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Abstract

Chronic stroke survivors have an increased incidence of falls during walking, suggesting changes in dynamic balance control post-stroke. Despite this increased incidence of falls during walking, balance control is often studied only in standing. The purpose of this study was to quantify deficits in dynamic balance control during walking, and to evaluate the influence of visual feedback on this control in stroke survivors. Ten individuals with chronic

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stroke, and ten neurologically intact individuals participated in this study. Walking performance was assessed while participants walked on an instrumented split-belt treadmill with different types of visual feedback. Dynamic balance control was quantified using both the extent of center of mass (COM) movement in the frontal plane over a gait cycle (COM sway), and base of support (step width). Stroke survivors walked with larger COM sway and wider step widths compared to controls. Despite these baseline differences, both groups walked with a similar ratio of step width to COM sway (SW/COM). Providing a stationary target with a laser reference of body movement reduced COM sway only in the stroke group, indicating that visual feedback of sway alters dynamic balance control post-stroke. These results demonstrate that stroke survivors attempt to maintain a similar ratio of step width to COM movement, and visual cues can be used to help control COM movement during walking post-stroke.

Keywords: Balance; Stroke; Gait; Visual feedback

1. Introduction

Visual feedback provides important information about the walking environment, which can then be used to update dynamic balance control and avoid potential falls in stroke survivors. Stroke survivors have a higher occurrence of falls (Jørgensen et al., 2002), with many of these falls occurring during walking (Mackintosh et al., 2005). Additionally, walking function post-stroke is strongly predicted by clinical measures of balance control (Michael et al., 2005). Improvements in both standing balance control and walking function are observed when rehabilitation techniques targeting sensorimotor integration are combined with traditional standing balance exercises post-stroke (Smania et al., 2008). However, despite an increased reliance on visual feedback for balance control (Slaboda et al., 2009), it is unknown whether altered visual feedback can be used to improve dynamic balance control and walking function for stroke survivors.

Balance control during walking is largely focused on frontal plane instability (Bauby and Kuo, 2000), and is complicated by both center of mass (COM) translation, and base of support variations in size and position. Lateral foot placement adjustments to keep the COM within the base of support are the most effective mechanism for dynamic balance control during walking (Hof, 2008). Visual feedback signals are an integral part of this lateral foot placement control, both during a step (Reynolds and Day, 2005), and over the course of multiple steps (Marigold and Patla, 2008). Clinically, stroke survivors are often observed watching their feet while walking, presumably using visual cues to aid in stepping. Even with this additional feedback, stroke survivors have difficulties making visually-guided medial–lateral step corrections with the paretic limb (Nonnekes et al., 2010), and walk with asymmetries in medial–lateral foot placement relative to the pelvis (Balasubramanian et al., 2010). These findings suggest that impairments in foot placement control, and likely dynamic balance control, persist even with vision of the feet.

In addition to guiding foot placement, visual feedback might aid in controlling COM movement by providing feedback of body position during walking. Stroke survivors demonstrate increased levels of frontal plane COM movement during quiet standing, with further increases observed when visual feedback is removed (Marigold and Eng, 2006a). Deficits in trunk (Ryerson et al., 2008) and whole body (Rao et al., 2010) position sense post-stroke likely contribute to an increased reliance on visual feedback for COM control (Slaboda et al., 2009). This increased reliance on visual feedback may provide a mechanism to improve balance control. For example, providing visual feedback of center of pressure location during standing significantly reduces frontal plane sway in chronic stroke survivors, although sway is still greater than controls (Dault et al., 2003). During walking, young individuals are able to utilize multi-sensory feedback of trunk position to improve trunk control (Verhoeff et al., 2009). However, it is unknown whether stroke survivors can utilize similar strategies to improve dynamic balance control during walking.

In this study we assessed walking performance with and without visual feedback of COM movement in stroke survivors. We hypothesized that visual feedback of body movement would reduce frontal plane COM movement in chronic stroke survivors during walking, with the largest improvements when a stationary visual reference was provided.

2. Methods

2.1. Participants

Ten chronic (>6 month) stroke survivors with unilateral brain injury, and ten age and sex-matched neurologically intact individuals participated in this study. Exclusion criteria for this study included inability to walk independently (with or without use of an assistive device), lesion to brainstem centers, diagnosis of other neurologic disorders, or inability to provide informed consent. Prior to beginning the experimental session, a licensed physical therapist conducted a clinical evaluation of the stroke participants, consisting of the lower extremity Fugl-Meyer Test (Fugl-Meyer et al., 1975), Berg Balance Assessment (Berg et al., 1992), Dynamic Gait Index (Jonsdottir and Cattaneo, 2007), and 10 m walking test (Mudge and Stott, 2009). Only self-selected overground walking speed was obtained for control participants. Participant characteristics are summarized in Table 1. The Marquette University Institutional Review Board approved all experimental procedures, and written informed consent was obtained from all individuals participating in this study.

Table 1. Participant characteristics**.** Lower extremity Fugl-Meyer (LE FM) maximum 34, Berg Balance maximum 56, Dynamic Gait Index (DGI) maximum 24.

ID	Sex	Age [yrs]	Time post-stroke [months]	Affected side	LE FM	Berg	DGI	Overground walking speed [m/s]	Treadmill speed [m/s]
S01	M	54	71	L	24	49	15	0.988	0.55
S02	F	62	317	L	19	46	21	0.837	0.36
S03	F	55	30	R	31	56	24	1.271	0.63
S04	M	54	42	L	30	43	17	1.136	0.48
S05	F	65	117	L	32	55	23	1.298	0.60
S06	F	62	144	R	32	49	21	1.270	0.58
S07	M	62	95	L	21	39	14	0.502	0.29
S08	M	59	120	R	29	46	21	1.361	0.75
S09	F	54	68	L	28	41	17	0.635	0.30
S10	M	65	7	R	27	54	19	0.995	0.65
C01	M	56	–	–	–	–	–	1.471	1.00
C02	F	62	–	–	–	–	–	1.212	0.96
C03	F	54	–	–	–	–	–	1.212	0.85
C04	M	57	–	–	–	–	–	1.515	0.90
C05	F	66	–	–	–	–	–	1.242	1.00
C06	F	61	–	–	–	–	–	1.299	0.75
C07	M	63	–	–	–	–	–	1.429	0.95
C08	M	58	–	–	–	–	–	1.333	0.90
C09	F	54	–	–	–	–	–	1.325	0.95
C10	M	63	–	–	–	–	–	0.980	0.84

2.2. Experimental protocol

Walking trials were conducted on an instrumented split-belt treadmill (FIT, Bertec Inc., Columbus, OH) with both belts set to the same speed. Belt speed was determined after a period of acclimatization at the beginning of the session, during which treadmill speed was slowly increased until participants self-selected the most comfortable speed. This self-selected belt speed was used for all the subsequent walking trials (see Table 1). Individuals were placed in a fall arrest harness, and held onto a side handrail with the non-paretic hand for safety. The handrail was instrumented with a six DOF load cell (MC3A-250, AMTI, Watertown, MA) to quantify handrail forces and torques throughout the trials. Control participants held onto the handle with the hand opposite of the randomly chosen test leg, maintaining consistency between groups.

Walking performance was evaluated under six experimental conditions altering the amount and type of visual information provided during walking. An initial period of treadmill walking was completed to obtain a baseline measure of walking performance prior to the altered visual feedback conditions. During the initial period, participants viewed an unmarked wall 3.8 m in front of the treadmill, with room lighting dimmed. In the reduced vision condition, visual feedback of foot placement was removed by having the individual wear goggles with black tape obstructing the lower half of the visual field. These goggles blocked the view of the participant's legs, while maintaining visual feedback of body motion relative to the room. Augmented visual feedback was provided through the use of a laser attached to a headband, which produced a visible circle (r=0.01 m) on the wall in front of the treadmill (3.8 m). Movement of the circle was related to the movement of the participant's head (and body) during walking. First, normal walking and reduced visual feedback trials were conducted, both with and without the laser feedback. In the initial laser-walking trials, the laser was turned on for the duration of the walking trial, but the participant was given no explicit instruction on use of the laser. These trials were conducted to evaluate the effect of providing an additional visual source of body movement and orientation on COM movement during walking without an explicit reference point. After these trials were completed, two laser target trials were conducted to determine whether stroke survivors could use position feedback from the laser to reduce COM movement during walking. During these target trials, a projector mounted above the treadmill displayed a target on the wall in front of the treadmill that either remained stationary or moved during the trial. The stationary target trial consisted of a large circular target (r=0.22 m) that the participant was instructed to keep the laser within, while walking. This trial provided a stationary reference point for the visual feedback signal, while also encouraging the participant to actively attend and control the movement of the laser using compensatory head movements, or by reducing body sway. During the moving target condition, a smaller target (r=0.06 m) randomly moved through a 1.5 by 1.0 m area on the wall, with the position changing every 1.0–2.0 s. This moving target would require the participant to actively attend and control head movement to adjust the laser's position, while the target's movement would potentially act to destabilize balance control. The center of the stationary target, and middle of the moving target area were located approximately at the center of the visual field when looking straight ahead.

Throughout all walking trials, walking performance was characterized over a period of 100 gait cycles at the participant's self-selected, comfortable treadmill speed. Fifteen passive infrared reflective markers were placed at anatomical locations according to the Plug-In-Gait model (Davis et al., 1991), with an additional seven markers placed at the left and right shoulder, C7, and four markers placed on the head. A six camera Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, UK) recorded marker location at 100 Hz. Treadmill ground reaction forces, and handrail forces were collected at 1000 Hz using a Vicon Mx Giganet to synchronize the analog and video data.

2.3. Data analysis

The data were initially processed in Vicon Nexus software to label markers, visually indicate gait events, and run the lower extremity Plug-In-Gait model. Additional data analysis was completed in Matlab (Mathworks, Natick, MA). An eight-segment model consisting of the foot, shank, thigh, pelvis, and trunk was used to estimate whole body COM location (Winter, 2009). COM movement in the frontal plane, or COM sway, was measured as the peak-to-peak displacement over a gait cycle. Foot placement locations were quantified from the Center of Pressure (COP), with lateral distance between successive steps at the midpoint of single limb support used to calculate step width (similar to Donelan et al. (2001)), and COP location at heel strike was referenced to the pelvis COM to characterize foot placement in the frontal plane (Balasubramanian et al., 2010). The ratio of step width to COM movement (SW/COM) was calculated to compare the size of the base of support to the extent of COM movement. Temporal and spatial gait parameters were calculated to characterize changes in walking performance during the different testing conditions. Contribution of handrail hold was evaluated by calculating the mean handle force during single limb stance of the paretic leg (test leg in controls).

Statistical analyses were conducted using SPSS 20.0 (IMB, Armonk, NY). Measures of walking performance were averaged across all gait cycles within each trial to obtain the participant's typical response to each experimental condition. A repeated measures ANOVA was conducted separately for each variable to evaluate differences between the experimental conditions and groups. A Greenhouse–Geisser correction was used to correct for non-spherical data when comparing within-subject effects. Post-hoc analyses were carried out for significant factors using a Sidak correction to account for multiple comparisons. A Pearson correlation analysis was carried out between the change in SW/COM ratio and the clinical tests to understand how changes in dynamic balance control post-stroke related to standard clinical measures.

3. Results

3.1. Balance measures

In general, stroke participants walked with a larger COM movement in the frontal plane (Group, p=0.003) and larger step widths (Group, p=0.001) compared to age and gender-matched neurologically intact individuals (Fig. 1). Stroke survivors also placed their paretic foot more lateral to the COM at heel strike compared to controls (Group, $p<0.001$), but no difference was observed between groups for the non-paretic limb. Despite these baseline differences in step width and COM movement, stroke participants maintained a similar SW/COM ratio (Group, $p=0.958$).

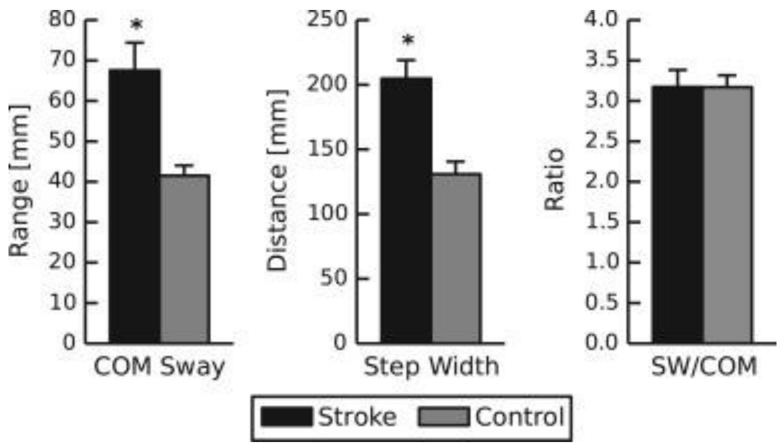

Fig. 1. Group differences in measures of frontal plane balance control. Average (±standard error) across all testing conditions for both groups indicating stroke participants walked with larger amounts of frontal plane COM movement and step widths compared to controls. The ratio of step width to COM movement was not different between groups. (*ANOVA, Group $p<0.05$).

COM sway (Condition, $p<0.001$) and SW/COM ratio (Condition, $p=0.002$) were statistically different between experimental conditions, but experimental conditions did not impact step width ($p=0.243$) or frontal plane foot placement (paretic $p=0.371$, non-paretic $p=0.211$). Changes in COM sway were different between the stroke and control groups (Condition*Group, $p=0.034$) (Fig. 2). The stationary target condition resulted in lower COM sway compared to normal ($p=0.034$) and reduced visual feedback walking ($p=0.016$) trials without the laser. Additionally, adding laser feedback to the normal walking and reduced visual feedback trials slightly reduced COM sway compared to the no laser trials, but these differences were not statistically significant for either the stroke ($p=0.227$) or control ($p=0.396$) group.

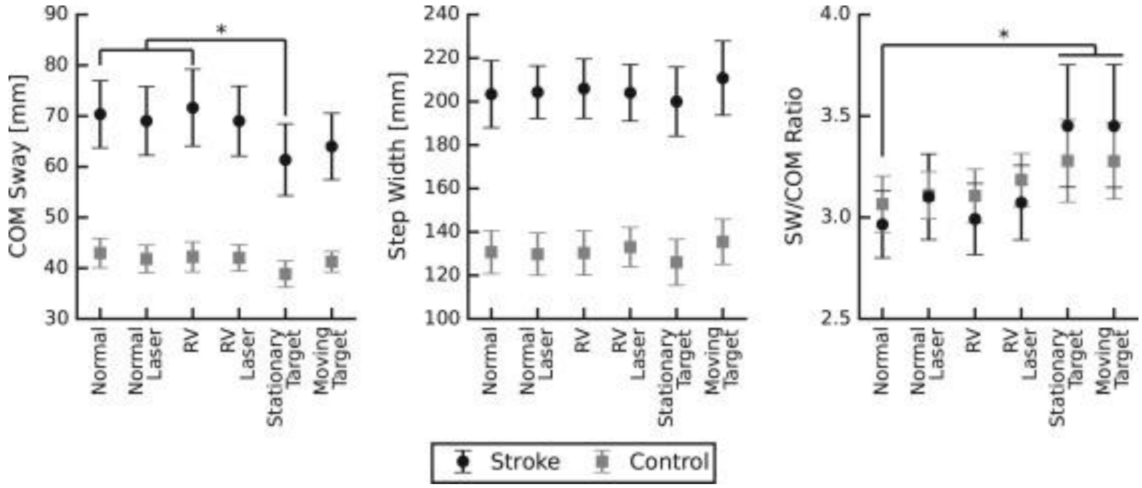

Fig. 2. Effect of testing condition on COM sway and step width. Group average (±standard error) for each testing condition. Significant reductions in COM sway were observed in the stroke group for the stationary target condition compared to normal and reduced visual feedback (RV) trials without the laser (*post-hoc, $p<0.05$).

The SW/COM ratio provided insight into the frontal plane balance strategy by relating the base of support to the COM range of movement across the gait cycle. This ratio was significantly altered by testing condition ($p=0.002$), with larger values observed during stationary (post-hoc, $p=0.025$) and moving (post-hoc, $p=0.041$) target trials compared to baseline walking (Fig. 2). Larger ratios might indicate a more conservative balance strategy, with a larger base of support chosen for a given amount of COM movement. However, no significant changes in step width (Fig. 2) or frontal plane foot placement (Fig. 3) were observed across conditions, indicating that changes in this ratio were mainly influenced by COM sway. The change in this ratio from baseline walking to the stationary target condition correlated with lower extremity Fugl-Meyer score ($r=0.777$, $p=0.004$) and self-selected overground walking speeds ($r=0.554$, $p=0.048$) (Fig. 4). As lower extremity Fugl-Meyer scores and walking speeds increased, individuals demonstrated larger increases in this ratio.

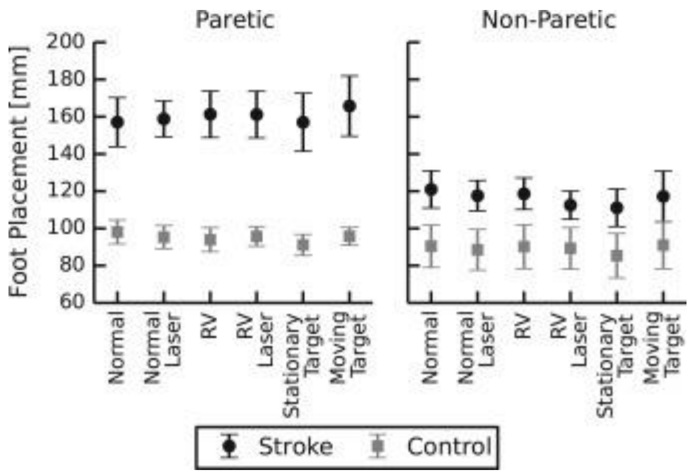

Fig. 3. Frontal plane foot placement across testing conditions. Average (±standard error) frontal plane foot placement location relative to pelvis COM at heel strike for paretic and non-paretic limbs, and test and non-test limbs in controls. Stroke participants placed the paretic foot more lateral to the pelvis than controls. The stroke group tended to maintain paretic limb foot placement location across all conditions, compared to reductions during the stationary target condition for the non-paretic, and both limbs in the control group.

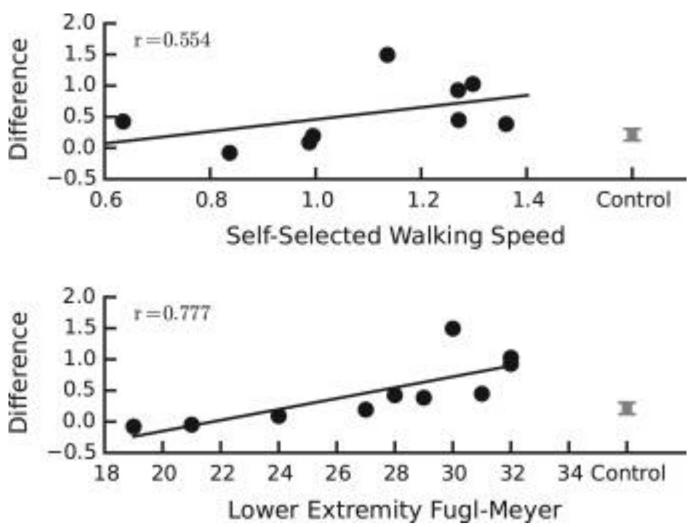

Fig. 4. Change of stationary targeting SW/COM ratio from baseline correlates with clinical measures. The change in the SW/COM ratio in the stationary targeting task from baseline correlated with self-selected walking velocity and lower extremity Fugl-Meyer score. Individuals with higher lower extremity Fugl-Meyer scores and walking speeds were better able to increase the SW/COM ratio by making larger reductions to COM sway while minimally altering step width.

3.2. Handrail forces

In general, stroke participants applied lateral and downward forces with the non-paretic hand when the paretic limb was in single limb support, and control participants maintained a relatively consistent low force level throughout the gait cycle. Group differences were observed in the vertical force (p=0.015), but not for the medial–lateral (p=0.229) or anterior–posterior (p=0.301) forces. No significant main effect of condition or group by condition interaction effect was observed for any of the forces, indicating handrail use was consistent across testing conditions.

3.3. Spatio-temporal measures

Gait cycle duration decreased in both groups during the moving target trial compared to normal walking with (p=0.005) and without (p=0.014) the laser, reduced visual feedback without the laser (p=0.015), and stationary target (p=0.005) trials. Cadence increased during the moving target trial compared to normal walking with the laser (p=0.003) and reduced visual feedback without the laser (p=0.003). Coupled with these temporal changes, a main effect of condition was observed for paretic (p=0.035) and non-paretic (p=0.001) step lengths, with significant reductions during the moving target condition relative to the other conditions (post-hoc, p<0.05) only for the non-paretic (non-test) leg. No significant interaction effect of group and testing condition was observed in any of the spatio-temporal measures.

4. Discussion

The results of this study demonstrate that stroke survivors were able to utilize visual feedback signals to modify dynamic balance control during walking. This effect was task specific, requiring the presence of a stationary target to produce significant decreases in COM sway. This reduction in COM sway increased the SW/COM ratio, with the change correlating with clinical measures of walking speed and sensorimotor recovery. Additionally, although stroke survivors walked with greater movement of the COM and larger step widths, the ratio between these measures was similar between groups. These results support our initial hypothesis that providing visual feedback of trunk movement can help stroke survivors reduce COM sway.

Visual feedback supplied by a head mounted laser provides a potential mechanism to improve COM control post-stroke. This visual cue may have had a larger impact in the stroke group due to an increased reliance on visual feedback for balance control post-stroke (Marigold and Eng, 2006a). In addition, the laser provided feedback of body movement during walking, which might be used to compensate for impaired sense of trunk position (Ryerson et al., 2008). Providing additional feedback of trunk movement through multiple sensory modalities reduces sway during standing (Huffman et al., 2010) and walking (Verhoeff et al., 2009) in young adults. In our study, the control group trended towards decreased COM sway during the stationary target task, but these changes were not significant. Due to increased baseline COM sway in the stroke group, it is unclear if the lack of significant changes in the control group represents an increased reliance on visual feedback for dynamic balance control post-stroke, of if the stationary targeting task was more difficult in stroke survivors than controls because of higher baseline sway.

The effectiveness of laser feedback was dependent on the context of the task. Simply turning on the laser during walking, while providing visual cues related to body movement in space, did not provide the appropriate context for the visual cue to have a significant impact on COM sway. While the addition of laser feedback to the normal walking and reduced vision conditions slightly decreased COM sway relative to the no laser conditions, these decreases were not statistically significant. Decreased COM sway was also observed in the moving target condition post-stroke, however the additional body movement necessary to track the target likely contributed to the lack of significance in when compared to normal walking. Coupling the laser feedback with a stationary target provided the necessary visual context for the laser feedback to significantly reduce COM sway during walking.

Analysis of changes in the SW/COM ratio provided insight into the overall balance control strategy in response to altered visual feedback conditions. Both groups increased this ratio during the targeting conditions, potentially representing the selection of a more conservative walking pattern to reduce fall risk. However, no significant changes in step width were observed for either group, suggesting changes in the SW/COM ratio were driven by reductions in

COM sway. The stroke group had larger increases in the SW/COM ratio during the stationary target condition, with this change positively correlated with the lower extremity Fugl-Meyer score and self-selected overground walking speed. Higher functioning participants increased SW/COM ratio by lowering COM sway, while keeping step width relatively consistent. However, lower functioning participants made smaller reductions in COM sway, which were often coupled with similar step width reductions, producing no net change in the SW/COM ratio. The differences in these responses suggests an inability of more impaired participants to decouple COM sway and step width in order to adapt COM movement to the task demands, which may also explain increased fall incidence. This reduced control may bias stroke subjects towards selection of a more conservative dynamic balance strategy, such as wider step widths, to reduce the risk of falls.

Interestingly, despite baseline differences in step width and COM sway, the ratio of these parameters was preserved after stroke. Step width and frontal plane COM movement are strongly associated by both the biomechanics of walking and the balance control strategy, making it difficult to determine which factor drove the observed baseline differences. Increased COM sway could be due to deficits in control of COM movement (Marigold and Eng, 2006b), or due to slower walking speeds post-stroke (Orendurff et al., 2004). However, we do not attribute increased COM movement solely to slower walking speeds post-stroke, since larger step widths were observed when walking speeds are matched between groups (Chen et al., 2005). This presence of increased step width at matched walking speeds suggests that increases in COM sway post-stroke could be driven by a desire to walk with a wider step width. While walking with a wider step width has been shown to be less energy efficient (Donelan et al., 2001), there may also be negative balance implications for stroke survivors. Wider step widths reduce the muscle activity needed to redirect COM movement in standing (Henry et al., 2001), but neural feedback gains must be adjusted to maintain stability (Bingham et al., 2011). Increased muscle activation latencies in the paretic limb (Kirker et al., 2000) potentially limit the ability of the underlying neural control to maintain stability at wider step widths, which could explain the increased incidence of falls despite a wider step width post-stroke.

Given the complex nature of dynamic balance control during walking, additional outside factors may be influencing our measures. The handrail hold, while ensuring participant safety, would also provide both a touch cue and potential stabilizing force during walking. Although stroke survivors produced more downward force than controls, the stabilizing influence of the handrail was consistent across testing conditions, with no significant differences between conditions in either group. Another potential confounding factor is differences in walking speed between groups, which would impact COM movement (Orendurff et al., 2004). Dynamic balance control was assessed at the participant's self-selected speed to avoid additional confounds when requiring one group to walk faster or slower than their comfortable speed. However, the fastest walking stroke survivor (S208) and slowest walking control participant (C206) had the same treadmill speed. In this speed-matched pair, the stroke participant still had larger amounts of COM sway (77.34 mm versus 44.56 mm), suggesting stroke-related changes in COM control.

Taken together, these results provide further insight into walking balance control post-stroke. Interestingly, chronic stroke survivors maintain a similar ratio between COM movement and step width, but walk with greater baseline levels of both variables compared to neurologically intact individuals. While previous studies have demonstrated an increased reliance on visual feedback for standing balance control post-stroke, we have demonstrated that visual feedback of body movement coupled with a stationary reference point improved frontal plane COM control during walking in chronic stroke survivors. Further research into the mechanisms and delivery of this augmented visual feedback signal is necessary to translate this technique to the clinical as a therapeutic approach to improve dynamic balance control post-stroke. Specifically, future work is needed to evaluate if similar COM control improvements are observed when the laser feedback signal is used with visual cues in a real-world walking environment.

Conflict of interest statement

The authors have no known financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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