Journal of Biomechanics 48 (2015) 1782–1788

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

A functional tracking task to assess frontal plane motor control in post stroke gait

Megan E Reissman [a,b,*], Yasin Y Dhaher [a,c]

[a] *Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, IL, USA*
[b] *Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA*
[c] *Department of Biomedical Engineering, Northwestern University, Evanston, IL, USA*

ARTICLE INFO

Article history:
Accepted 6 May 2015

Keywords:
Gait
Locomotion
Sensory-motor control
Tracking task
Rehabilitation
Foot placement
Step width

ABSTRACT

The ability to execute appropriate medio-lateral foot placements during gait is thought to require active frontal plane control and to be critical in maintaining upright posture during gait. The aggregate frontal plane metrics of step width and step width variability have been assessed for post-stroke populations, but only under normal walking conditions. However, in the case of stroke, limb specific differences in sensory-motor control are likely. Thus, an investigation of limb specific motor control characteristics under tracking task conditions is needed to appropriately characterize frontal plane sensory-motor control post-stroke. Chronic stroke subjects ($n=15$) and age matched control subjects ($n=10$) tracked static, bilateral foot placement targets at self-selected walking speeds and completed a free walking trial. Variability and error of tracking performance were analyzed for step width and foot placement. Stroke subjects demonstrated reduced ability to control step width variability and foot placement variability, compared to control subjects. Step width variability and affected limb foot placement variability were sensitive to task complexity, increasing significantly in response to a decrease in step width target size. These results show that stroke mediated changes in the sensory-motor integration processes are manifested as inter-limb differences in frontal plane motor variability during a gait tracking task, with an additional sensitivity to task complexity. Additionally, the proposed step width tracking paradigm presents a clinically reproducible motor control metric that can be used for diagnostic assessment or as a potential outcome for a gait training regimen.

1. Introduction

Stroke survivors frequently exhibit asymmetric kinematics between the affected and unaffected limbs and abnormal frontal plane movement patterns such as hiking of the pelvis, circumduction of the affected leg, and increased step width (Kerrigan et al., 2000; Chen et al., 2005). Such frontal plane deviations have been implicated in decreased walking efficiency and limited duration of functional locomotion (Lewek et al., 2012; Chen et al., 2005). Moreover, these abnormal frontal plane gait movements can also result in less stable walking patterns (Inman et al., 1981) and a high incidence of sideways falls during walking (Mackintosh et al., 2005). While motor control impairments, including muscle weakness (Chae et al., 2002), decreased movement and muscle coordination (Nowak et al., 2007; Levin et al., 2000), and reduced degrees of freedom between movements in different planes (Sukal et al., 2007; Tan and Dhaher, 2014) have been identified, the sensory-motor deficits underlying abnormal frontal plane behaviors during post-stroke gait remain poorly understood and therapeutic strategies remain lacking.

A previous examination of healthy adults has indicated that the control of frontal plane foot placements requires active engagement of the sensory-motor processes utilizing visual and proprioceptive feedback (Hof et al., 2010). Additionally, frontal plane gait movements have been shown to require greater active control than sagittal plane gait movements (Bauby and Kuo, 2000) suggesting that frontal plane examinations may provide a greater understanding of sensory-motor deficits affecting gait. Moreover, frontal plane gait metrics in post-stroke gait have shown that overall step width (Chen et al., 2005), but not step width variability (Balasubramanian et al., 2009), is significantly increased compared to healthy controls. While informative, these examinations explore sensory-motor characteristics of bilateral coordination and provide

---

[*] Corresponding author at: Rehabilitation Institute of Chicago, Sensory Motor Performance Program, 345 East Superior Street, Chicago, IL 60611, USA. Tel.: +1 312 238 1685; fax: +1 312 238 2208.

E-mail address: meb475@u.northwestern.edu (M. Reissman).

http://dx.doi.org/10.1016/j.jbiomech.2015.05.008
0021-9290/© 2015 Elsevier Ltd. All rights reserved.

no data on limb specific characteristics exhibited by the sensory-motor system to environmental changes during gait.

Accordingly, our goal was to examine the post-stroke inter-limb differences in the sensory-motor integration processes under controlled walking conditions. To achieve this goal, we developed a visual tracking paradigm consisting of bilateral medio-lateral foot placement targets, effectively creating a static step width (SW) target. With this paradigm we use SW as a measure of bilateral motor coordination and the individual foot placement as a measure of limb specific sensory-motor expression. The level of challenge or complexity that a motor task presents has been shown to affect short-term motor performance (Mani et al., 2013), and under long-term training conditions it has been proposed that the modification of task complexity, with regard to an individual's skill level (Guadagnoli and Lee, 2004), plays a key role in mediating enhanced motor skill learning and neuroplasticity responses (Onla-or and Winstein, 2008; Perez et al., 2004). Thus we modified task complexity by presenting discrete reductions in SW targets, producing an increase in the biomechanical demand on the motor control system to perform the task while maintaining a viable locomotor behavior.

We hypothesized that the introduction of a SW tracking task would reveal significant differences in frontal plane variability measures, between stroke and control subjects, and in comparison to free walking measures. We further hypothesized that bilateral coordination (SW) and limb specific sensory-motor performance measures will be sensitive to tracking task changes (reductions in the target SW). Knowledge gleaned from this study will improve our understanding of frontal plane motor control under dynamic walking conditions and inform the development of gait metrics which improve characterization of post-stroke sensory-motor impairments.

2. Methods

2.1. Study participants

All protocols and recruitment procedures were approved by Northwestern's Institutional Review Board and in accordance with institutional guidelines. Informed, written consent was obtained from 15 subjects with hemiparesis, aged 51.9 ± 9.3 (mean ± standard deviation (SD)) years, who had experienced a single unilateral stroke occurring 58.5 ± 57.5 months prior to testing (Table 1). Stroke events occurred a minimum of 3 months prior to the study, and events were free from cerebellar or brain stem involvement. Subjects had no history of lower limb surgery or injury, severe cognitive deficits, or concurrent severe medical illness. Stroke subjects with a range of walking speeds and impairment levels were recruited (Table 1). During the study, subjects who walked with an ankle foot orthosis or knee brace wore the walking aid, but cane users walked without their cane. In addition, 10 healthy, aged matched controls, (46.7 ± 10.4 years, 60% male) were tested for comparative purposes and walked at their own self-selected speeds (1.02 ± 0.15 m/s).

2.2. Experimental procedures

Kinematic data was recorded at 100 Hz using an 8-camera video system (Motion Analysis, Santa Rosa, CA). Reflective markers ($n=24$) were placed on the pelvis and lower limbs. Subjects wore a safety harness which did not provide body weight support during regular walking. To determine self-selected walking speed, subjects walked on the treadmill while wearing a fore-aft position sensor. As the subject's walking speed changed relative to the treadmill speed, the treadmill speed was updated to match their preferred speed and keep them centered on the treadmill. Following training with the system, subjects walked for three minutes and the speed during the final minute was averaged to define the self-selected speed. For all subsequent trials treadmill speed was held static.

Average step width (SW) was determined at the self-selected speed over a two minute period following five minutes of acclimation to treadmill walking. This average SW defined the 100% tracking target and the narrower 90% and 80% targets are defined as the corresponding percentages of this average SW. For the free walking task, subjects walked at their self-selected speed without any foot placement targets. Subjects were directed to avoid touching the handrails and were monitored for any touch events. To avoid subject fatigue, walking and break times were monitored by the treadmill control system, with five minute rest periods given between different tasks and subjects never performing more than eight minutes of continuous walking. Tracking task targets were defined with two adjustable, calibrated laser lines projected onto the treadmill belt (Fig. 1) and were presented in decreasing size, beginning with the 100% task. Subjects were directed to place their foot such that the lateral edge of their shoe was as close to the target line as possible, to match both feet as accurately as possible, and to avoid focusing on one foot only. A full-length mirror placed in front of the treadmill allowed subjects to see their whole body and the tracking targets without looking down. Foot placement was determined using kinematic markers placed on the lateral shoe edges at the metatarsal-phalangeal joint (Fig. 1).

2.3. Experimental analysis

A target of 100 steps was set with 90 steps being the minimum required for inclusion in data analysis. Incomplete step data from the beginning and ends of motion capture files, and step data for which the subject tripped or touched the

Table 1
Subject Characteristics.

	Lesion side	Sex	Device	Age (years)	Time since stroke (months)	Mean step width (cm)	Self-selected speed (m/s)	Lower Fugl-Meyer (score)[a]	Timed up & go (s)	Mini mental (score)[b]	Berg balance (score)[c]
S1	R	M	SC, AFO	57.9	54	34.7	0.5	13	15.5	28	54
S2	L	M	SC, AFO	50.3	52	39.2	0.7	25	12.0	26	43
S3	L	M	SC	57.6	114	41.8	0.7	26	12.0	30	55
S4	L	M	–	46.3	9	29.8	0.9	30	8.5	30	54
S5	L	M	SC	53.2	15	29.5	0.7	25	9.8	30	55
S6	L	M	SC	70.5	26	34.5	0.5	30	11.3	30	53
S7	L	M	–	39.6	27	33.9	0.5	27	13.4	26	46
S8	R	M	SC	56.7	71	34.6	0.9	30	11.3	30	51
S9	L	F	SC	32.4	20	30.9	0.4	18	11.7	29	51
S10	L	F	–	52.9	39	35.5	0.4	18	11.4	26	46
S11	L	F	KB	50.4	17	34.3	0.7	26	13.5	30	54
S12	R	F	SC	55.1	240	27.0	0.6	24	13.1	29	51
S13	L	F	SC	51.7	23	28.7	0.5	24	17.0	26	49
S14	R	F	SC, AFO	40.7	66	37.9	0.5	26	13.8	30	40
S15	L	F	SC, AFO	63.9	104	34.9	0.7	20	15.3	30	55
Mean				**51.9**	**58.5**	**33.8**	**0.61**	**24.1**	**12.6**	**28.7**	**50.5**
SD				**9.3**	**57.5**	**3.9**	**0.15**	**4.8**	**2.2**	**1.7**	**4.6**

SD – Standard Deviation, R – Right, L – Left, M – Male, F – Female, AFO – Ankle Foot Orthosis, SC – Single Cane, KB – Knee Brace.

[a] Lower Fugl-Meyer motor exam has a maximum score of 34.

[b] Mini Mental exam has a maximum score of 30.

[c] Berg Balance exam has a maximum score of 56.

hand rail, were excluded. If more than 120 were recorded, all steps beyond the first 120 were trimmed from the end of the data set. The final data sets included 108.5 ± 6.3 steps (mean ± SD) per trial for stroke subjects and 104.9 ± 7.8 steps per trial for control subjects (Table 2). The primary outcome measures were error and variability, which were analyzed for both SW and foot placement. Medio-lateral foot placement position was accessed as the average during a 0.2 s window following the condition that the foot was in full contact with the floor, determined using heel and toe kinematic height data with thresholds based on marker heights during standing. SW is defined as the medio-lateral distance between lateral foot markers on consecutive steps. Step width error (SWE) is defined as the difference between the measured SW and the target SW. Foot placement error (FPE) is defined as the difference between the recorded foot position and the target foot position. SWE and FPE are defined as the mean of each error data set. Step width variability (SWV) and foot placement variability (FPV) are defined as the SD of each data set. The sagittal plane of the motion capture coordinates is parallel to the treadmill belt and the target line axis, thus FPV represents both spatial variability and error variability. Normality assessment of data sets suggested SD as an appropriate variability measure; please see supplementary details.

We examined the accuracy of our variability measurements by calculating the running SD of foot placement and SW for each data set. We determined the number of steps, prior to the final step, for which all running SD values remained within ± 10% of the cumulative variability value (Table 2). On average, after 55 steps have been collected both FPV and SWV measures will reach a value within 10% of what will be measured with the collection of 50 additional steps. The relative flatness of the second half of both foot placement and SW running SD functions suggests a good estimate of the variability measures of interest.

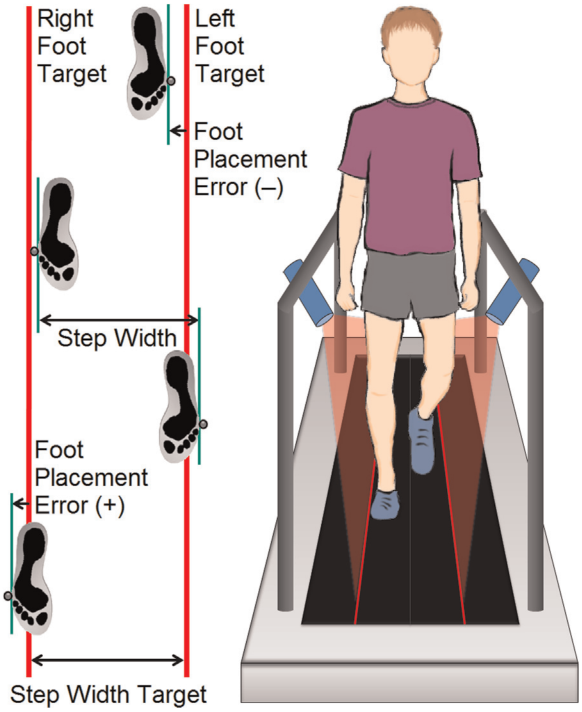

Fig. 1. Foot placement error (FPE) is defined as the medio-lateral distance between the foot placement tracking target and the lateral edge of the foot, where lateral errors are positive and medial errors are negative. Step width (SW) is defined as the medio-lateral distance between the lateral edges of the feet at successive foot placements.

All statistical analysis of significance was performed using NCSS software (v9.0). Tukey-Kramer post-hoc testing was used to assess significance (set at $p < 0.05$ for all comparisons). First, we accessed differences in variability and error in response to tracking task changes. SW data and group foot placement data were compared using analysis of variance (ANOVA) with factors of group (stroke, control) and condition (80%, 90%, and 100%). Stroke group side-specific data was compared using ANOVA with factors of limb (affected, unaffected) and condition (80%, 90%, and 100%).

Second, we accessed differences between free walking variability and tracking task variability. SW data and group foot placement data were compared using ANOVA with factors of group (stroke, control) and condition (80%, 90%, 100%, and free walking). Stroke group side-specific data was compared using ANOVA with factors of limb (affected, unaffected) and condition (80%, 90%, 100%, and free walking). Significant between group differences were consistent for assessments of the two hypotheses. One stroke subject was excluded from the free walking variability comparisons due to an insufficient number of steps for the free walking condition.

3. Results

On each boxplot: central mark is the median, edges of the box are the 25th and 75th percentiles, whiskers extend to all non-outlier data points, and outliers are plotted individually.

3.1. Step width variability

Stroke subjects showed no significant difference in SWV between the free walking and the 100% tracking task (Fig. 2A). Stroke subject SWV increased significantly between the 100% and 80% tracking tasks ($p < 0.01$). Control subjects significantly reduced their SWV between the free walking task and each of the tracking tasks (all $p < 0.01$), but did not demonstrate any significant differences between tracking tasks. In the free walking condition SWV was not significantly different between the stroke group and the control group (Fig. 2B). However, for all tracking tasks stroke subject SWV was significantly higher than that of control subjects (all $p < 0.001$).

3.2. Foot placement variability

In the group comparison, stroke group FPV was significantly reduced between the free walking task and the 100% ($p < 0.01$) and 90% ($p < 0.05$) tasks (Fig. 3A). Control group FPV was significantly reduced between the free walking task and each of the three tracking tasks (all $p < 0.001$). FPV did not significantly change across tracking tasks for either group. FPV was not significantly different between the stroke and control groups during the free walking condition (Fig. 3B). However, for all tracking tasks

Table 2
Assessment of Variability.

	80% Task (mean ± SD)	90% Task (mean ± SD)	100% Task (mean ± SD)	Free walking (mean ± SD)	All tasks (mean ± SD)
Stroke subjects					
Total number of steps	108.6 ± 7.3	107.8 ± 5.1	108.4 ± 5.3	109.1 ± 7.2	108.5 ± 6.3
Foot placement within 10%[a]	49.8 ± 12.1	51.1 ± 17.4	56.5 ± 16.7	44.2 ± 17.8	50.5 ± 16.8
Step width within 10%[b]	57.9 ± 18.3	53.4 ± 26.1	61.0 ± 21.4	56.6 ± 21.3	57.2 ± 22.3
Control subjects					
Total number of Steps	102.0 ± 10.3	106.5 ± 5.5	104.8 ± 4.8	106.5 ± 8.1	104.9 ± 7.8
Foot placement within 10%[a]	57.2 ± 12.7	51.5 ± 5.8	47.3 ± 23.1	44.9 ± 10.3	50.0 ± 15.9
Step width within 10%[b]	57.2 ± 19.1	60.8 ± 21.6	51.1 ± 19.5	54.5 ± 12.9	55.3 ± 18.5

[a] Number of final steps for which the running SD of foot placement remains within 10% of the cumulative value.
[b] Number of final steps for which the running SD of step width remains within 10% of the cumulative value.

FPV of the stroke group was significantly higher than controls (all $p < 0.001$).

In the stroke group limb specific comparison, both the affected and unaffected limbs demonstrated a significant decrease in FPV between the free walking task and the 100% ($p < 0.001$) and 90% ($p < 0.05$) tracking tasks (Fig. 4A). For the affected side, FPV in the 80% task was significantly increased compared to the 90% ($p < 0.01$) and 100% ($p < 0.001$) tracking tasks, but not for the unaffected side. For all conditions the FPV of the affected leg was significantly higher (all $p < 0.01$) than the FPV of the unaffected leg (Fig. 4B). An equivalent control group comparison between the dominant and non-dominant limbs revealed no significant differences in FPV between limbs for any task or between tracking tasks for either side.

3.3. Tracking error

SWE was analyzed for the tracking tasks by comparing average SW to the target SW. In the SWE comparison, the stroke and control groups were not significantly different. Stroke group SWE was significantly different between all three tracking tasks (100–90%:$p < 0.05$, 90–80%:$p < 0.001$, 100–80%:$p < 0.001$) (Fig. 5). Control group SWE increased significantly between the 100% and 80% tasks ($p < 0.05$).

In the group FPE comparison, the stroke and control groups were not significantly different. Stroke group FPE was significantly different between all three tracking tasks (100–90%:$p < 0.05$, 90–80%:$p < 0.001$, 100–80%:$p < 0.001$) (Fig. 6A). Control group FPE increased significantly between the 100% and 80% task ($p < 0.05$).

In the stroke group limb specific FPE comparison, the limbs were not significantly different. Affected limb FPE in the 80% task was significantly increased compared to the 100% ($p < 0.001$) and 90% ($p < 0.01$) tasks (Fig. 6B). Unaffected limb FPE in the 80% task was significantly increased compared to the 100% ($p < 0.01$) task. An equivalent control group comparison between the dominant and non-dominant limbs revealed no significant difference in FPE between limbs.

4. Discussion

In this study, we examined the hypothesis that post-stroke changes in the sensory-motor integration process would manifest as inter-group and inter-limb differences in frontal plane motor characteristics during gait. Performance measures included

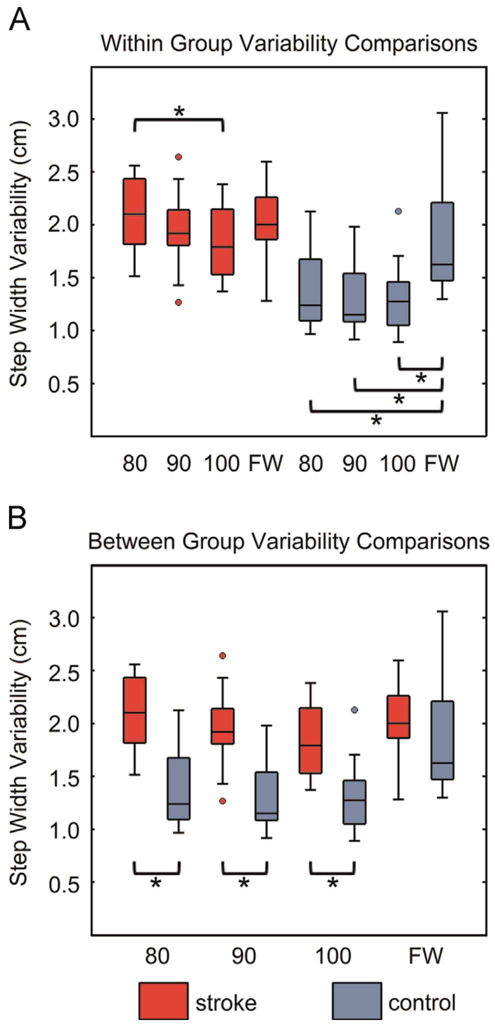

Fig. 2. (A) Within group step width variability comparisons for stroke and control. (B) Between group step width variability comparisons for stroke and control. All variability measures are SD of individual data sets. Conditions '80', '90', and '100' are tracking tasks at the given percentage of the average self-selected SW and 'FW' is the free walking task. Significance ($p < 0.05$) is denoted by *.

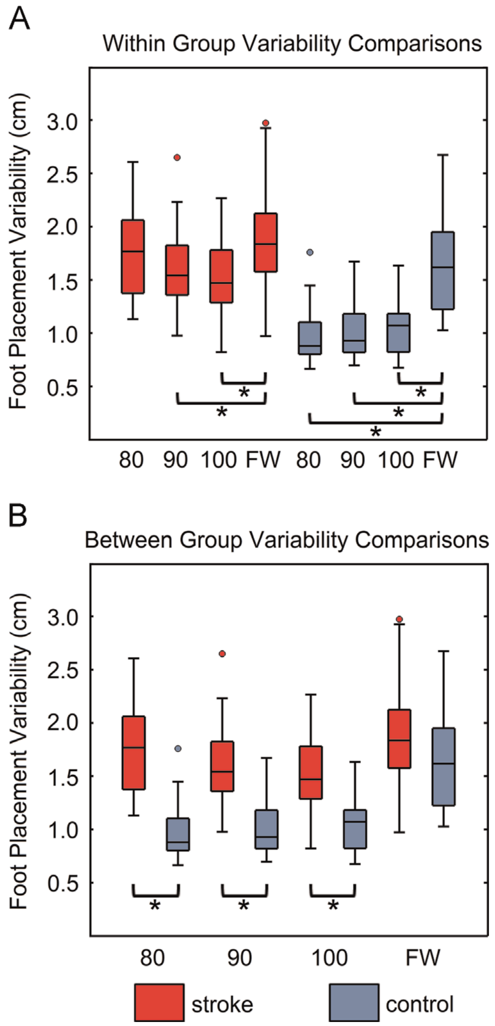

Fig. 3. (A) Within group foot placement variability comparisons for stroke and control. (B) Between group foot placement variability comparisons for stroke and control. All variability measures are SD of individual data sets. Conditions '80', '90', and '100' are tracking tasks at the given percentage of the average self-selected SW and 'FW' is the free walking task. Significance ($p < 0.05$) is denoted by *.

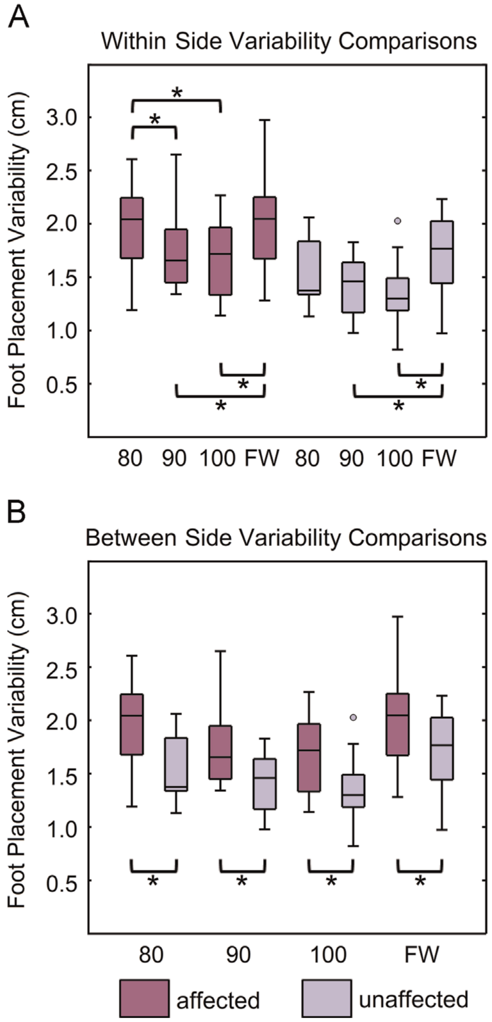

Fig. 4. (A) Stroke specific within side foot placement variability comparisons. (B) Stroke specific between side foot placement variability comparisons. All variability measures are SD of individual data sets. Conditions '80', '90', and '100' are tracking tasks at the given percentage of the average self-selected SW and 'FW' is the free walking task. Significance ($p < 0.05$) is denoted by *.

variability and error, assessed for foot placement and SW, during free walking and during a SW tracking task with accompanying increases in task complexity. The interpretation and analysis of naturally occurring motor variability remains a topic of discussion, with several temporal analyses being utilized to identify underlying motor control strategies (Todorov and Jordan, 2002; Dingwell et al. 2010). However, the implemented tracking task provided explicit goals, facilitating a direct interpretation of variability as a manifestation of the underlying sensory-motor integration processes. The primary outcomes indicate limb dependence of FPV for all conditions, with higher FPV for the affected, as compared to the unaffected side. For both limbs, the tracking task presentation resulted in significant reductions in FPV between the biomechanically similar conditions (free and 100%). With the increase in the biomechanical demand, limb specific performance emerged. FPV of the affected limb increased with decreasing SW, however the unaffected limb showed statistical invariance. Stroke subject FPE did not demonstrate significant inter-limb differences, and both stroke and control groups significantly increased FPE as the SW tracking task was narrowed.

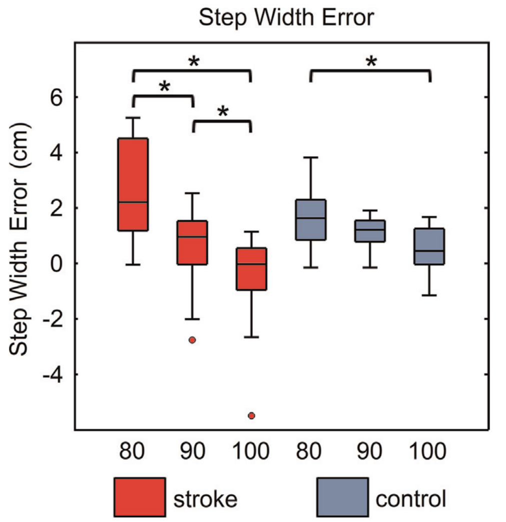

Fig. 5. Step width tracking error averaged for each data set, where step widths narrower than the target have negative error and step widths wider than the target have positive error. Conditions '80', '90', and '100' are tracking tasks at the given percentage of the average self-selected SW. Significance ($p < 0.05$) is denoted by *.

4.1. Step width variability

Regardless of tracking task condition, stroke group SWV was significantly higher than for the control group and was sensitive to changes in task complexity, increasing in response to decreasing target width. This result is supported by previous studies in which tracking performance was sensitive to task conditions including limb orientation, target direction (Mani et al., 2013), range (Cho et al., 2007), and number (Madhavan et al., 2010). As tracking conditions deviate away from 100% (nominal gait pattern) greater variability in motor output may be expected; however our results suggest that healthy adults are able to perform SW tracking changes without any corresponding variability changes.

The expression of SWV during free walking was statistically indistinguishable between groups, findings consistent with earlier examination (Balasubramanian et al., 2009). Between the free walking and 100% task, stroke subjects reduced their FPV for both sides but did not significantly alter their SWV. This result may be attributed in part to the aggregate nature of the metric in combining the behavior of the affected and unaffected limbs or may suggest a post-stroke sensory-motor deficit specific to bilateral coordination. A walking task, which manipulated bilateral coordination requirements using a split-belt paradigm, found that post-stroke subjects remain able to modify both limb specific and inter-limb motor patterns in response to imposed tasks (Reisman et al., 2007). It remains to be seen if metrics of bilateral coordination or of limb specific behavior better characterize therapy mediated changes in gait performance.

4.2. Foot placement variability

Affected limb FPV was significantly higher than unaffected limb FPV during the repetitive motor tasks considered in this study. These differences may be attributed, in part, to aberrant post-stroke motor synergies in the lower limb. Altered motor synergies following stroke have been investigated as a potential mechanism for reductions in achievable motor space (Sukal et al., 2007) and a loss of independent motor control between sagittal plane and frontal plane movements (Tan and Dhaher, 2014). The reported post-stroke coupling between knee flexion and hip abduction

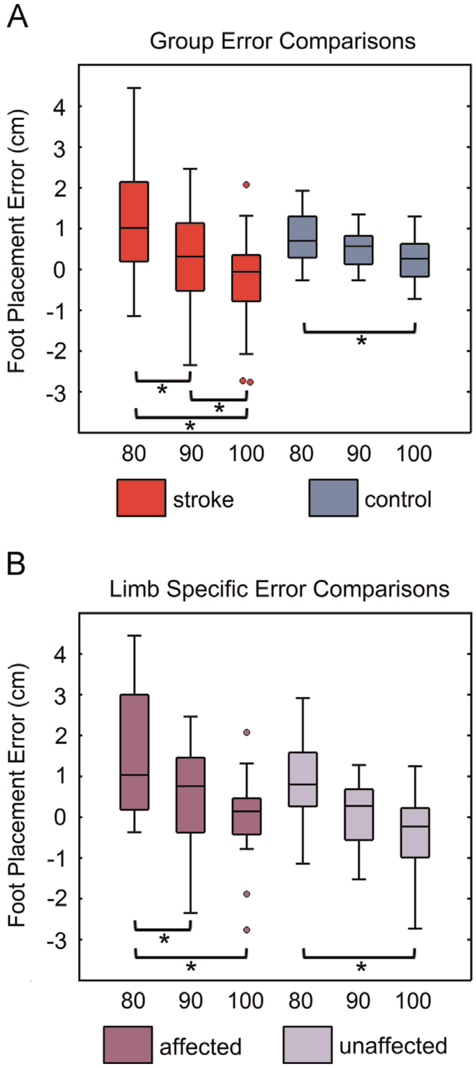

Fig. 6. (A) Foot placement error comparisons for stroke and control. (B) Stroke specific foot placement error comparisons. Foot placement tracking error averaged for each data set, where foot placements narrower than the target have negative error and foot placements wider than the target have positive error. Conditions '80', '90', and '100' are tracking tasks at the given percentage of the average self-selected SW. Significance ($p < 0.05$) is denoted by*.

during walking (Sulzer et al., 2010) would increase the difficulty for stroke subjects to match precise medio-lateral foot placement targets, particularly as the SW target is narrowed and the hip adduction requirement is increased. This potentially explains our result of increasing affected limb FPV with decreasing SW target. Arguably, these differences may be confounded by intrinsic inter-limb differences in motor performance. Yet, the control group revealed no inter-limb differences in FPV, findings consistent with other examination of limb dominance during an isolated multi-joint trajectory tracking task (Maffiuletti et al., 2005), and no FPV sensitivity for the range of SW investigated.

Additionally, stroke group FPV was significantly higher (all $p < 0.001$) than the control group during all tracking tasks. This suggests that, following stroke, FPV of the unaffected limb may also be increased compared to healthy controls and may have contributed to this difference. The existence of bilateral post-stroke motor deficits is supported by prior examinations of visuomotor tracking in the unaffected lower extremity, which have shown significant deficits during seated unilateral tasks including foot tapping (Kim et al., 2003), force production (Chow and Stokic, 2011), and foot trajectory tracking (Kawahira et al., 2005). Given the potential implication to locomotor stability, further examination of the mechanisms underlying bilateral impairment in lower limb motor performance is warranted.

4.3. Tracking error

Our tracking examination revealed no significant differences in FPE between stroke and control groups, or between affected and unaffected limbs of stroke subjects. Previous studies of unilateral tracking tasks have shown increased kinematic tracking accuracy for the joint of the unaffected limb compared to the affected limb (Cho et al., 2007; Madhavan et al., 2010). However, for a bilateral anti-phase tracking condition, the accuracy of the affected limb was reported to be significantly higher (Madhavan et al., 2010). Although this anti-phase condition is kinematically similar to walking, the examination was conducted at a single joint, performed during seated posture, and unlike our study dual targets were tracked continuously. This difference suggests that lower limb motor characteristics identified under unilateral or constraint conditions may differ from motor characteristics presented during a functional walking behavior. Arguably, our error results may also be mediated by the overriding constraint of maintaining stability during gait.

4.4. Potential issues

The use of a treadmill may limit the generalizability of our findings, as it has been established that treadmill and overground walking will lead to differences in SW and SWV in healthy young subjects (Rosenblatt and Grabiner, 2010). While potentially a confounding factor, our goal was to identify the differences in sensory-motor integration across groups under identical experimental conditions. Moreover, treadmill walking allows for the acquisition of the required large number of steps needed to robustly identify differences across conditions and groups.

In the experimental design, a non-randomized protocol was used. To establish baseline data the free walking condition was completed prior to any tracking tasks. Presentation of tracking tasks was systematic starting with 100% target and ending with the 80% target. While a significant limitation, previous studies have shown that motor variability decreases during motor learning of a task (Cohen and Sternad, 2009; Shmuelof et al., 2012). Thus the finding of increased variability during tasks examined later in the session suggests that the effect of increasing task complexity on motor variability is significant despite any intra-session motor learning that may have occurred.

Additionally, our tracking results may be affected by the high proportion of left-affected stroke subjects in our population, as response to motor and tracking tasks may be affected by the lesion side (Mani et al., 2013). However, due to the limited number of right-affected subjects, analysis of lesion location effect could not be performed. Future studies which examine the effect of left and right hemisphere lesions on lower limb sensory-motor performance are warranted.

5. Conclusions

Our goal in this study was to examine frontal plane motor control capabilities during post-stroke gait. Our findings support the idea that there are post-stroke motor control differences which are not apparent from evaluating normal behaviors such as walking. Tasks which challenge the motor control system, such as tracking and perturbation tasks, are needed to reveal these sensory-motor integration and motor control deficits. We argue that tracking tasks may have advantages over perturbation (slip/trip) paradigms due to their simplicity of implementation in clinical settings. When tracking tasks are used, our findings indicate that post-stroke motor deficits are better characterized by differences in variability than differences in error. Specifically, motor control deficits in both FPV and SWV were identified for the stroke group compared to controls. Additionally, FPV demonstrated inter-limb differences, which suggests that in the case of stroke, limb specific metrics may provide additional utility over aggregate metrics, such as SWV, in evaluating motor control deficits.

Tracking tasks utilized under training conditions appear useful in improving lower limb motor control and walking performance (Cho et al., 2007). The SW tracking paradigm has potential as a training tool as it captures many desirable training characteristics, including bilateral tasks (Summers et al., 2007), skillful movements (Jensen et al., 2005), and the ability to challenge the motor system by modifying task complexity (Guadagnoli and Lee, 2004). Thus, the paradigm may assist stroke patients with improving their ability to control foot placements and to respond effectively to frontal plane instability.

Conflict of Interest

The authors declare that they have no conflicts of interest regarding this work.

Funding

This work has been supported by the National Institute of Neurological Disorders and Stroke (R01NS064084-02).

Acknowledgments

The authors thank Natalie Bhesania and Kathryn Berry for their assistance in data collection and post processing.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2015.05.008.

References

Balasubramanian, C.K., Neptune, R.R., Kautz, S.A., 2009. Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke. Gait Posture 29 (3), 408–414.

Bauby, C.E., Kuo, A.D., 2000. Active control of lateral balance in human walking. J. Biomech. 33 (11), 1433–1440.

Chae, J., Yang, G., Park, B.K., Labatia, I., 2002. Muscle weakness and cocontraction in upper limb hemiparesis: relationship to motor impairment and physical disability. Neurorehabil. Neural Repair 16 (3), 241–248.

Chen, G., Patten, C., Kothari, D.H., Zajac, F.E., 2005. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. Gait Posture 22 (1), 51–56.

Cho, S.H., Shin, H.K., Kwon, Y.H., Lee, M.Y., Lee, Y.H., Lee, C.H., Jang, S.H., 2007. Cortical activation changes induced by visual biofeedback tracking training in chronic stroke patients. NeuroRehabilitation 22 (2), 77–84.

Chow, J.W., Stokic, D.S., 2011. Force control of quadriceps muscle is bilaterally impaired in subacute stroke. J. Appl. Physiol. 111 (5), 1290–1295.

Cohen, R.G., Sternad, D., 2009. Variability in motor learning: relocating, channeling and reducing noise. Exp. Brain Res. 193 (1), 69–83.

Dingwell, J.B., John, J., Cusumano, J.P., 2010. Do humans optimally exploit redundancy to control step variability in walking? PLoS Comput. Biol. 6 (7), e1000856.

Guadagnoli, M.A., Lee, T.D., 2004. Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. J. Mot. Behav. 36 (2), 212–224.

Hof, A.L., Vermerris, S.M., Gjaltema, W.A., 2010. Balance responses to lateral perturbations in human treadmill walking. J. Exp. Biol. 213 (15), 2655–2664.

Inman, V.T., Ralston, H.J., Todd, F., 1981. Human Walking. Williams & Wilkins, Baltimore, London.

Jensen, J.L., Marstrand, P.C., Nielsen, J.B., 2005. Motor skill training and strength training are associated with different plastic changes in the central nervous system. J. Appl. Physiol. 99 (4), 1558–1568.

Kawahira, K., Shimodozono, M., Ogata, A., Etoh, S., Ikeda, S., Yoshida, A., et al., 2005. Impaired visuomotor skills in the unaffected lower limb of patients with stroke. Int. J. Neurosci. 115 (9), 1315–1332.

Kerrigan, D.C., Frates, E.P., Rogan, S., Riley, P.O., 2000. Hip hiking and circumduction: quantitative definitions. Am. J. Phys. Med. Rehabil. 79 (3), 247–252.

Kim, S.H., Pohl, P.S., Luchies, C.W., Stylianou, A.P., Won, Y., 2003. Ipsilateral deficits of targeted movements after stroke. Arch. Phys. Med. Rehabil. 84 (5), 719–724.

Levin, M.F., Selles, R.W., Verheul, M.G., Meijer, O.G., 2000. Deficits in the coordination of agonist and antagonist muscles in stroke patients: implications for normal motor control. Brain Res. 853 (2), 352–369.

Lewek, M.D., Osborn, A.J., Wutzke, C.J., 2012. The influence of mechanically and physiologically imposed stiff-knee gait patterns on the energy cost of walking. Arch. Phys. Med. Rehabil. 93 (1), 123–128.

Mackintosh, S.F., Hill, K., Dodd, K.J., Goldie, P., Culham, E., 2005. Falls and injury prevention should be part of every stroke rehabilitation plan. Clin. Rehabil. 19 (4), 441–451.

Madhavan, S., Rogers, L.M., Stinear, J.W., 2010. A paradox: after stroke, the non-lesioned lower limb motor cortex may be maladaptive. Eur. J. Neurosci. 32 (6), 1032–1039.

Maffiuletti, N.A., Bizzini, M., Schatt, S., Munzinger, U., 2005. A multi-joint lower-limb tracking-trajectory test for the assessment of motor coordination. Neurosci. Lett. 384 (1–2), 106–111.

Mani, S., Mutha, P.K., Przybyla, A., Haaland, K.Y., Good, D.C., Sainburg, R.L., 2013. Contralesional motor deficits after unilateral stroke reflect hemisphere-specific control mechanisms. Brain 136 (4), 1288–1303.

Nowak, D.A., Grefkes, C., Dafotakis, M., Küst, J., Karbe, H., Fink, G.R., 2007. Dexterity is impaired at both hands following unilateral subcortical middle cerebral artery stroke. Eur. J. Neurosci. 25 (10), 3173–3184.

Onla-or, S., Winstein, C.J., 2008. Determining the optimal challenge point for motor skill learning in adults with moderately severe Parkinson's disease. Neurorehabil. Neural Repair 22 (4), 385–395.

Perez, M., Lungholt, B.S., Nyborg, K., Nielsen, J., 2004. Motor skill training induces changes in the excitability of the leg cortical area in healthy humans. Exp. Brain Res. 159 (2), 197–205.

Reisman, D.S., Wityk, R., Silver, K., Bastian, A.J., 2007. Locomotor adaptation on a split-belt treadmill can improve walking symmetry post-stroke. Brain 130 (7), 1861–1872.

Rosenblatt, N.J., Grabiner, M.D., 2010. Measures of frontal plane stability during treadmill and overground walking. Gait Posture 31 (3), 380–384.

Shmuelof, L., Krakauer, J.W., Mazzoni, P., 2012. How is a motor skill learned? Change and invariance at the levels of task success and trajectory control. J. Neurophysiol. 108 (2), 578–594.

Sukal, T., Ellis, M., Dewald, J.A., 2007. Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications. Exp. Brain Res. 183 (2), 215–223.

Sulzer, J.S., Gordon, K.E., Dhaher, Y.Y., Peshkin, M.A., Patton, J.L., 2010. Preswing knee flexion assistance is coupled with hip abduction in people with stiff-knee gait after stroke. Stroke 41 (8), 1709–1714.

Summers, J.J., Kagerer, F.A., Garry, M.I., Hiraga, C.Y., Loftus, A., Cauraugh, J.H., 2007. Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a TMS study. J. Neurol. Sci. 252 (1), 76–82.

Tan, A.Q., Dhaher, Y.Y., 2014. Evaluation of lower limb cross planar kinetic connectivity signatures post-stroke. J. Biomech. 47 (5), 949–956.

Todorov, E., Jordan, M.I., 2002. Optimal feedback control as a theory of motor coordination. Nat. Neurosci. 5 (11), 1226–1235.