged 53.7 ± 7.3 years; 5 males) and 7 with RCVA (57.1 ± 7.6 years; 5 males)], occurred at least 6 months before the study (LCVA: 50.1 ± 32.6 and RCVA: 68.7 ± 55.1 months), participated in the study. Summary of the characteristics of each group is presented in Table 1. They were able to stand in an upright position independently when performing the reaches with their ipsilesional limb. The motor function of the contralesional upper limb of the LCVA and RCVA groups was measured using the Fugl-Meyer Assessment of the Upper Extremity [FMA-UE; (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975)]. Based on the FMA-UE scores, stroke participants of both groups were considered to present from mild to moderate impairment in their contralesional upper limb. Eight age-matched, healthy individuals (57.2 ± 5.9 years; 4 males) were included in a control group (CG). Participants involved in the study had no diagnostics of cardiovascular or other neurological diseases and musculoskeletal disorders that restrain the participation in the experiment. All participants were right-handed dominant (CVA individuals prior to the brain lesion) as determined by the Edinburgh handedness questionnaire (Oldfield, 1971). They had normal or corrected vision according to the Snellen Test (Lee & Scudds, 2003), and had no cutaneous sensitivity deficits in the hands and feet according to the Semmes-Weinstein monofilaments test (Lehman, Orsini, & Nicholl, 1993). The Mini-Mental State Exam (MMSE) was also used to verify cognitive changes that would undermine the understanding of verbal commands (Brucki, Nitrini, Caramelli, Bertolucci, & Okamoto, 2003). All participants gave written informed consent, consistent with the Declaration of Helsinki, and approved by the University's Human Subjects Review Board.

2.2. Apparatus and experimental task

For all trials, participants stood barefoot in an upright position, with one foot on each force plate (Model OR6-7, AMTI). The feet were parallel to each other and approximately at hip-width apart. Their positions were marked on the force plates to be reproduced in all experimental trials. Kinematic data at the sagittal plane of the body were recorded by one video camera (Qualisys Proreflex240, Qualisys Medical AB). Individual markers were placed on the following anatomical points: lateral aspect of the acromion process of the shoulder; ulnar styloid processes of the wrist, lateral epicondyle of the elbow, lateral projection of the sixth thoracic vertebra; anterior iliac crest; greater femoral trochanter; lateral femoral epicondyle; lateral malleolus; calcaneus; and head of the fifth metatarsal. A marker was placed on the extremity of a splint with a length equal that to the index finger (i.e., from the base of the proximal phalanx to the tip of the index finger), fixed in the hand by a fingerless glove. A rigid touch bar composed by a tridimensional force sensor (ATI Nano 17) with 1.7 cm diameter fixed in a tripod with adjustable height was used in the reaching experimental tasks. The vertical force recorded by the sensor was used to determine the movement onset during the experimental trials and to control the initial position of the fingertip. The force plate, force sensor, and kinematic data were acquired at a sampling frequency of 100 Hz. A customized code written in LabView 2010 software (National Instruments Corporation) was used to record the force plate and force sensor data and to control the tasks.

In the first two trials, participants performed the quiet standing task. They were instructed to maintain the arms hanging at the side of their bodies, parallel to the trunk, and remain as quiet as possible for 35 s. Participants were asked to look forward to a target (black 2-cm diameter circle in a white background) displayed in the center of a touch-screen monitor (ELO 17″). The target was centered on the participant's midline, placed one meter-distant ahead and set at eye's height of each participant.

After these trials, participants performed the reaching tasks in standing position. CVA groups performed the tasks only with ipsilesional upper limb (i.e., right and left arm respectively for the RCVA and LCVA groups). Participants of the control group performed the tasks with left and right limbs, but the order of the arm was alternated for each participant. In the reaching tasks, they stood in the same position as in the previous trials but with the elbow of the moving arm flexed at 90° and the index fingertip in contact with the touch bar (Fig. 1A). From this position, participants were asked to reach and touch, as fast as possible, a target

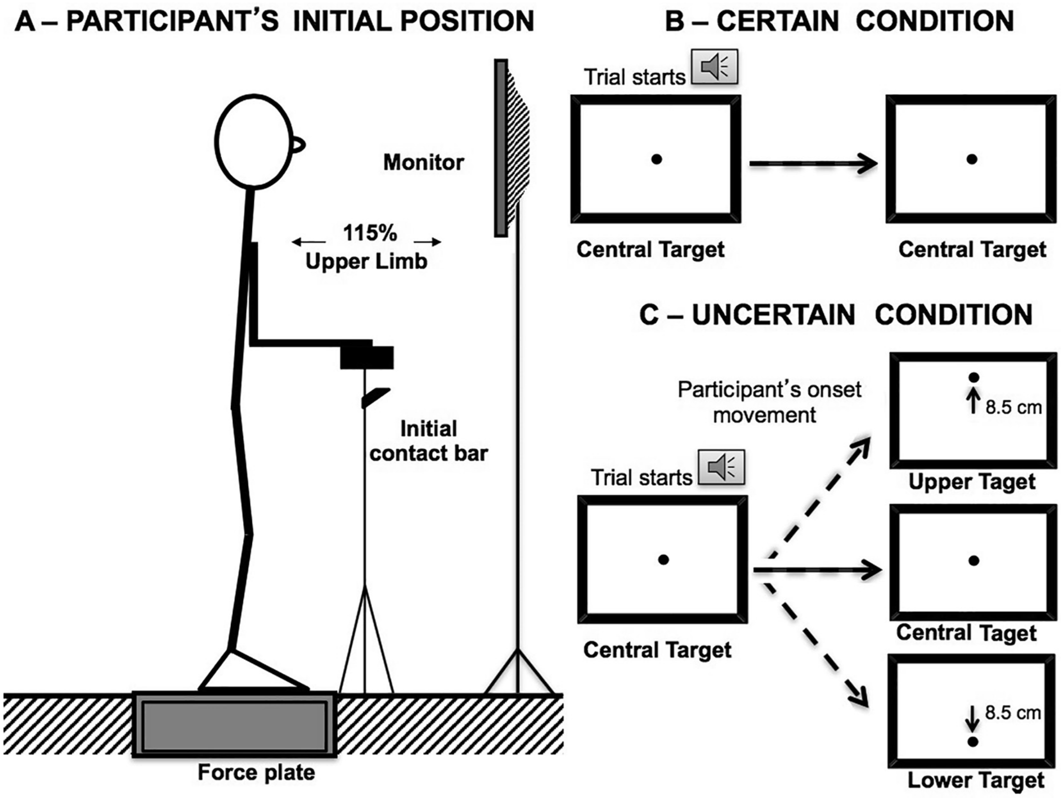

Fig. 1. Illustration of the experimental set-up (A) and target position presented at the onset of each trial and when the participant started to move under the certain (B) and uncertain (C) conditions.

displayed on the touch-screen monitor. The monitor was positioned at a distance equal to 115% of the arm length (i.e., from the acromion process of the shoulder to the tip of the index finger) and in the direction of the shoulder joint of the arm used to reach. Participants were not required to start the movement as soon as the trial began as they could move as they felt comfortable. Therefore, the task was not a reaction time task.

The target could be shown in three different positions: in the center of the monitor (central target) aligned with the shoulder at eye's level of each participant or 8.5 cm superior (upper target) or inferior (lower target) than the central target position. Initially, participants performed five reaches towards the central target (*certain condition;* Fig. 1B). Then, they performed 15 trials under the *uncertain condition;* Fig. 1C) where the central target could move at the movement onset for the upper or lower target positions (66%) or remain in the same central target position (33%). The order of the trials for each target position was randomized. Resting intervals were allowed between the two conditions and when requested by the participants. Fatigue was never reported.

2.3. Processing and data analysis

The signals of the three forces and three moments obtained from each force platform were used to calculate the COP displacement in the anterior-posterior (COP_{AP}) and medial-lateral (COP_{ML}) directions of right and left lower limbs. Before the COP computation, the signals from the force plates were low-pass filtered at 10 Hz with a second-order, zero-lag Butterworth filter in Matlab 2011. The time-series of the coordinates of the markers were also low-pass filtered at 10 Hz with a second-order, zero-lag Butterworth filter and used to compute six sagittal plane joint angles (degrees of freedom, DOF): wrist, elbow, shoulder, hip, knee, and ankle. Kinematic analysis was run only for the side of the moving arm.

For the reaching trials, movement onset (t_0) and termination were defined using 3% of the peak index fingertip resultant velocity. The displacements of the COP of each lower limb and amplitudes of joint excursions of the lower limb were then calculated into two intervals: 150 ms before the movement onset (i.e., t_0-150) until t_0; defined as the APA phase, and during the total time of arm movement (i.e., time interval from movement onset until movement termination). The arm joints amplitudes were calculated only during the movements. Four temporal measures related to the performance of the reaching tasks were examined: *Movement Time* (MT, total duration of the reach), *Movement Onset Time* (MOT, time elapsed from the auditory signal indicating the trial onset until the time participants actually started their reaches, i.e., t_0), *Peak Velocity* (PVel, maximum value of the hand velocity), and *Time to Peak Velocity* (TPVel, time interval to achieve the hand peak velocity). Two spatial measures were computed: *Hand Trajectory Amplitude* (HTA, magnitude of the index fingertip trajectory from movement onset until termination) and *Variable Error* (VE, deviation of the fingertip position at each trial from its across-trials mean position at the movement termination) during the reaching.

For the quiet standing task, the first and last 2.5 s of the trial were removed from the analysis after filtering the force plate data. The mean sway amplitude was computed for each lower limb as the standard deviation of the time series of COP_{AP} and COP_{ML}. Data of two participants of CG could not be used due to technical problems during data collection, and then, only for this task, CG was composed of six individuals.

2.4. Statistical analysis

Statistical analyses were performed in SPSS 19.0 (SPSS Inc., Chicago, USA). Normality and homogeneity of variances tests were initially performed.

For the arm reaching tasks, the averaged values of the dependent variables computed across trials toward only the central target were compared across groups and conditions. Firstly, analyses comparing the dependent variables of the CG obtained from the movements performed with the right and left arms were run. Differences between arms and COP displacements were not observed and, therefore, the averaged results obtained between the conditions were utilized for further analyses involving CG.

Analyses of Variance (ANOVA) were used to test the effect of one between-subject factor (*group*, RCVA *vs.* LCVA *vs.* CG) and one repeated-measures, within-subject factor (*condition*, certain *vs.* uncertain) as factors were performed on the temporal and spatial measures of reaching tasks (i.e., MT, MOT, PVel, TPVel, HTA, and VE). For the amplitude of joint excursions, three ANOVA were run with one additional within-subject factor, the *joint* factor, in which one analysis was performed for the arm joints during the movement and other two for the lower limb joints involved in the postural adjustments before (APA phase) and during the movements.

Two ANOVA were run to verify the effect of *group* as a between-subject factor and two repeated-measures, within-subject factors: *condition* and *lower limb* (*lower limb*, dominant for controls/ipsilesional for CVA groups *vs.* non-dominant for controls/contralesional for CVA groups) on the amplitude of the COP_{AP} and CP_{ML} displacements measured before and during the movements.

For the quiet standing task, two ANOVA were run to test the effect of *group* and one repeated-measures, within-subject factor (*lower limb*) on the amplitude of COP_{AP} and CP_{ML} displacements. Post-hoc tests with Bonferroni adjustments were performed, if necessary. The level of significance was set at $p < 0.05$.

3. Results

3.1. Arm reaching characteristics

All participants were able to perform the arm reaching movements in the standing position regardless of the experimental condition. The temporal (MOT, MT, TPVel, and PVel) and spatial (HTA and VE) characteristics of the arm reaching movements averaged (± standard error) across participants are presented in Table 2 for each group (RCVA, LCVA and CG) and experimental condition (certain and uncertain).

A summary of the results of statistical analyses (F, *p* and generalized effect size) for temporal and spatial variables is presented in the top part of Table 3. Only one temporal performance variable, the MOT, was affected by the uncertainty in the final target location ($p < 0.01$) as revealed by two-way ANOVA (*group* × *condition*). Participants took longer time to start their movements in the uncertain than in the certain condition (about 170 ms, averaged across groups). Regarding the spatial variables, there was only a *group* effect ($p < 0.05$; see Table 3) and the pairwise comparisons indicated that this effect was because LCVA presented greater HTA compared to RCVA.

The reaches were performed with a similar kinematic pattern of the arm joints across groups (see Table 3 with the results of statistical analyses related to the *group* factor on the angular amplitude of the arm joints). The angular amplitude of the shoulder, elbow and wrist joints averaged across participants are presented in Fig. 2A. The pairwise comparisons revealed greater shoulder angular amplitude compared to the elbow and wrist joints. These results were confirmed by a *joint* effect ($p < 0.001$; Table 3). There

Table 2
Averaged values (± S.E.) across participants of the RCVA, LCVA and CG for temporal (MOT, MT, PVel, and TPVel) and spatial (HTA and VE) measures for certain and uncertain conditions.

	LCVA		*RCVA*		*CG*	
	Certain	**Uncertain**	**Certain**	**Uncertain**	**Certain**	**Uncertain**
MOT (ms)	613.8 (± 90.4)	668.5 (± 89.4)	572.5 (± 96.7)	824.8 (± 95.6)	432.3 (± 90.4)	635.6 (± 89.4)
MT (ms)	878.7 (± 54.1)	869.3 (± 53.8)	813.9 (± 57.9)	893.6 (± 57.5)	866.7 (± 54.1)	851.7 (± 53.8)
PVel (cm/s)	189.1 (± 11.4)	187.9 (± 86)	188.2 (± 12.1)	169.3 (± 91.4)	202.3 (± 11.4)	194.4 (± 86)
TPVel (ms)	251.3 (± 14.5)	255 (± 21.5)	210.1 (± 23.1)	208.6 (± 19)	233.8 (± 11.5)	243.1 (± 14.2)
HTA (cm)	82.2 (± 3.8)	79.8 (± 4.1)	65.9 (± 4.1)	67 (± 4.4)	80.9 (± 3.8)	77.4 (± 4.1)
VE (cm)	1.8 (± 0.4)	2.9 (± 0.9)	1.8 (± 0.5)	2.3 (± 0.9)	1.2 (± 0.4)	2.2 (± 0.9)

Abbreviations: LCVA = Left Cerebrovascular Accident; RCVA = Right Cerebrovascular Accident; CG = Control group; MOT = Movement Onset Time; MT = Movement Time; PVel = Peak Velocity; TPVel = Time of Peak Velocity; HTA = Hand Trajectory Amplitude; VE = Variable Error.

Table 3
Statistical results (F, *p* and generalized effect size, η^2) for each temporal-spatial variable and angular displacement of the arm joints during the reaching and lower limb joints before and during the reaching movements (APA and movement phases, respectively).

VARIABLES	F	*p*	η^2	F	*p*	η^2
Temporal						
		MOT			*MT*	
Group	1.01	0.38	0.08	0.04	0.96	0.004
Condition	***13.38***	***0.002***	***0.11***	0.61	0.44	0.004
Group x Condition	1.64	0.22	0.03	1.61	0.22	0.02
		PVel			*TPVel*	
Group	1.15	0.34	0.08	2.25	0.13	0.14
Condition	***2.54***	***0.03***	***0.13***	***0.15***	***0.002***	***0.7***
Group × Condition	0.75	0.49	0.02	0.08	0.92	0.002
Spatial						
		HTA			*VE*	
Group	***3.71***	***0.04***	***0.26***	0.36	0.71	0.02
Condition	3.34	0.08	0.006	2.31	0.14	0.04
Group × Condition	2.49	0.11	0.008	0.11	0.89	0.004
Angular Displacements						
		Arm joints				
Group	1.79	0.19	0.07			
Condition	3.24	0.09	0.019			
Joint	***753.64***	< ***0.001***	***0.94***			
Group × Condition	1.43	0.26	0.017			
Group × Joint	0.43	0.79	0.018			
Condition x Joint	***6.57***	***0.003***	***0.015***			
Group × Condition × Joint	1.17	0.34	0.006			
			Lower Limbs			
		APA phase			*Movement phase*	
Group	0.39	0.68	0.02	0.63	0.54	0.02
Condition	***7.17***	***0.014***	***0.05***	0.05	0.82	< 0.001
Joint	***17.41***	< ***0.001***	***0.11***	***118.18***	< ***0.001***	***0.73***
Group × Condition	***4.13***	***0.03***	***0.06***	0.14	0.87	0.002
Group × Joint	0.62	0.65	0.01	0.83	0.52	0.039
Condition x Joint	1.38	0.26	0.009	1.89	0.17	0.005
Group × Condition × Joint	0.62	0.65	0.009	***4.21***	***0.006***	***0.024***

Note: Statistically significant p-values are shown in bold italic fonts.
Abbreviations: MOT = Movement Onset Time; MT = Movement Time; PVel = Peak Velocity; TPVel = Time of Peak Velocity; HTA = Hand Trajectory Amplitude; VE = Variable Error; APA = Anticipatory Postural Adjustments.

was also a *condition* × *joint* interaction ($p < 0.03$) because the reaches were performed with more shoulder and elbow angular displacement when participants knew in advance which target they should reach (certain condition) compared to the unknown condition as indicated by the pairwise comparisons.

3.2. Anticipatory and movement-associated postural adjustments

All participants performed the arm reaching movements in upright standing without losing their balance. Overall, the displacements of the joints of the lower limb were much smaller than the joints of the upper limb, whereas we did not run a statistical analysis to compare their amplitudes. The angular amplitudes of the hip, knee, and ankle are presented in Fig. 2 for the APA phase (in B) and during the movement (in C). The results of statistical analyses for the angular amplitudes of the lower limbs are presented in Table 3 also before and during the movement.

There were two main effects, *joint* and *condition*, on the angular amplitude of the lower limb joints as revealed by the ANOVA ($p < 0.001$ and $p < 0.02$, respectively) in the APA phase (Fig. 2B). First, the angular amplitude of the hip joint was greater than the knee and ankle joints; and, second, the angular amplitudes increased in the uncertain condition compared to the certain condition. There was also a significant *condition* × *group* interaction ($p < 0.05$). The pairwise comparisons indicated differences between conditions for the RCVA and CG groups but not for the LCVA.

During the movement, ANOVA indicated a main effect of *joint* ($p < 0.001$) on the angular amplitude of the lower limb joints, where hip joint amplitude was greater than that of knee and ankle joints as indicated by the pairwise comparisons. The

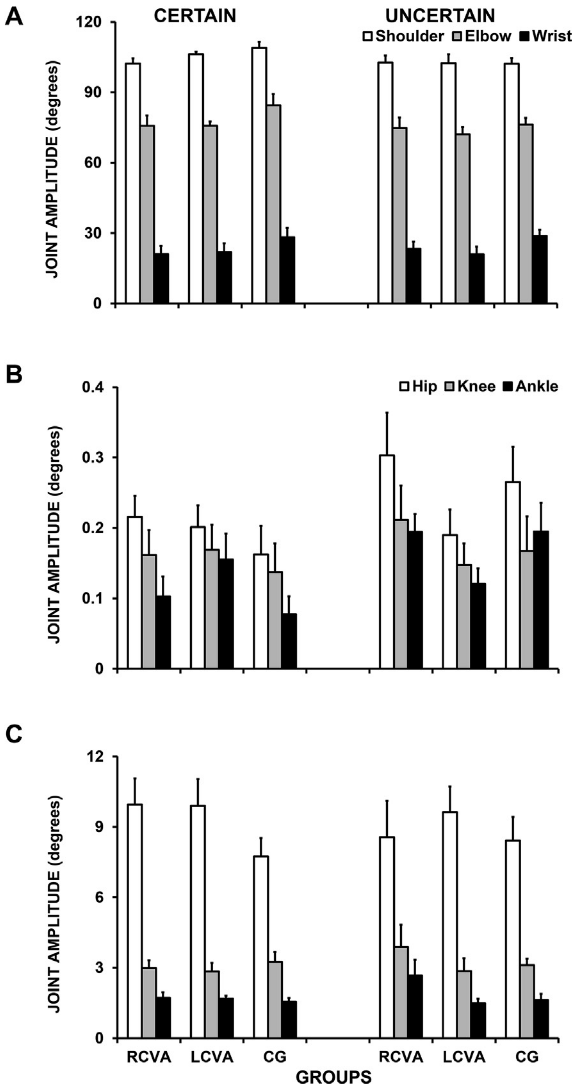

Fig. 2. Across-participant means and standard errors of each group for the angular amplitude of the upper limb (shoulder, elbow, wrist) during the arm movement (A) and of the lower limb (hip, knee and ankle) obtained 150 ms prior to the movement onset (B) and during the arm movement (C) performed under certain or uncertain condition.

condition × *joint* × *group* interaction ($p < 0.01$) was also revealed because, according to the pairwise comparisons, the amplitude of the ankle joint increased when participants of the RCVA reached the target under uncertain condition (Fig. 2C).

The differences in the lower limb joints amplitude between conditions did not reflect in the COP amplitude. For all conditions, a small shift of the COP_{AP} backward was followed by a larger shift of the COP_{AP} to reach the target. For the ML direction, the COP shifts were more variable across trials and did not show a specific pattern. Averaged values (± S.E.) of COP_{AP} and COP_{ML} amplitude of the shifts, for each group, lower limb and condition, are presented in Fig. 3 before (in A, APA phase) and during the reaching movement (in B). Note that the scales for COP_{AP} and COP_{ML} are different for better visualization. Also, the lower limbs are referred to as dominant and non-dominant limbs for the CG and, as ipsilesional and contralesional for the CVA groups.

During APA phase, the amplitude of both COP_{AP} and COP_{ML} differed between the limbs as indicated by the *lower limb* main effect in the two-way ANOVA ($p < 0.001$ for both directions, but see Table 4 for more results of statistical analyses). For both directions, the COP amplitudes of the contralesional lower limb of LCVA and RCVA and the non-dominant lower limb of CG were greater than that ipsilateral to the moving arm (Fig. 3A). Furthermore, a significant *lower limb* × *group* interaction ($p < 0.05$) was revealed only for the AP direction, suggesting that the difference in the COP_{AP} amplitude between the lower limbs was not similar for all groups. The pairwise comparisons revealed a larger difference between lower limbs for RCVA and LCVA compared to controls. Also, the COP_{AP} amplitude of the dominant lower limb of CG was greater than that of the ipsilesional lower limb of the RCVA as indicated by the pairwise comparisons.

During the movement, there was also a *lower limb* effect (see Table 4) but only for the COP_{AP} amplitudes ($p < 0.001$), where

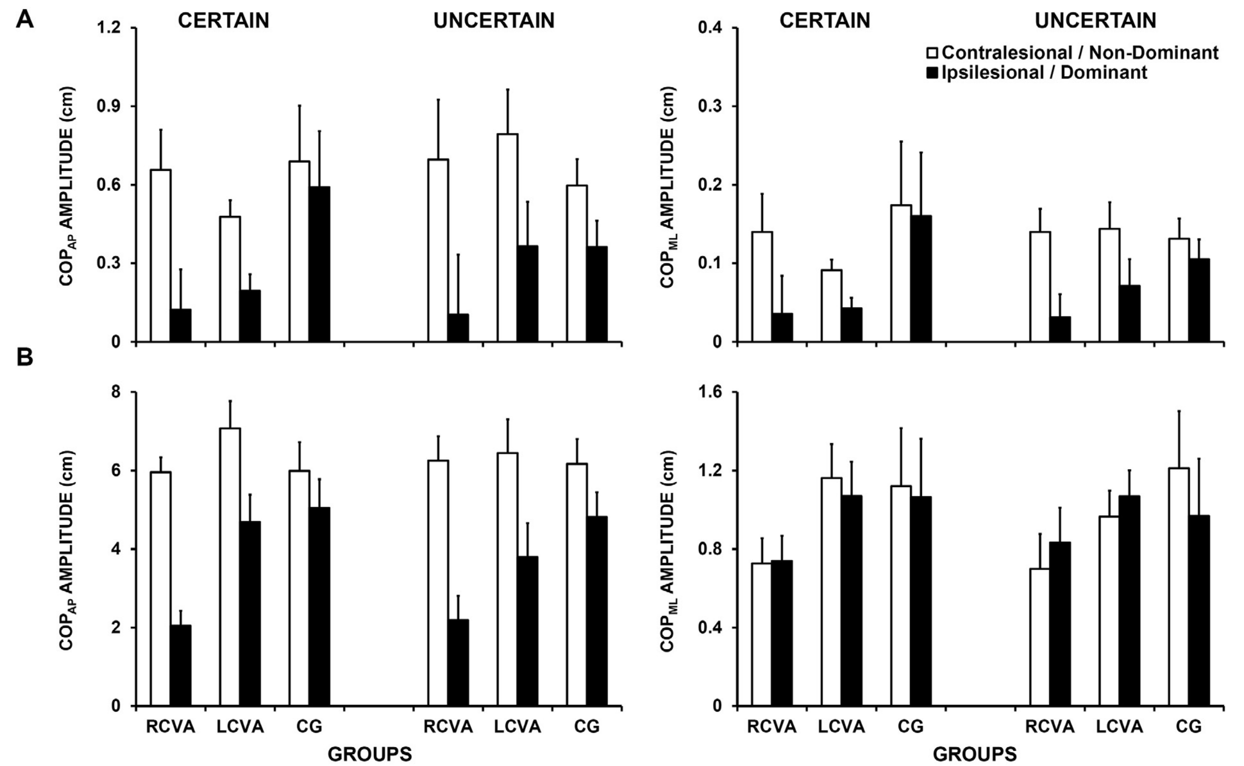

Fig. 3. Across-participant means and standard errors for the amplitude of the COP_{AP} (left graphs) and COP_{ML} (right graphs) of contralesional and ipsilesional lower limbs (respectively, non-dominant and dominant limbs for the CG) and group obtained 150 ms prior to the movement onset, t_0 (A) and during the arm movement (B) performed under certain or uncertain condition.

Table 4
Statistical results (F, *p* and generalized effect size, η^2) for the outcomes related to the COP_{AP} and COP_{ML} variables in the APA and movement phases of the reaching trials and during quiet standing trial.

VARIABLES	COP_{AP}			COP_{ML}		
APA phase	**F**	***p***	η^2	**F**	***p***	η^2
Group	0.72	0.5	0.03	1.09	0.36	0.05
Condition	0.1	0.76	0.002	0.011	0.92	< 0.001
Lower Limb	***38.08***	***< 0.001***	***0.19***	***21.39***	***< 0.001***	***0.07***
Group × Condition	1.47	0.25	0.05	0.65	0.54	0.03
Group × Lower Limb	***3.77***	***0.04***	***0.05***	3.33	0.06	0.02
Condition × Lower Limb	1.76	0.2	0.006	0.44	0.51	0.001
Group × Condition × Lower Limb	0.098	0.91	< 0.001	0.07	0.93	< 0.001
Movement phase						
Group	1.74	0.2	0.1	1.01	0.38	0.06
Condition	0.4	0.53	0.002	0.06	0.81	< 0.001
Lower Limb	***34.19***	***< 0.001***	***0.30***	0.04	0.85	< 0.001
Group × Condition	0.95	0.40	0.01	0.19	0.82	0.002
Group × Lower Limb	***3.44***	***0.05***	***0.08***	0.28	0.76	0.006
Condition × Lower Limb	0.96	0.34	0.001	0.16	0.7	< 0.001
Group × Condition × Lower Limb	0.07	0.93	< 0.001	1.27	0.30	0.005
Quiet Standing						
Group	***7.78***	***0.004***	***0.35***	1.32	0.29	0.09
Lower Limb	***26.83***	***< 0.001***	***0.36***	***8.42***	***0.009***	***0.13***
Group × Lower Limb	***10.95***	***0.001***	***0.31***	***3.46***	***0.05***	***0.11***

Note: Statistically significant p values are shown in bold italic fonts.
Abbreviation: APA = Anticipatory Postural Adjustments; COP = center of pressure; AP = anterior-posterior; ML = medial-lateral.

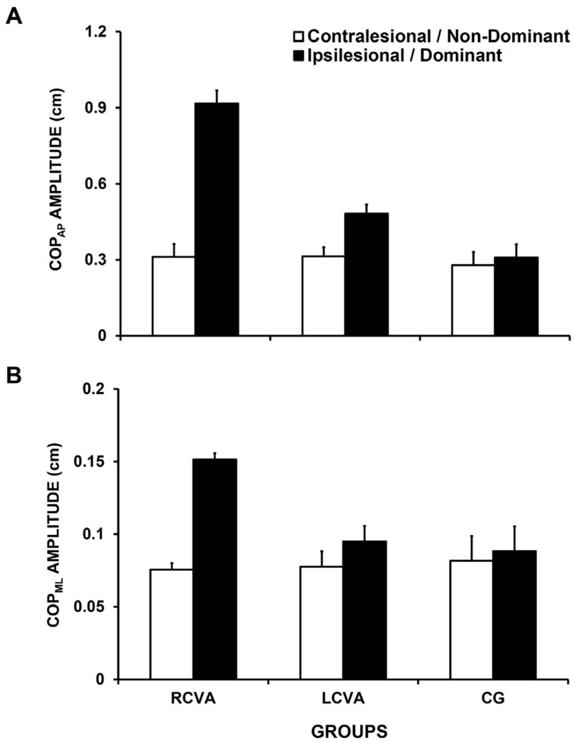

Fig. 4. Across-participant means and standard errors for the amplitude of COP_{AP} (A) and COP_{ML} (B) of contralesional and ipsilesional lower limbs (respectively, non-dominant and dominant limbs for the CG) during quiet standing.

COP_{AP} displacement of the contralesional/non-dominant limb was greater than the ipsilesional/dominant limb, regardless of *group* or *condition* (left graph in Fig. 3B).

3.3. Quiet standing

Although stroke individuals of both CVA groups and healthy controls were able to stand independently on the force plates during quiet standing, there were differences across them. The averaged across participants COP amplitudes of each group and lower limb during quiet standing are presented in Fig. 4 for the AP (in A) and ML directions (in B). For AP direction, the RCVA group showed greater COP amplitude than the LCVA and control groups as revealed by the main effect of *group* in the two-way ANOVA ($p < 0.005$; Table 4). Also, the COP amplitude of ipsilesional/dominant limb was larger compared to the contralesional/non-dominant limb confirmed by the main effect of *lower limb* for the AP ($p < 0.001$) and ML ($p < 0.01$) directions. The differences between ipsilesional and contralesional lower limbs depended on the group as revealed by the *group* × *lower limb* interaction also for the AP and ML directions ($p = 0.001$ and $p = 0.05$, respectively). For both directions, the pairwise comparisons indicated that the difference between lower limbs was greater for the RCVA compared to the other two groups.

4. Discussion

This study investigated the influence of target uncertainty and the side of the brain lesion on the performance of arm (focal) movements and postural control during reaching in a standing position by stroke individuals. Overall, the results support the hypotheses formulated in the introduction. The uncertainty affected the performance of the arm movements in standing; which also depended on the side of the brain lesion. To reach the central target under the uncertain condition, participants from all three groups took more time to start moving and increased the joint displacements compared to the certain condition. These results about the effects of target uncertainty corroborate and extend those from previous studies observed during arm reaching in sitting position (Freitas et al., 2011; Freitas & Scholz, 2009).

Some other effects of uncertainty in the current study depended on the side of the brain lesion. RCVA individuals shifted less the COP_{AP} of the ipsilesional limb compared to healthy controls prior to movement onset and increased the displacements of the ankle joint during the movement toward the uncertain target compared to the other two groups. LCVA individuals, on the other hand, performed the tasks in both conditions using similar motion of the lower limbs but with increased hand trajectory. These results could be associated with impairments in the postural control as observed in this and some earlier studies about postural control during quiet standing task (Cunha et al., 2012; Fernandes et al., 2018; Manor et al., 2010); changes in the ipsilesional arm specific to the side of the brain lesion (de Paiva Silva et al., 2014; Freitas et al., 2011; Schaefer et al., 2009); or both. The current findings indicated that stroke individuals use different strategies to perform the arm reaching movements while standing, which are more evident under uncertain target condition.

4.1. Target uncertainty affects the arm reaching in standing

Effects of target uncertainty on the arm reaching have been reported in both sitting and standing position (de Freitas, Scholz, & Stehman, 2007; Freitas & Scholz, 2009; Hua, Leonard, Hilderley, & Stapley, 2013; Leonard et al., 2011; Loureiro-Junior et al., 2012; Martin et al., 2000). In standing position, previous studies investigated only the effects of target uncertainty on the arm movements performed by healthy individuals (Leonard et al., 2011). The influence of target uncertainty on the APAs during arm reaching has been investigated only to movements performed toward a target that could shift to a new horizontal position (i.e., changes in movement direction) and not in the height of the target as in the current study. These earlier studies showed controversial findings about the uncertainty effects on either the focal action or postural balance (Leonard et al., 2011, Loureiro-Junior et al., 2012; Martin et al., 2000). These controversial results could be related to different biomechanical constraints imposed on the postural balance by the task in addition to the likeness of changes in the target location (Bouisset & Zattara, 1987). Specifically, when an individual starts to move from a central position toward a lateral target, some specific postural adjustments may be needed, such as changes in the weight-bearing between the lower limbs; which increases if the target is further shifted laterally. Therefore, in this case, both the direction and distance of the new targets could be responsible for the uncertainty effects observed in previously mentioned studies.

To our knowledge, this is the first study that examined the arm movements in the upright standing position when there was a possibility of changes in the target height performed by healthy and stroke individuals. Based on the studies with uncertainty in target direction, we hypothesized that individuals would take more time to start their movements towards a target that could change its height. The MOT results from all groups confirmed this hypothesis. We also expected a more significant effect on the MOT for the RCVA individuals as the right hemisphere has been described to play a major role in the movement planning (de Paiva Silva et al., 2014; Schaefer et al., 2009). However, this hypothesis has been falsified by our results.

The increased MOT with uncertainty is consistent with the findings in both healthy and stroke individuals reaching in a seated position when they were or not required to react to an imperative stimulus (de Paiva Silva et al., 2014; Freitas & Scholz, 2009; Haaland et al., 2009). In the current study, the MOT difference between target conditions was greater compared to previous studies with uncertainty in target direction in sitting as well as in standing position of healthy individuals (Loureiro-Junior et al., 2012). One could speculate whether the changes in target height led to the need for more time for planning the movements. Because the current study did not compare changes in direction and height of the target location, this is a speculative hypothesis that needs to be investigated. Together, these results confirmed the suggestion that target uncertainty leads to a longer time to plan the reaching movement in upright standing independent of whether the participants suffered a stroke.

One possible explanation to the increased uncertainty effect on the MOT is given by the number of possible target locations (superior, central and inferior), taking into consideration during the motor planning. Other studies argued that the central nervous system considers the uncertainty during the motor planning which requires some modifications of the joint combinations used under the condition that the target location was well known in advance (Freitas & Scholz, 2009; Martin et al., 2000). Overall, it is assumed that a more flexible motor strategy that allows making online corrections, if needed, is used when reaching to an uncertain target location. In this strategy, the joint movements should be combined in different ways when reaching the uncertain target while the task performance remains like the reaches toward the well-known target location. This strategy was called ‘constraint-relaxation strategy’ when individuals reached under target direction uncertainty in sitting position (Freitas & Scholz, 2009). In that study, the authors observed that more motor abundance was used to reach the same central target when there was likeliness of changes in the target position. Therefore, individuals needed more time for planning flexible motor strategies (MOT was about 65 ms longer in their study) under uncertainty, as only those movements with minimal interference in the task performance should be selected. The current data could support the idea of the use of ‘constraint-relaxation strategy’ to reach the target in the standing position for both healthy and stroke individuals.

In standing position, multiple combinations across whole body joint movements could be used in addition to the movements of the arm. In our study when the final target location was well-known prior to the trial onset, participants performed the task using mainly the hip joint. The target uncertainty imposed some changes on how the reaches were performed by increasing the amplitude of more distal joints of the arm and lower limb joints; although this was not the case for all groups and it will be discussed later.

Because reduced joint motion amplitude of shoulder was observed during the movement, it could be suggested that target uncertainty mainly influences the arm movement, in particular, constraining the most proximal joint of the arm while more movement of the elbow and wrist joints should be used to reach the target and make the final corrections, if needed. However, if this was the case, the wrist and elbow amplitudes should also increase during the reaches; which it was not observed in our results. On the other hand, the reduction in shoulder joint motion seems to be related to the increased amplitude of the postural joints found in our results. More trunk motion, for example, has been observed during reaching under the uncertain condition which provided a stable posture closer to the target while allowing the arm to make the online corrections to reach the final target (Martin et al., 2000).

In the current study, it was expected that CVA individuals had more involvement of the hip joint to perform the postural adjustments compared to healthy controls (Horak, 1987). By using more hip motion, the trunk and arm should also be moved further while the target is reached by a shorter arm trajectory (Berrigan, Simoneau, Martin, & Teasdale, 2006; Martin et al., 2000). Our results support this hypothesis since all groups followed the same pattern, that is, increased movement of the hip joints compared to the knee and ankle. This hip strategy allows faster displacement of the center of mass when compared with the ankle strategy (Cordo & Nashner, 1982; Friedli, Hallett, & Simon, 1984; Horak, 1987; Horak et al., 1984), and, then, it is possible that individuals prepared themselves to reach the target as fast as possible without losing their balance by adopting such strategy, independent of the brain lesion and the task condition.

The only exception was for the RCVA individuals that increased the ankle joint movements when compared with the other groups under uncertain condition. These results, together with the findings of other previously mentioned studies, indicated that the central nervous system takes advantage of a large number of degrees of freedom when reaching under uncertain condition. The motor flexibility was associated with the use of the degrees of freedom of the arm and postural joints to successfully reach an unknown target location in upright standing. It is important to emphasize that these findings cannot be attributed to temporal or spatial differences in task performance due to the uncertainty, as only the MOT differed between the two conditions for the RCVA. Hence, only the uncertainty may be responsible for changes in the motor strategies used to reach the target in standing.

4.2. Arm reaching performance in standing depends on the side of the lesion

Previous studies have described that the deficits on the ipsilesional arm of individuals who suffered a CVA are dependent on the side of the lesion (de Paiva Silva et al., 2014; Freitas et al., 2011; Haaland et al., 2009; Horak et al., 1984; Kitsos, Hubbard, Kitsos, & Parsons, 2013; Schaefer et al., 2009). These studies investigated the effects of lesion side when the individuals performed the arm movements in sitting position. In the current study, we extend these findings to the arm reaching movements performed in upright standing. Specifically, the LCVA group showed a longer hand trajectory to touch the target on the screen compared to the RCVA group. Two hypotheses could be formulated about this result.

First, it is possible that the LCVA individuals had more difficulty in controlling the hand in the space, which could cause a longer HTA. This hypothesis is supported by earlier studies that showed hemispheric lateralization on different aspects of the arm movements in both healthy and stroke individuals (Freitas et al., 2011; Freitas & Scholz, 2009; Schaefer et al., 2009). According to these studies, the left brain hemisphere has the advantage of interjoint coordination that could be reflected in a more curved hand path after LCVA. Although we did not measure the hand curvature in the current study, it is possible that our participants had more curved hand trajectories by using different combinations across the arm joints. It is worth to mention that the longer HTA could be due to the skill level of the arm as the LCVA performed the movements with their non-dominant arm (see methods section) considering the activities before the brain lesion. If the skill level was the only factor affecting the arm reaches, differences between right and left arm of healthy controls (not presented in the manuscript) should also be observed. However, this was not the case. Because the angular displacements of focal joints during the reaches were similar across groups, we can hypothesize that the LCVA group used different combinations across arm joints that affected their hand trajectory. Other analyses such as inter-trial variance based on the uncontrolled manifold approach (de Freitas et al., 2007; Freitas et al., 2011; Freitas & Scholz, 2009) could be used to investigate whether the larger hand trajectory is due to changes in the interjoint coordination.

Alternatively, it is possible that the LCVA group used different strategy defined by different displacements of the postural joints, mainly under uncertain condition. While the use of a more flexible strategy was observed for RCVA and healthy participants under uncertain condition; this was not the case for the LCVA participants. The LCVA group performed the movements with similar postural joint motions between the two experimental conditions. Regardless of these differences between groups, all participants reached the target with similar accuracy. Previous studies also demonstrated that the accuracy of the LCVA individuals was similar to the other groups, although they had deficits in the movement execution (de Paiva Silva et al., 2014; Schaefer et al., 2009). It is important to mention that, contrary to the studies discussed above, in the current study individuals were told to touch the screen at the center of the target. In the earlier studies, the task required more visuospatial processing comparing the cursor with the actual hand location. Then, this fact may also explain similar target error between RCVA and LCVA groups in our study. However, our results are inconsistent with those reported by other studies that individuals with RCVA present more deficits in the final position (de Paiva Silva et al., 2014; Haaland et al., 2009; Schaefer et al., 2009). Note that only the movements towards the same center target were assessed in the current study. Therefore, it is possible that RCVA participants had more difficulty in making online corrections when the target moved to a position superior or inferior to the center target as these conditions required more visual processing of the new target location compared to the actual hand position. The effects of RCVA on the online corrections toward the superior and inferior targets still need to be examined.

4.3. Postural adjustments are affected by the right brain lesion

Although the temporal and spatial characteristics of the movements were similar between RCVA participants and healthy controls, they used different strategies to reach the target. The RCVA group performed the movements with reduced APA of the ipsilesional lower limb and more involvement of the ankle joint which could be related to their postural control deficits. After the occurrence of a right CVA, individuals present increased postural instability due to inadequate postural control (Corriveau et al., 2004; Duclos et al., 2015; Fernandes et al., 2018). We also observed differences in postural sway between the sides of the brain lesion in our results of the quiet standing task. The RCVA group showed greater COP amplitude than the LCVA and control groups as well as more asymmetrical COP displacement between the ipsilesional and contralateral lower limbs. Together, these results suggested that these individuals could have more difficulty in performing the arm movements in upright standing.

The RCVA group showed some deficits in the APA compared to healthy controls, although they maintained similar arm performance. These findings confirm the right hemispheric specialization that has been documented on the postural control before a voluntary movement (Hendrickson, Patterson, Inness, McIlroy, & Mansfield, 2014; Lin, Wu, Chen, Chern, & Hong, 2007). Interestingly, the different motor strategies used to reach the central target under uncertain condition did not disturb the postural stability as there was no effect of condition on the COP displacements prior to or during the arm movements for all groups. However, the reaches were accomplished by the RCVA group with more involvement of the ankle joint compared to the other groups.

It is possible that the complexity of the tasks (i.e., reaching as fast as possible in standing position) induced the RCVA participants to use similar strategies for the focal movements as healthy individuals but with more compensatory strategies to maintain their balance. The compensatory strategy could be characterized by the reduced shifts of the COP on the APA phase in the ipsilesional lower limb. If the RCVA individuals had maintained the same motor strategy used during the quiet standing task observed in our results and previous studies (Genthon et al., 2008; Laufer, 2003; Manor et al., 2010; Mansfield, Mochizuki, Inness, & McIlroy, 2012), more COP displacements should be observed in the ipsilesional and not in the contralesional lower limb. This reduced COP amplitude in the ipsilesional limb during APAs for the RCVA group could be due to increased stiffness to reduce the postural sway in this limb to stabilize the posture before the motor action. Such stiffness has been observed, for example, when a suprapostural cognitive task is performed during standing aiming to maintain the posture and reduce the cognitive-motor interference (Hyndman, Ashburn, Yardley, & Stack, 2006). Note that the changes in the asymmetry of the COP displacements between the lower limbs were also presented by LCVA (left side of Fig. 3) but their APAs were similar to CG.

The APAs have also been described to be part of the voluntary movement and not only a strategy to maintain the postural balance (Leonard, Brown, & Stapley, 2009; Leonard et al., 2011). These cited studies observed that when healthy individuals reached with their right arm in an upright posture, asymmetrical APAs were observed, with changes in weight-bearing and increased muscle activity occurring in the contralateral lower limb. The asymmetry of the COP displacements was observed for all CVA participants in the present study in both quiet standing and arm reaching tasks, although it was more evident for the individuals who have suffered a right CVA.

The absence of more differences between the kinematic characteristics of the arm movements performed by CVA and healthy individuals groups may be because they reached the targets with their upper limb ipsilateral to the brain lesion. However, many studies have documented deficits in the ipsilesional arm in sitting position (de Paiva Silva et al., 2014; Freitas et al., 2011; Kitsos et al., 2013; Schaefer et al., 2009). Because the target was always at the same spatial position (i.e., the center of the monitor screen) in the current study, changes of the arm movements were not needed. The possibility of the changes in the target location (uncertain condition) affecting the APAs of the ipsilesional lower limb of the RCVA group may be related to their deficits in postural control. Future studies should investigate whether the uncertainty also affects the reaching movements using the contralesional arm while standing.

5. Conclusion

In summary, the uncertainty of target location influences the arm reaching and APAs in upright standing mainly during the movement planning phase. The motor strategies used by RCVA individuals are more affected by the target uncertainty, although they reach the target with the same accuracy. On the other hand, the LCVA individuals presented more deficits in the arm trajectory during reaching in a standing position. These latter findings suggested a hemispheric specialization for the performance of arm reaching while standing, mainly when the final target location is uncertain.

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