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## ABSTRACT

Gait asymmetry and dynamic balance impairments observed in post-stroke individuals increase their risk of fall. Moreover, walking while performing a cognitive task (*i.e.* dual-task) disturbs the control of balance in post-stroke individuals. Here we investigated the mediolateral dynamic stability in twenty-two community-dwelling participants (12 post-strokes and 10 healthy controls) while walking in single-task (normal gait) and four different dual-tasks (cognitive-motor interference). Positions of the extrapolated center of mass and mediolateral widths of both margin of stability and base of support were extracted from 35 marker trajectories. Post-stroke participants presented larger margin of stability and base of support than controls during single-task (both  $p < 0.01$ ), with a larger margin of stability on the non-paretic side than on the paretic side at ipsilateral foot-strike ( $p < 0.05$ ). No significant effect of the dual-task was found between groups. In post-stroke participants, dual-task induced slight modification of the mediolateral stability strategy, as the margin of stability was not different between the two limbs at foot-strike, and significantly reduced the performance in every cognitive task. Post-stroke participants increased their dynamic stability in the frontal plane in single-task by extending their base of support and mainly relying on their non-paretic limb. Under cognitive-motor interference (dual-task), post-stroke participants prioritized dynamic stability over cognitive performance to ensure a safe locomotion. Thus, rehabilitation programs should consider both dynamic balance and dual-task training, even at a chronic delay following stroke, to reduce the risk of fall in post-stroke individuals.

Keywords: Stroke; Dynamic stability; Hemiparesis; Gait; Dual-task

## List of abbreviations

| <b>Abbreviation</b> | <b>Definition</b>                   |
|---------------------|-------------------------------------|
| BoS                 | Base of Support                     |
| CB                  | Counting Backward                   |
| CF                  | Counting Forward                    |
| CoM <sub>WB</sub>   | Whole-body Center of Mass           |
| FAn                 | Verbal fluency (“Animals” category) |
| FP                  | Verbal fluency (“P” first letter)   |
| MoS                 | Margin of Stability                 |
| XCoM                | eXtrapolated Center of Mass         |

# 1. INTRODUCTION

Surviving stroke individuals usually come with balance impairments that may increase instability during locomotion. For instance, a reduced forward walking velocity (Hak et al., 2013), reduced lower-limb joints excursions (Lamontagne, Stephenson, & Fung, 2007) or a reduced whole-body angular momentum (Nott, Neptune, & Kautz, 2014) have been associated with increased instability in post-stroke individuals. Instability reflects the individuals' deficits (Hof, van Bockel, Schoppen, & Postema, 2007; Kao, Dingwell, Higginson, & Binder-Macleod, 2014) in his/her ability to prevent falling despite a perturbation (Bruijn, Meijer, Beek, & van Dieën, 2013; Hof, Gazendam, & Sinke, 2005). Dynamic (in)stability can be assessed by the margin of stability (MoS), defined as the shortest distance between the current position of the extrapolated center of mass (XCoM) and the edges of the base of support (BoS) (Hof et al., 2005). MoS is usually computed along the mediolateral axis (Hak et al., 2013; Hof et al., 2007; Kao et al., 2014; Vistamehr, Kautz, Bowden, & Neptune, 2016), because the frontal plane is critical during forward-propelled locomotion (Rosenblatt & Grabiner, 2010) and step initiation (Tisserand, Robert, Chabaud, Bonnefoy, & Chèze, 2016). In addition, control of balance along the mediolateral axis requires an active control during locomotion (Bauby & Kuo, 2000). Thus, investigating mediolateral dynamic stability during locomotion allows to better understand impairments in motor strategies used to control balance. This study focuses on how post-stroke hemiparetic individuals control their dynamic stability while walking.

Asymmetrical patterns and dynamic balance impairments characterize the locomotion of post-stroke individuals (Beyaert, Vasa, & Frykberg, 2015; Chen, Patten, Kothari, & Zajac, 2005; De Bujanda, Nadeau, & Bourbonnais, 2004; Hak et al., 2013; Hendrickson, Patterson, Inness, McIlroy, & Mansfield, 2014; Lewek, Bradley, Wutzke, & Zinder, 2014; Melzer, Goldring, Melzer, Green, & Tzedek, 2010; Olney & Richards, 1996; Patterson, Gage, Brooks, Black, & McIlroy, 2010) and may contribute to an increased risk of falling in the mediolateral direction (Kao et al., 2014; Vistamehr et al., 2016). Compared to healthy subjects during normal gait, post-stroke individuals had larger dynamic stability (Nott et al., 2014; Vistamehr et al., 2016), with a higher MoS variability (Kao et al., 2014), especially during the balance-challenging paretic single-leg stance phase (Nott et al., 2014). Post-stroke individuals also showed a reduced capacity to adapt their MoS during gait while performing concurrent motor tasks

(Hak et al., 2013, 2015). These observations may arise from adaptations in their locomotor strategies: increased step width (Chen et al., 2005; De Bujanda et al., 2004; Hak et al., 2013; Kao et al., 2014; Vistamehr et al., 2016), frequency and length (Hak et al., 2015). However, the increase in mediolateral dynamic stability found in post-stroke individuals needs to be interpreted with caution, as it is also associated with reduced performance in clinical balance assessments (Nott et al., 2014; Vistamehr et al., 2016).

In addition to motor impairments, post-stroke hemiparetic individuals may have cognitive impairments, and especially attentional deficits (Plummer-D'Amato et al., 2008; Plummer et al., 2013). Situations where individuals need to provide attention to other tasks while walking are countless in daily living (*e.g.* conversing with someone, carrying objects, remembering an appointment, *etc.*). Consequently, performing a cognitive task while simultaneously walking (*i.e.* a dual-task) is more challenging for post-stroke than for healthy individuals (Hausdorff, 2005; Yang, Chen, Lee, Cheng, & Wang, 2007), resulting in modified spatiotemporal locomotor patterns such as reduced velocity and cadence coupled with increased stride time when compared to single-task (Beyaert et al., 2015; Cockburn, Haggard, Cock, & Fordham, 2003; Plummer-D'Amato, Altmann, Behrman, & Marsiske, 2010; Plummer et al., 2013). These locomotor adaptations may allow post-stroke individuals to maintain their balance (Bowen et al., 2001; Hyndman, Ashburn, Yardley, & Stack, 2006; Plummer-D'Amato et al., 2008) while attention is divided by the dual-task. However, no study has evaluated the influence of cognitive-motor dual-tasking on mediolateral dynamic stability in post-stroke individuals during gait.

Falls mainly occur during locomotion in post-stroke survivors, reducing their independence and life expectancy (Weerdesteyn, De Niet, Van Duijnhoven, & Geurts, 2008). Which is why identifying the biomechanical factors critical in dynamic balance control is of clinical and rehabilitative interests. The objective of this study was to quantify the mediolateral dynamic stability in chronic ambulatory hemiparetic post-stroke individuals while walking, in single-task and under various dual-task conditions of different cognitive loads. We hypothesized that the mediolateral dynamic stability in post-stroke individuals compared to controls will be (1) increased, especially on the non-paretic side, traducing a voluntary motor adaptation to increase their stability, and (2) reduced in dual-tasks compared to single-task, as a result of altered attention to locomotion.

## 2. MATERIAL AND METHODS

### 2.1. Study design and population

### 2.2. Experimental protocol

Gait assessments were performed barefoot at spontaneous speed on a 10-meter walkway in the Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals. Subjects were equipped with 35 reflective markers, according to the Plug-In-Gait model (Davis, Ounpuu, Tyburski, & Gage, 1991; Vicon®, 2002). The markers' trajectories were recorded with 12 cameras from a motion capture device (Oqus 7+, Qualisys, Sweden) at 100Hz, and low-pass filtered digitally (6Hz cut-off frequency, 4<sup>th</sup> order dual-pass Butterworth filter).

After three familiarization trials, each participant performed five 10 m walking trials: one consisted in walking normally (single-task) and four consisted in walking while performing one of the four interfering cognitive tasks simultaneously (dual-task). Our dual-task paradigm proposed four different cognitive tasks of various attention load (Allali, Laidet, Assal, Armand, & Lalive, 2014), randomly performed: counting forward (CF, serial 1+1), counting backward (CB, serial 100-1), semantic verbal fluency of words in the category of "Animals" (FAn) and phonemic verbal fluency with words beginning with the "P" letter (FP). Our protocol consisted of only one trial per situation due to the increased fatigability of post-stroke participants.

In dual-tasks, participants were asked to perform the two tasks (cognitive and locomotor) at the best of their ability without any task prioritization. After completion of the locomotion assessments, all participants performed each cognitive task in a sitting position, in the same order and duration than during the dual-task walking evaluations, accounting for their single-task cognitive performance. The number of correct answers and errors were recorded in all conditions. The Correct Response Rate [= Response rate per second × Percentage of correct responses] was calculated for each cognitive task in dual-task and sitting position, and accounted for cognitive performance (Hall, Echt, Wolf, & Rogers, 2011).

### 2.3. Dynamic stability

The horizontal trajectory of the whole-body center of mass ( $CoM_{WB}$ ) was directly extracted from the data collected for every participant, using the Plug-In-Gait model computed with Visual 3D (C-Motion, USA). The XCoM was then computed from the  $CoM_{WB}$ 's trajectory using the following equation (Hof et al., 2005):

$$XCoM = CoM_{WB} + \frac{1}{\omega_0} Co\dot{M}_{WB} \quad \omega_0 = \sqrt{\frac{g}{h}} \quad (1)$$

$Co\dot{M}_{WB}$  is the velocity of the  $CoM_{WB}$ , obtained from the first derivative of the  $CoM_{WB}$ 's horizontal trajectory, and low-pass filtered digitally (20Hz cutoff frequency, 2<sup>nd</sup>-order dual pass Butterworth filter).  $g$  is the gravitational constant ( $9.81 \text{ m}\cdot\text{s}^{-2}$ ) and  $h$  is the pendulum length measured as  $1.34 \times \text{leg length}$  (m) (Hof et al., 2007). Dynamic stability was then estimated by calculating the MoS, defined as the distance in the mediolateral axis between the XCoM and the base of support (BoS) edges (Hof et al., 2005):

$$MoS = BoS_{Edge} - XCoM \quad (2)$$

Relative to the gait analysis experimental set-up, BoS edges were defined as a point localized at a mid-distance position between the heel and the 2<sup>nd</sup> metatarsal markers on each foot. This estimation took into account the lateral orientation of the foot and represents a functional BoS, rather than a strict mechanical BoS, which has been recently recommended (Hof & Curtze, 2016; Vallée, Tisserand, & Robert, 2015).

*[Figure 1 about here]*

MoS was computed in the mediolateral axis for the two lower limbs at two particular events, which delimited the single- and double-support phases of the gait cycle: at foot-strike (first swing foot contact) relative to the BoS edge on ipsilateral side ( $MoS_{FS}$ ) and at foot-off (last swing foot contact) relative to the BoS edge on contralateral side ( $MoS_{FO}$ ) (Figure 1). Incomplete single support phases, *i.e.* missing data because the participant stepped outside the measurement area, were removed from the analysis. Mediolateral stability at the end of the double-support phase was quantified using  $MoS_{FO}$ , while mediolateral stability at the beginning of the double-support phase was quantified using  $MoS_{FS}$ . Each foot-strike and foot-off were automatically identified with data from two synchronized forceplates

(Accugait, AMTI, USA) and autocorrelated (Stanhope, Kepple, McGuire, & Roman, 1990)\*, and checked manually for accuracy. The mediolateral size of the BoS was also identified at each foot-off and each foot-strike and defined as  $BoS_{FO}$  and  $BoS_{FS}$ , respectively.

## 2.4. Statistics

Due to the small sample size and non-linear distributions of main outcomes (Shapiro-Wilk test), non-parametric statistics were utilized. Medians and interquartile ranges were used to report results within the text, tables and figures. Since no difference was found for the MoS between the right and left lower limbs in Control group (Wilcoxon signed-rank test  $p=0.61$  and  $p=0.36$  at foot-strike and toe-off, respectively), data of the left lower limb was identified as control and used for further between-group comparisons. Kruskal-Wallis tests were performed to evaluate the influence of the factor “Side” (paretic, non-paretic and control) and the factor “Task” (single-task, CF, CB, FAn and FP) on MoS and BoS sizes in each experimental condition. If an effect was found, a post-hoc Mann-Whitney U-test was performed with Holm conservative corrections to account for multiple comparisons.

Wilcoxon signed-rank tests were used for all between-group comparisons of continuous variables, except for comparing the number of female participants, where a Chi<sup>2</sup>-test was utilized (Table 1).

All statistical tests were performed using R software (version 3.3.1) and a two-tailed  $\alpha$  level of 0.05 was used as the cut-off value for significance.

## 3. RESULTS

### 3.1. Single-task assessments

Stroke participants walked significantly slower compared to controls ( $0.93 \pm 0.43$  versus  $1.48 \pm 0.20$  m.s<sup>-1</sup> respectively,  $p < 0.001$ ).  $MoS_{FO}$  was not influenced by the factor “Side” ( $p = 0.49$ ), unlike  $MoS_{FS}$  ( $H(2) = 14.17$ ,  $p < 0.001$ ) (Figure 2). The post-hoc analyses revealed that  $MoS_{FS}$  of both paretic and non-paretic limbs were significantly larger than  $MoS_{FS}$  of the control limb ( $p < 0.05$  and  $p < 0.001$ , respectively). In the Stroke group,  $MoS_{FS}$  was significantly larger on the non-paretic side compared to

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\* For more details, see: [http://c-motion.com/v3dwiki/index.php?title=Automatic\\_Gait\\_Events](http://c-motion.com/v3dwiki/index.php?title=Automatic_Gait_Events)

the paretic side ( $p < 0.05$ ). Similar to MoS measurements, BoS<sub>FO</sub> was not influenced by the factor “Side” ( $H(2) = 5.32$ ,  $p = 0.07$ ), unlike BoS<sub>FS</sub> ( $H(2) = 11.12$ ,  $p < 0.01$ ) (Figure 2). Post-hoc analyses revealed that BoS measured at both paretic and non-paretic foot-strikes were significantly larger than BoS<sub>FS</sub> of the Control group (both  $p < 0.01$ ). However, no difference was found for inter-limb comparisons (paretic *versus* non-paretic) in the Stroke group ( $p = 0.71$ ).

Cognitive tasks assessments performed in the sitting position showed that the Stroke group presented a significantly lower correct response rate for the CF ( $p < 0.01$ ), CB ( $p < 0.05$ ) and FP ( $p < 0.001$ ) tasks compared to the Control group. No difference was found between the two groups for the FAn task ( $p > 0.15$ ) (Table 1).

*[Figure 2 about here]*

### 3.2. Dual-task assessments

Walking velocity was significantly slower for the Stroke group than for the Control group in all the conditions (all  $p < 0.01$ ). No effect of the factor “Task” was found for the Stroke group ( $p = 0.65$ ) unlike the Control group ( $H(4) = 21.64$ ,  $p < 0.001$ ). Post-hoc tests revealed that walking velocity was not different between the FAn and FP conditions ( $p = 0.62$ ), but both of them were slower when compared to all other conditions (all  $p < 0.05$ ) (Figure A, supplementary materials).

For each condition, like in the single-task, the factor “Side” presented no significant effect on MoS<sub>FO</sub> (all  $p > 0.05$ , Figure 3) and a significant effect on MoS<sub>FS</sub> (all  $p < 0.01$ , Figure 4). Post-hoc analyses revealed a significantly larger MoS<sub>FS</sub> in the Stroke group than in the Control group, independently of the limb (all  $p < 0.05$ ). However, no difference was found between the paretic and the non-paretic limbs for MoS<sub>FS</sub> in the Stroke group in each dual-task (all  $p > 0.2$ ). A significant effect of the factor “Side” was found in every dual-task, both on BoS<sub>FO</sub> (all  $p < 0.05$ , Figure 3) and BoS<sub>FS</sub> (all  $p < 0.05$ , Figure 4). Post-hoc analyses revealed that BoS widths were always significantly larger than the control limb (all  $p < 0.05$ ), regardless of the limb compared with the Stroke group. No difference was found in inter-limb comparisons in the Stroke group (paretic *versus* non-paretic limb, all  $p > 0.05$ ). Finally, no effect of the factor “Task” was found for each of the four analyzed variables (MoS<sub>FO</sub>, MoS<sub>FS</sub>, BoS<sub>FO</sub> and BoS<sub>FS</sub>, all  $p > 0.5$ ).

Assessments of the cognitive tasks showed that the Stroke group had a lower correct response rate compared to the Control group in all tasks (all  $p < 0.05$ ). Moreover, the Stroke group presented a significant decrease in their cognitive performances in the dual-task compared to the cognitive assessment performed in the sitting position (all  $p < 0.05$ ), whereas the Control group presented a significant decrease only in their CF performance.

*[Figures 3 and 4 about here]*

## **4. DISCUSSION**

The aim of this study was to quantify the mediolateral dynamic stability of community-dwelling chronic post-stroke individuals during gait, in both single-task and cognitive-motor dual-tasking. Our results showed that post-stroke participants had a larger mediolateral MoS compared to control participants at foot-strike, regardless of the limb and the task. Of note, mediolateral stability strategy in post-stroke participants was asymmetrical in the single-task, as illustrated by a significantly larger MoS on the non-paretic limb than on the paretic one, and their cognitive performance was significantly decreased in all dual-tasks.

### *4.1. Post-stroke participants increased dynamic stability asymmetrically during single-task walking*

In the single-task, BoS was significantly larger for post-stroke participants than for controls at foot-strike whereas a trend towards a larger BoS was observed at foot-off ( $p = 0.07$ ). A larger BoS width is typically observed in post-stroke individuals (Chen et al., 2005; De Bujanda et al., 2004; Hak et al., 2013; Vistamehr et al., 2016). Although taking wider steps increases the energetic cost of walking (Kuo, 2001), it also allows post-stroke individuals to enlarge their MoS while walking at spontaneous speed (Hak et al., 2013). Consistent with previous works (Nott et al., 2014; Vistamehr et al., 2016), we found an increased dynamic stability at foot-strike in post-stroke participants compared to controls. Such a locomotor strategy probably indicates an adaptation from post-stroke individuals to reduce their instability during the single-support phase (*i.e.* when BoS is reduced to only one foot).

Focusing on inter-limb asymmetries in post-stroke participants during the single-task, the MoS at foot-strike was significantly larger on the non-paretic side than on the paretic side (Figure 2). This result indicates that the XCoM of post-stroke participants was more distant from the non-paretic foot position at non-paretic foot-strike, and by extension closer to the paretic foot position during the preceding single-support stance phase (*i.e.* reduced instability). Biomechanically, the mediolateral foot position relative to the horizontal location of the CoM<sub>WB</sub> established at foot-strike is the most important factor affecting the frontal plane whole-body balance during gait (Mackinnon & Winter, 1993). The larger MoS measured on the non-paretic side may indicate that post-stroke participants “overstepped” laterally with their non-paretic foot, to recover from the instability of the paretic side stance phase (Hendrickson et al., 2014; Kajrolkar & Bhatt, 2016; Nott et al., 2014). This “overstep” strategy used to improve dynamic stability could contribute to the observations reported in post-stroke individuals such as reduced walking velocity (Figure A, supplementary materials), increased time spent on the non-paretic foot (Chen et al., 2005; Melzer et al., 2010; Olney & Richards, 1996; Patterson et al., 2008), increased lateral oscillations (Chen et al., 2005; De Bujanda et al., 2004; Hak et al., 2013; Melzer et al., 2010) and increased fatigability (Kuo, 2001). On the other hand, a smaller MoS on the paretic side compared to the non-paretic side indicates that post-stroke participants did not “overstep” laterally with their paretic foot. No difference was observed between the paretic and non-paretic sides regarding MoS at foot-off. During double-support phases, the BoS is maximal in the mediolateral direction. Thus, one can hypothesize that double-support phase preceding the foot-off represents a stabilization phase that allows post-stroke participants to ensure a safe step transition, regardless of the side.

As previously suggested (Hendrickson et al., 2014; Lewek et al., 2014), our results show that post-stroke participants used an asymmetrical stability strategy during single-task gait that mainly relies on their non-paretic limb to control lateral balance. This observation suggests a central integration of their sensory and motor deficits, and a resulting adaptation in their balance control strategy (Beyaert et al., 2015; Patterson et al., 2010) that may aim at reducing their risk of fall in the mediolateral direction.

#### *4.2. Dual-tasking modulates the dynamic stability strategy of post-stroke participants*

As well as in single-task, we observed a significant increase in both MoS (only at foot-strike) and BoS widths in post-stroke participants compared to controls in all dual-tasks. These observations differ from Hak et al.'s (2013), who found that post-stroke individuals can have lateral MoS similar to controls at foot-strike because of their ability to adapt their walking pattern during concurrent motor tasks. Although the same 'stability scheme' observed in single-task was observed in all dual-tasks (*i.e.* non-paretic  $\geq$  paretic  $>$  control, Figure 4), the MoS measured at foot-strike was no longer different between the non-paretic and paretic limbs in post-stroke participants, regardless of the cognitive task. This observation may result from the slightly increased values of the MoS on the paretic side at foot-strike in all dual-tasks compared to single-task (although not significant across tasks) (Figure 4). An increase in MoS measured at the paretic limb foot-strike indicates that the XCoM starts to be more distant from the paretic foot in the mediolateral direction compared to single-task. This stability strategy suggests that post-stroke participants attempted to reduce instability during the preceding non-paretic limb stance phase. But the consequence of a reduced instability in the non-paretic limb stance phase is a larger lateral balance recovery on the paretic-limb's side during the following double-support phase. Because balance recovery is more difficult for post-stroke individuals than for healthy controls, especially on their paretic limb's side due to their deficits (Kajrolkar & Bhatt, 2016), the locomotor adaptations undertaken by post-stroke participants in dual-tasks (Beyaert et al., 2015; Cockburn et al., 2003; Plummer et al., 2013) may be used to ensure sufficient stability while walking.

Locomotion is a cognitively-demanding task (Hausdorff, 2005). The cognitive deficits induced by stroke may limit the post-stroke participants' ability to perform one of two concurrent tasks as efficiently as during a single-task, implying a prioritization strategy between the two tasks (Plummer-D'Amato et al., 2008; Plummer et al., 2013). Also because balance in the mediolateral direction needs to be actively controlled during locomotion (Bauby & Kuo, 2000), the dual-tasks probably reduced the amount of cognitive resources available to post-stroke participants to control their mediolateral balance while walking. This may explain why we found only a slight difference of mediolateral stability between the single-task and dual-tasks. Thus, the ability of post-stroke participants to adapt their locomotor pattern to increase mediolateral stability suggested by Hak et al. (2013) is true for a single-task but seems

challenged under cognitive-motor interference (dual-task). Hence, the apparent consistency in mediolateral dynamic stability observed in post-stroke participants during dual-tasks may result from adaptations of their locomotor pattern and is cognitively onerous (Beyaert et al., 2015; Cockburn et al., 2003; Plummer et al., 2013). Post-stroke individuals have poorer dynamic balance than healthy controls in locomotor/stepping activity (Kajrolkar & Bhatt, 2016; Nott et al., 2014; Vistamehr et al., 2016). Although mediolateral dynamic stability measurements might look improved at first glance when compared to controls, the locomotor adaptations previously described under cognitive-motor dual-tasks may paradoxically compensate for an altered balance control, aiming at an increased stability for a safe locomotion. Our results suggest that balance strategy for control of mediolateral dynamic stability employed by post-stroke participants who regained the ability to walk independently even at a chronic delay following stroke (20  $\pm$ 17.5 months) may still have not been automatized.

The different cognitive tasks used in our dual-task protocol were meant to involve attention (CF), working memory (CB), and executive function (FAn and FP) resources, respectively (Allali et al., 2014; Plummer-D'Amato et al., 2010). Consistently with previous literature, we found a reduced cognitive capacity in stroke survivors during the walking dual-tasks compared to the cognitive task performed in the sitting position.

Taken together, our results suggest that post-stroke participants may have prioritized the control of dynamic balance at the expense of cognitive performance to ensure safety while walking. This hypothesis has been previously suggested by Brauer et al. (2002), in the context of protective steps performed by elderly subjects. Thus, what we observed appears to be a “*motor-related cognitive interference*” scenario (Plummer et al., 2013), as the motor performance remains stable across the tasks while the cognitive performance deteriorates. Because cognitive capacity is directly related to the risk of fall (Mirelman et al., 2012), a reduced cognitive performance may strongly increase the risk of fall for post-stroke individuals when they walk.

#### *4.3. Study limitations*

The main limitation of this study is the small sample size, limiting the applicability of our results. Only one trial was performed for each task, limiting the strength of our analysis and interpretation.

However, we choose a compromise between the number of tasks and the number of steps by task. Due to the high rate of fatigue of our subjects, an increased number of steps would have increased the risk of stopping the experimental protocol early. Secondly, the MoS does not give information about forces segmental inertial momentums and the rotation movements involved during gait that could influence the dynamic balance of stroke participants (Vistamehr et al., 2016). Finally, while measure of MoS provided insights to dynamic balance and potential adaptations to instability during post-stroke gait, impaired reactive responses may also contribute to the increased prevalence of falls during post-stroke gait (Kajrolkar & Bhatt, 2016; Lakhani, Mansfield, Inness, & McIlroy, 2011). Thus, balance instability captured with MoS in this study does not allow us to conclude on the ability of MoS to capture impaired reactive balance control responses that may happen during post-stroke gait.

## **5. CONCLUSION AND PERSPECTIVES**

This study pointed out that post-stroke individuals use an asymmetrical stability strategy at foot-strike in the mediolateral direction, when walking in single-task. In dual-tasks, post-stroke individuals probably prioritized mediolateral stability at the expense of the cognitive performance. The apparently improved dynamic stability observed during dual-tasks may paradoxically reflect an altered balance control and may result from adaptations of the locomotor pattern, aiming at enough stability to ensure a safe locomotion. Our results suggest that control of dynamic stability in the mediolateral direction at chronic delay following stroke is still not automatized.

The results of this study are of clinical and rehabilitative relevancies: since cognitive loads can be added daily during locomotion for community-dwelling stroke survivors, physicians and physiotherapists should consider both dynamic balance and dual-task training even at a prolonged delay following stroke. More studies are needed to investigate the impact of dual-tasking on dynamic stability, in order to elucidate the motor and balance control strategies developed by stroke survivors and to design rehabilitative programs that may help them to improve dynamic stability during locomotion.

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## **7. CONFLICT OF INTEREST STATEMENT**

The authors have no conflicts of interest to declare.

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## TABLES

Table 1

Clinical, stroke, cognitive and gait characteristics of the Stroke and Control groups. Measures are presented as median (interquartile range). Significant p-values are indicated in bold.

|   | <b>STROKE<br/>(n = 12)</b> | <b>CONTROL<br/>(n = 10)</b> | p-value         |
|---|----------------------------|-----------------------------|-----------------|
| <b>Subjects characteristics</b>               |                            |                             |                 |
| <i>Age (years)</i>                            | 58 (12.8)                  | 58.5 (4.0)                  | 0.54            |
| <i>Women (n)</i>                              | 5                          | 6                           | 0.67            |
| <i>Height (m)</i>                             | 1.66 (0.17)                | 1.68 (0.18)                 | 0.70            |
| <i>Weight (kg)</i>                            | 85.5 (35.5)                | 72 (14.7)                   | 0.19            |
| <i>BMI (kg.m<sup>-2</sup>)</i>                | 26.2 (5.6)                 | 25.1 (3.2)                  | 0.56            |
| <i>Fall in the past year (n)</i>              | 1 (0)                      | 0 (0)                       | -               |
| <b>Stroke characteristics</b>                 |                            |                             |                 |
| <i>Delay since stroke onset (months)</i>      | 20 (17.5)                  | -                           | -               |
| <i>Lesion lateralization (n Left/n Right)</i> | 4/8                        | -                           | -               |
| <i>Stroke type (n Ischemic/n Hemorrhagic)</i> | 7/5                        | -                           | -               |
| <b>Cognitive assessment</b>                   |                            |                             |                 |
| <i>MMSE Score (/30)</i>                       | 29 (2.0)                   | 29 (0.3)                    | 0.16            |
| <i>Single task assessment (CRR)</i>           |                            |                             |                 |
| <i>CF</i>                                     | 223.1 (113.6)              | 332.9 (151.5)               | <b>&lt;0.01</b> |
| <i>CB</i>                                     | 122.4 (53.3)               | 138.6 (68.3)                | <b>&lt;0.05</b> |
| <i>FAn</i>                                    | 38.3 (36.1)                | 70.7 (47.5)                 | 0.18            |
| <i>FP</i>                                     | 62.8 (22.4)                | 94.5 (10.4)                 | <b>&lt;0.01</b> |
| <i>Dual task assessment (CRR)</i>             |                            |                             |                 |
| <i>CF</i>                                     | 135.7 (101.8)              | 260.9 (84.8)                | <b>&lt;0.01</b> |
| <i>CB</i>                                     | 79.9 (82.4)                | 154.9 (99.8)                | <b>&lt;0.01</b> |
| <i>FAn</i>                                    | 30.3 (39.5)                | 59.6 (21.9)                 | <b>&lt;0.05</b> |
| <i>FP</i>                                     | 50.3 (32.1)                | 87.1 (54.5)                 | <b>&lt;0.01</b> |
| <b>Gait independency</b>                      |                            |                             |                 |
| <i>nFAC Score (/8)</i>                        | 6 (0)                      | -                           | -               |

Abbreviations used: BMI = Body Mass Index, MMSE = Mini Mental State Examination, nFAC = new Functional Ambulation Classification, CRR = Correct Response Rate.

## FIGURES CAPTIONS

### Figure 1

Schematic representation of both the Margins of Stability (MoS), relative to the positions of the eXtrapolated Center of Mass (XCoM, blue dots), and functional Bases of Support edges (BoS, middle line inside schematic foot) measured in this study. MoS and BoS were both computed at Foot-Off (FO, left side) and at Foot-Strike (FS, right side) relative to both limbs. For a stroke participant, the grey foot represents the hemiparetic foot and the white foot represents the healthy foot. MoS at FO ( $\mathbf{MoS}_{FO}$ ), MoS at FS ( $\mathbf{MoS}_{FS}$ ), and BoS ( $\mathbf{BoS}_{FO}$  &  $\mathbf{BoS}_{FS}$ ) are represented with green double arrows, orange double arrows and red double arrows, respectively. The red area represents the BoS area. The circles in the feet schematically indicate the foot portion in contact with the ground at events' identification.

### Figure 2

Margin of Stability (MoS, top) and Base of Support (BoS, bottom) widths measured at foot-off (FO) and foot-strike (FS) in the single-task. Results are presented with median and interquartile range. For the Stroke group, the paretic limb is depicted in dark grey and the non-paretic limb in light grey. Only the left lower limb (control limb) is presented for Control group and depicted in white. \* indicates a significant difference between groups reported by the Mann-Whitney test.

### Figure 3

Margin of Stability (MoS, top) and Base of Support (BoS, bottom) widths measured at foot-off (FO) in both the single-task (ST) and the dual-tasks. Results are presented with median and interquartile range. For the Stroke group, the paretic limb is depicted in dark grey, and the non-paretic limb in light grey. Only the left lower limb (control limb) is presented for the Control group and depicted in white. \* indicates a significant difference between groups reported by the Mann-Whitney test. The vertical dotted line separates the single-task condition, on the left, from the dual-task conditions (CB, CF, FAn, FP) on the right. Results for the single-task are the same as in Figure 2.

#### Figure 4

Margin of Stability (MoS, top) and Base of Support (BoS, bottom) widths measured at foot-strike (FS) in the single-task (ST) and the dual-tasks. Results are presented with median and interquartile range. For the Stroke group, the paretic limb is depicted in dark grey, and the non-paretic limb in light grey. Only the left lower limb (control limb) is presented for the Control group and depicted in white. \* indicates a significant difference between groups reported by the Mann-Whitney test. The vertical dotted line separates the single-task condition, on the left, from the dual-task conditions (CB, CF, FAn, FP) on the right. Results for the single-task condition are the same as presented in Figure 2.

## **SUPPLEMENTARY MATERIAL**

#### Figure A

Walking velocity measured across conditions for both Stroke and Control groups. Results are presented with median and interquartile range. The stroke group is depicted in dark grey and the control group in white. \* indicates a significant difference between groups and # indicates a significant difference between single task (ST) and dual-task conditions (CB, CF, Fan and FP) in the Control group, both reported by the Mann-Whitney test.

# FIGURES

Figure 1

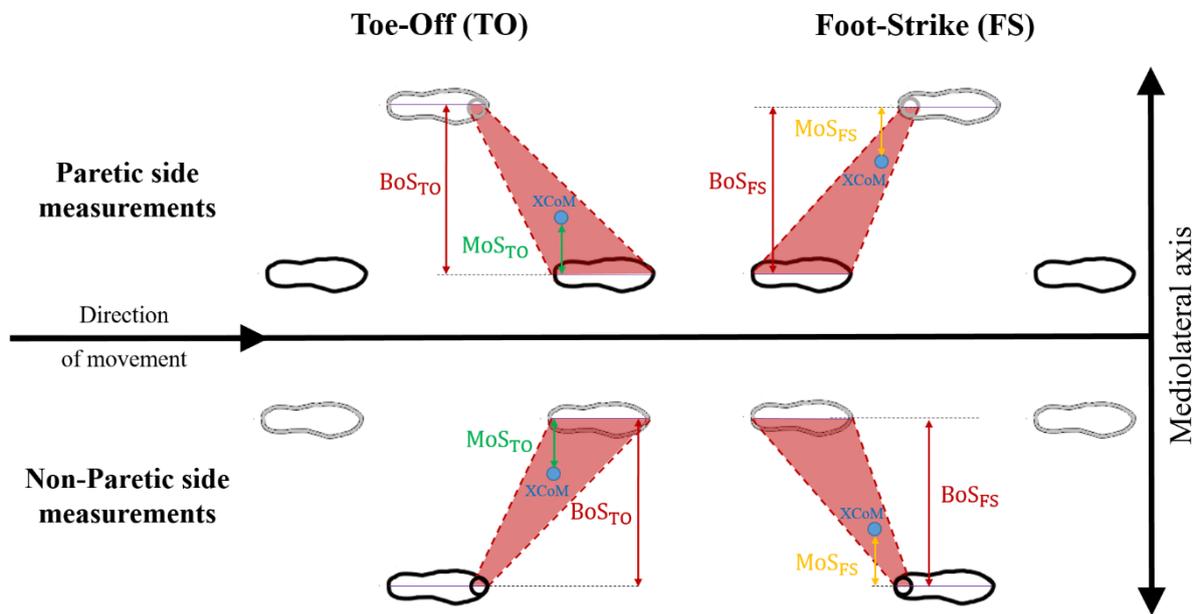


Figure 2

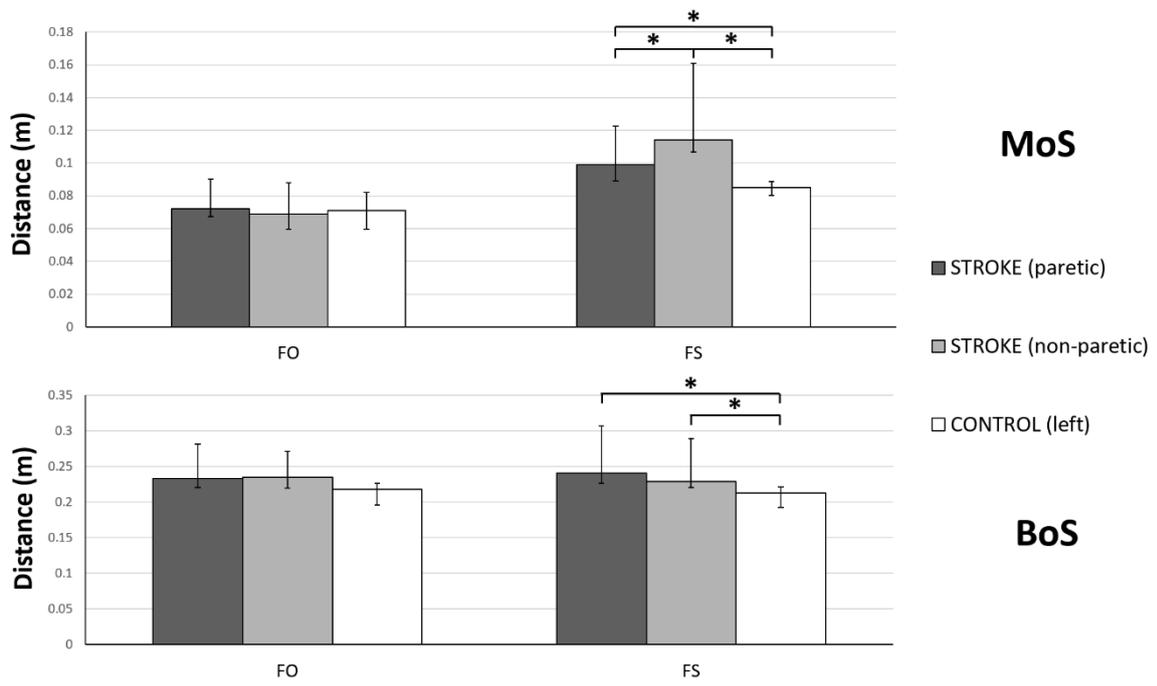


Figure 3

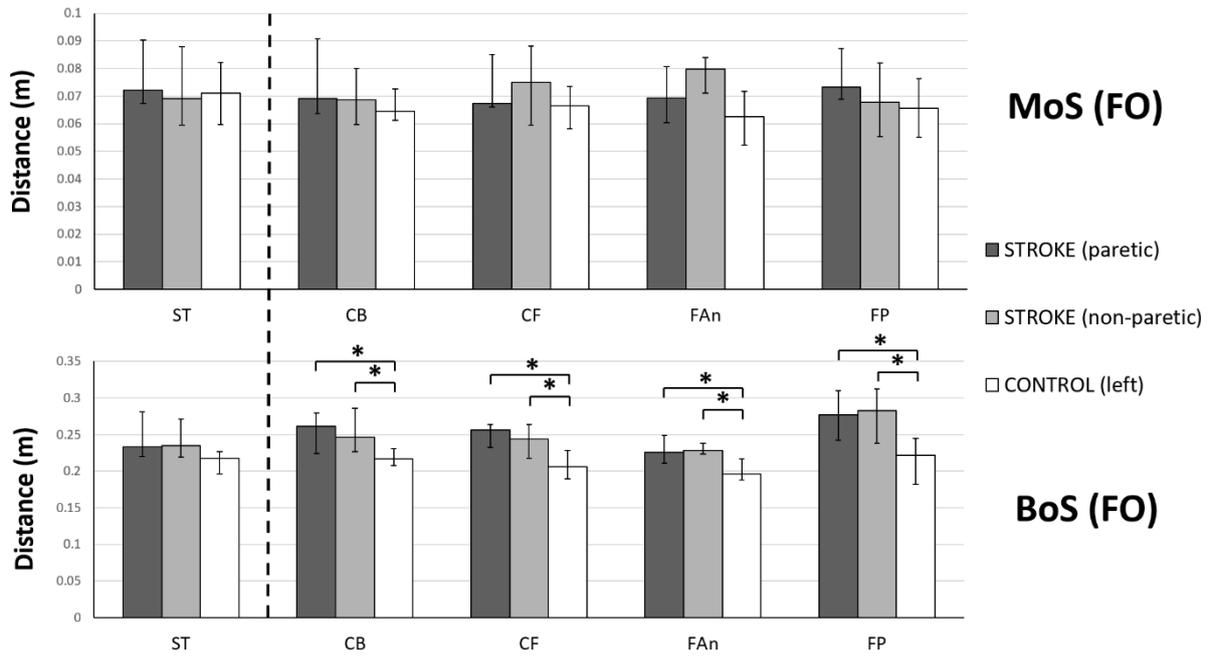


Figure 4

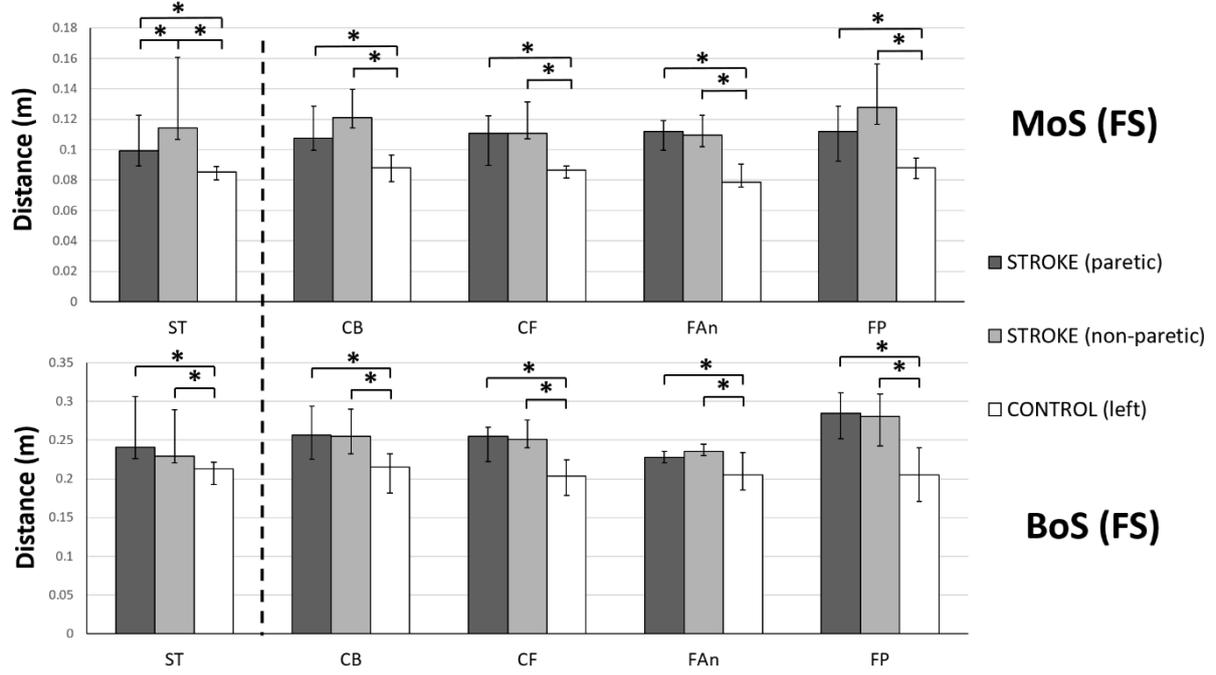


Figure A

