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A comparison of the effects of mediolateral surface and foot placement perturbations on balance control and response strategies during walking

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ABSTRACT

Background: Balance perturbation studies during walking have improved our understanding of balance control in various destabilizing conditions. However, it is unknown to what extent balance recovery strategies can be generalized across different types of mediolateral balance perturbations.

Research question: Do similar mediolateral perturbations (foot placement versus surface translation) have similar effects on balance control and corresponding balance response strategies?

Methods: Kinetic and kinematic data were previously collected during two separate studies, each with 15 young, healthy participants walking on an instrumented treadmill. In both studies, medial and lateral balance perturbations were applied at 80% of the gait cycle either by a treadmill surface translation or a pneumatic force applied to the swing foot. Differences in balance control (frontal plane whole body angular momentum) and balance response strategies (hip abduction moment, ankle inversion moment, center of pressure excursion and frontal plane trunk moment) between perturbed and unperturbed gait cycles were evaluated using statistical parametric mapping.

Results: Balance disruptions after foot placement perturbations were larger and sustained longer compared to surface translations. Changes in joint moment responses were also larger for the foot placement perturbations compared to the surface translation perturbations. Lateral hip, ankle, and trunk strategies were used to maintain balance after medial foot placement perturbations, while a trunk strategy was primarily used after surface translations.

Significance: Surface and foot placement perturbations influence balance control and corresponding response strategies differently. These results can help inform the development of perturbation-based balance training interventions aimed at reducing fall risk in clinical populations.

1. Introduction

Balance perturbations are often used to gain insight into the underlying mechanisms of balance control in both healthy and pathological populations. Previous work has shown humans are more sensitive to balance perturbations in the frontal plane compared to the sagittal plane [18,23,31]. A number of protocols have been used to induce balance disruptions, including treadmill surface or platform perturbations [3,15,17,28,31], forces applied to the pelvis [13,12,11], optical flow perturbations [23,29,35] and galvanic stimulation [30]. Maintaining balance requires full body coordination, as mediolateral balance perturbations can induce reactions at the hip and ankle [1,7,19,33] as well as the trunk muscles in response to mediolateral slips [25] and continuous optical flow perturbations [35]. While these studies have improved our understanding of balance control in various destabilizing environments, it is unknown whether the observed responses can be generalized across different perturbation types.

While some studies have directly compared the effects of perturbations occurring at different phases of the gait cycle [9,13,17] or perturbation direction and magnitude [23,24], there are few situations where the same balance response metrics are studied across different types of perturbations of the similar timing and magnitude. For example, comparison of pseudo-random mediolateral visual and mechanical perturbations suggests that while balance measures are more sensitive to mechanical than visual perturbations [36], as visual perturbations may be more cognitively demanding and evoke a response in a different part

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of the brain than mechanical perturbations [27]. Thus, visual and mechanical perturbations provide different approaches for evaluating balance responses. Similarly, mechanical perturbations such as altered mediolateral foot placement and surface translations are both intended to disrupt balance in the frontal plane, but may not yield the same balance responses.

Individuals control balance in the frontal plane by regulating whole-body angular momentum through the modulation of ground reaction forces and foot placement [8,10,20]. Mediolateral surface translations [1] and foot placement perturbations (e.g. [32]) use different mechanisms to disrupt balance control, as foot placement perturbations directly alter step width, while surface translations primarily affect ground reaction forces. Despite these differences, both perturbations may produce similar balance responses because both apply a force at the foot to produce a mediolateral balance disturbance. Lateral hip and ankle strategies have been observed following medial foot placement perturbations [7,19,33] while bilateral hip reactions were observed after mediolateral surface translations, presumably to alter foot position relative to the body center of mass [1]. Together, these responses modulate the external moment about the center of mass to control whole-body angular momentum. However, during mediolateral surface translations, some individuals allow their whole body to translate with the perturbation rather than attempting to keep their center of mass stationary [5]. This strategy is not possible during a foot placement perturbation. Thus, balance responses following surface translations would need to control the lateral momentum of the body as it suddenly starts and stops translating, while lateral ankle and hip strategies that modulate the external moment during rotational disturbances may not be necessary.

The purpose of this study was to identify the balance responses that occurred after two different mediolateral perturbations of similar timing and magnitude (foot placement perturbations and surface translations). We determined whether each perturbation produced changes in balance control, foot placement, and responses at the hip, ankle and trunk, with the overall goal of evaluating the specificity of the balance response to the type of perturbation. Because surface perturbations allow whole body translation over the foot while foot placement perturbations do not, we hypothesized that foot placement and surface translation perturbations of similar timing and magnitude would produce different balance response strategies.

2. Methods

2.1. Data collection

Data were previously collected during two separate studies. In each study, kinematic, kinetic, and electromyography (EMG) data were collected on an instrumented treadmill (Motek, Amsterdam, NL) from 15 young healthy adults (Surface Translation – age: 25 ± 4 years, mass: 69 ± 12 kg, 8 female/7male. Foot Placement Perturbation – age: 25 ± 3 years, mass: 67 ± 10 kg, 9 female/6 male). See Appendix Table A1 for complete participant characteristics. All participants provided written informed consent in compliance with the University of Texas at Austin Institutional Review Board. Kinematic data were collected at 120 Hz from a 10-camera motion capture system (Vicon, Oxford, UK) using identical full-body marker sets (56 reflective markers) for each study. Ground reaction forces (GRFs) were collected at 960 Hz. Participants performed all walking trials at their over-ground self-selected walking speed, which was determined from the average of three trials of a 10 m walk test.

2.2. Surface translation perturbations

A custom D-flow (Motek, Amsterdam, NL) script was developed to determine heel strike timing using the Zeni method [38]. The treadmill then performed one medial and one lateral 3.0 cm surface translation to the right leg in late stance during randomized gait cycles (Fig. 1). Perturbations were separated by at least four gait cycles. Each trial lasted between 24 and 34 s, with the average trial lasting 30 ± 3 s

2.3. Foot placement perturbations

As previously described [7], perturbations were produced using a custom-built pneumatic device that released compressed air medially or laterally at the left ankle during mid-swing of randomized gait cycles to perturb foot placement by approximately 3.5 cm from the unperturbed trajectory (Fig. 1). Perturbations were separated by at least five gait cycles. Each trial lasted between 28 and 42 s, with the average trial lasting 34 ± 4 s. Data for two medially- and two laterally-perturbed gait cycles were analyzed for each participant. Perturbed gait cycles were chosen from 10 trials collected at a self-selected walking speed. Out of these 10 trials, 9 included cognitive tasks. While these tasks had no effect on balance control or balance responses [34], they were excluded so that the number of trials in the foot placement group was consistent with the number of trials in the surface translation group.

2.3.1. Unperturbed gait cycles

Unperturbed gait cycles included any gait cycles that did not include a perturbation, were not a recovery step, and were not a crossover step. An average of 20.1 ± 2.5 and 22.2 ± 5.5 unperturbed gait cycles were recorded for participants in the surface translation group and foot placement perturbation group, respectively.

2.4. Data analysis

Kinematic and kinetic data were analyzed in Visual3D (C-Motion, Germantown, MD, USA). Marker data were low-pass filtered at 6 Hz and force plate data were low-pass filtered at 15 Hz with a 2nd order Butterworth filter. For trials containing surface translations, the inertial forces due to the treadmill accelerations were removed from the analog force signals using force data from unloaded surface translations and the mediolateral center of pressure (COP) location was shifted from the force plate to a lab reference frame. A 13-segment inverse dynamics

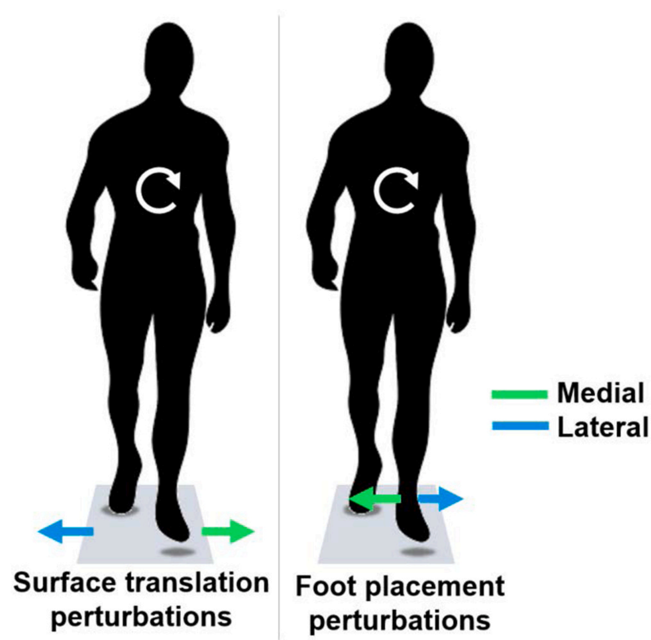

Fig. 1. Medial and lateral balance perturbations were produced by (A) treadmill surface translations and by (B) a pneumatic force applied to the ankle to alter foot placement approximately 180 ms before foot strike. Arrows indicate the direction of positive rotation in the lab reference frame.

model was created for each participant. Ankle and hip muscle joint moments were calculated in the shank and thigh coordinate systems, respectively. Trunk moments and whole-body angular momentum were calculated in the lab reference frame. Step width, defined as the lateral distance between right and left heel markers, was calculated at the first heel strike following the perturbation and the subsequent contralateral heel strike. Lateral COP positions were calculated relative to the foot COM during stance. Joint moments, whole-body angular momentum (*H*) and GRFs were normalized by each participant's mass and walking speed and were time normalized to 100% of the gait cycle.

2.5. Statistical analysis

Statistical tests evaluated whether there were differences in balance control and response strategies at the hip, ankle and trunk following each type of perturbation. The fastest balance responses after mediolateral perturbations during walking occur at the ankle with a latency of about 200 ms, while changes to foot placement are delayed by at least 300 ms [13]. Because the perturbations in this study were designed to occur only 180 ms before heel strike, balance responses were evaluated in the gait cycle after the perturbation. Statistical tests were performed during this period of interest, from left (ipsilateral) heel strike to left heel strike. Left single leg stance was especially of interest because it is a key time period to recover from balance perturbations (i.e., angular momentum is heightened during this time and instability is greater in clinical populations [22]).

Differences in continuous variables over time (frontal-plane whole-body angular momentum, ankle eversion moments, lateral COP position, frontal-plane trunk moment, hip abduction moment, frontal plane trunk moment) were assessed using one-dimensional statistical parametric mapping two-tailed paired t-tests (Pataky, 2012), which identified periods of the gait cycle where variables from medial or laterally perturbed gait cycles differed from the average of each participant's unperturbed gait cycles. For these tests, p-values are provided for each period of the gait cycle where time series data differs significantly from unperturbed signals. Likewise, paired two-tailed t-tests were used to assess differences in step width after perturbations relative to the average unperturbed step width. Changes in step width at the first (left) heel strike after the perturbation would show the effect of the perturbation itself, as that heel strike occurs too early for a balance response [13]. Changes in step width at the second (right) heel strike after the perturbation would characterize a stepping balance response. A Bonferroni correction was used to correct for multiple comparisons, resulting in a significance level of $\alpha = 0.025$. To assess whether subject demographics influenced differences in balance control and balance responses strategies between the two experiments, differences in participant age, walking speed, height, weight and normalized unperturbed peak-to-peak range of frontal plane whole-body angular momentum between the two groups of participants were evaluated using two-sample two-tailed t-tests assuming equal variances. All statistical analyses were performed in Matlab (Mathworks, Natick, MA, USA).

3. Results

There were no significant differences in participant age, height, mass, or walking speed, or unperturbed *H*-range between the surface perturbation and foot placement perturbation studies (Appendix A1). On average, surface and foot placement perturbations occurred at 83 ± 5% and 82 ± 2% of the ipsilateral gait cycle, respectively. Surface and foot placement perturbations occurred 185 ± 62 and 192 ± 27 ms before left heel strike.

3.1. Effect of Perturbations on Step width

Relative to the whole-body center of mass, the step immediately following the perturbation was unchanged after medial surface translations and 0.7 cm more narrow after lateral surface translations (Table 1, $p = 0.003$) compared to unperturbed steps. In contrast, step width was 3.3 cm more narrow after medial foot placement perturbations and 3.5 cm wider after lateral foot placement perturbations (Table 1, $p < 0.001$). The second step after medial foot placement perturbations was 0.6 cm wider than unperturbed steps ($p = 0.002$).

3.2. Balance control

After medial surface translations, the magnitude of frontal plane *H* increased briefly during the ipsilateral swing phase ($p = 0.0003$) and second double support ($p = 0.0001$) (Fig. 2A). After medial foot placement perturbations, the magnitude of frontal plane *H* increased during ipsilateral swing and double support ($p < 0.0001$) and during the second double support and ipsilateral swing phases ($p = 0.0032$) (Fig. 2B).

After lateral surface translations, the magnitude of frontal plane *H* decreased slightly during ipsilateral swing ($p = 0.0001$) (Fig. 2A). After lateral foot placement perturbations, the magnitude of frontal plane *H* decreased during ipsilateral swing and into double support ($p < 0.0001$), and also decreased slightly during the following contralateral foot stance phase ($p = 0.0085$) and ipsilateral swing ($p < 0.0001$) (Fig. 2B).

3.3. Lateral ankle strategy

After medial and lateral surface translations, there were no changes in ipsilateral ankle eversion moment (Fig. 3A) or COP excursion (Fig. 3B). After medial foot placement perturbations, there were no significant changes in ankle eversion moment (Fig. 3C), although the moment trended towards more inversion in single leg stance and COP excursion was more lateral ($p < 0.0001$) (Fig. 3D). After lateral foot placement perturbations, the ankle eversion moment was higher during single leg stance ($p < 0.0001$) (Fig. 3C) with more medial COP excursion ($p < 0.0001$) (Fig. 3D).

3.4. Lateral hip strategy

After medial surface translations, the stance leg hip abduction moment was slightly higher during first double support ($p < 0.0001$) (Fig. 4A). After medial foot placement perturbations, the hip abduction moment was lower during single leg stance ($p < 0.0001$) (Fig. 4B). There were no significant changes in hip abduction moment after lateral perturbations.

3.5. Trunk strategy

After medial surface translations, there were no significant changes to the frontal plane trunk moment, but the moment trended more negative (Fig. 5A). Likewise, after medial foot placement perturbations the trunk moment was more negative during single leg stance ($p = 0.0007$) (Fig. 5B), acting to rotate the trunk away from the perturbed leg in the same direction as the perturbation. After lateral surface

Table 1
Average step width relative to the center of mass for each type of perturbation during the left heel strike (LHS) and right heel strike (RHS) after the perturbation. '*' indicates a significant difference from unperturbed step width.

	Surface Translation Step Width (cm)		Foot Placement Step Width (cm)	
	Step 1 (LHS)	Step 2 (RHS)	Step 1 (LHS)	Step 2 (RHS)
Unperturbed	11.0 ± 2.8	-	8.0 ± 1.5	-
Medially Perturbed	10.7 ± 3.4	10.5 ± 3.1	4.6 ± 1.8 * ($p < 0.001$)	8.6 ± 1.9 * ($p = 0.002$)
Laterally Perturbed	10.3 ± 2.8* ($p = 0.003$)	11.1 ± 3.1	11.4 ± 1.6* ($p < 0.001$)	8.3 ± 2.1

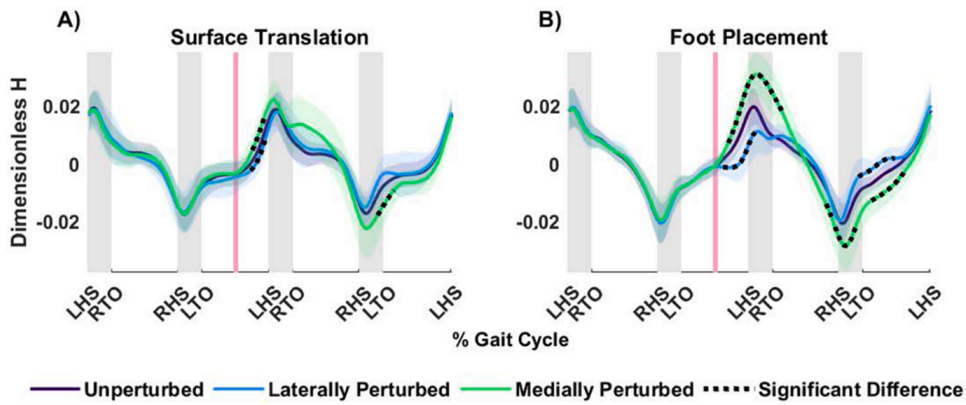

Fig. 2. Frontal plane whole-body angular momentum during unperturbed steps and after medial and lateral (A) surface and (B) foot placement perturbations. The vertical solid line indicates the timing of the perturbation. Dotted lines indicate a significant difference between the perturbed and unperturbed signals.

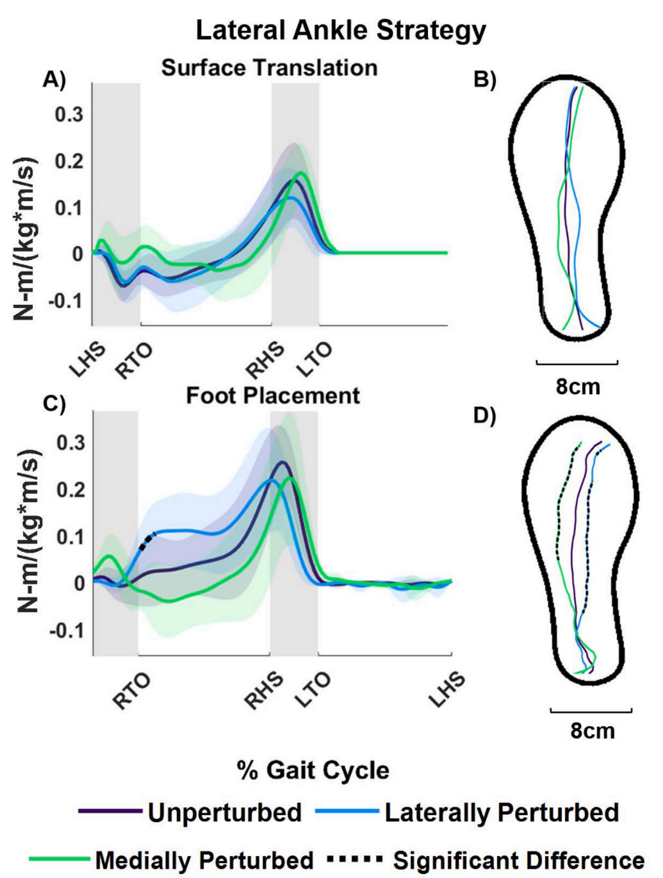

Fig. 3. Ankle eversion moment (left) and COP excursion (right) during unperturbed steps and after medial and lateral treadmill (top) and foot placement (bottom). The vertical line indicates the timing of the perturbation. Dotted lines indicate a significant difference between the perturbed and unperturbed signals.

translations, the trunk moment was less negative during single leg support ($p = 0.001$) (Fig. 5A), but there were no changes after lateral foot placement perturbations.

4. Discussion

The purpose of this study was to identify balance responses after two similar mediolateral balance perturbations to evaluate the specificity of the response strategies to the type of perturbation. Our hypothesis that different balance responses would result from each type of perturbation was supported.

Overall, the medial foot placement perturbations appeared to cause a greater disruption to balance control than the medial surface translations (Fig. 2) while lateral perturbations caused only minimal changes to balance control in both groups. A post-hoc analysis showed that relative to unperturbed steps, the peak-to-peak range of frontal-plane angular momentum increased by $57 \pm 26\%$ after foot placement perturbations but only $29 \pm 28\%$ after surface translations. The percentage increase of angular momentum after medial foot placement perturbations was greater than the increase in angular momentum after medial surface perturbations according to a two-sample t-test ($p = 0.007$), indicating that the foot placement perturbations were more disruptive to balance control. Foot placement perturbations were applied to the swing foot, which limited the body's linear translation due to the constraint of the stance foot on the ground and produced a change in frontal plane whole-body angular momentum about the COM. Increases in angular momentum, which were observed after medial foot placement perturbations, are linked to poor balance control [20]. Conversely, during surface translations, participants could translate their body linearly with the treadmill and limit changes in angular momentum (Table 1). These results are consistent with a previous investigation of mediolateral treadmill oscillations, where most participants allowed their COM to translate linearly during the perturbations while some participants remained fixed in space but allowed their body to rotate [5]. Greater rotational motion was associated with a reliance on visual over proprioceptive feedback [5]. Thus, these results may have implications for elderly adults who increasingly rely on visual input over other senses to control balance [26]. Future work should investigate how participants use sensory information to develop a balance response.

As previously noted [7], medial foot placement perturbations produce a decrease in hip abduction moment and a lateral shift of the COP caused by an ankle inversion moment. Lateral foot placement perturbations produce a medial COP shift due to an ankle eversion moment. However, in the present study no hip or ankle responses were observed following medial or lateral surface translations (Figs. 3 and 4). These results are consistent with previous work investigating lateral surface translations of a similar magnitude, where no gluteus medius response was observed after a lateral perturbation to the opposite leg during single leg stance [1]. As only minimal changes in angular momentum occurred following the surface translations, hip and ankle strategies were not needed to modulate the frontal plane external moment and restore balance control.

No changes in step width were observed after the surface translations. Previous work found that changes in angular momentum after mid-to-late stance surface perturbations were correlated with step width during the recovery gait cycle [14], but the smaller perturbations in the

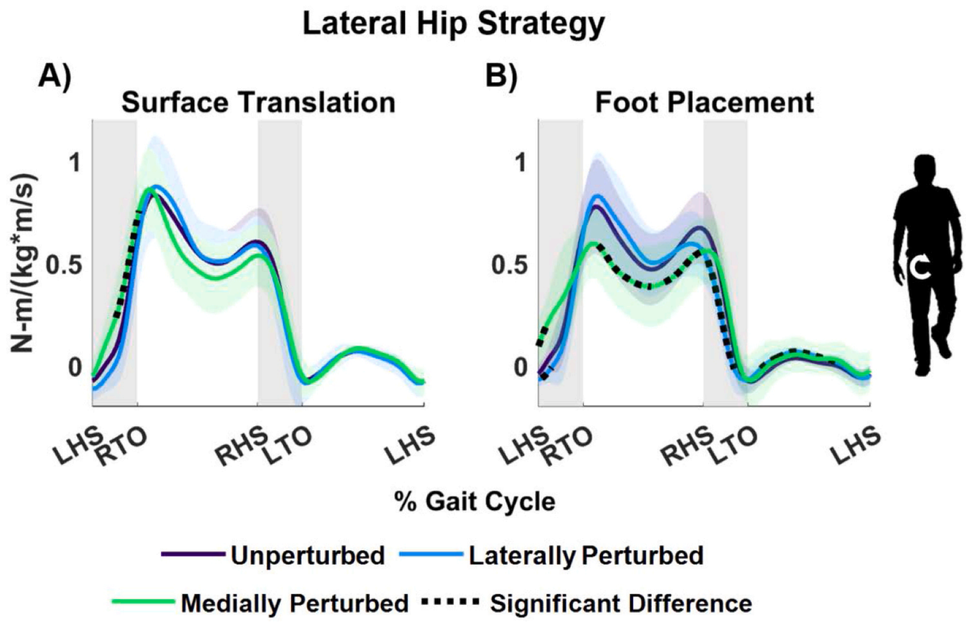

Fig. 4. Hip abduction moment during unperturbed steps and after medial and lateral (A) surface and (B) foot placement perturbations. Dotted lines indicate a significant difference between the perturbed and unperturbed moments.

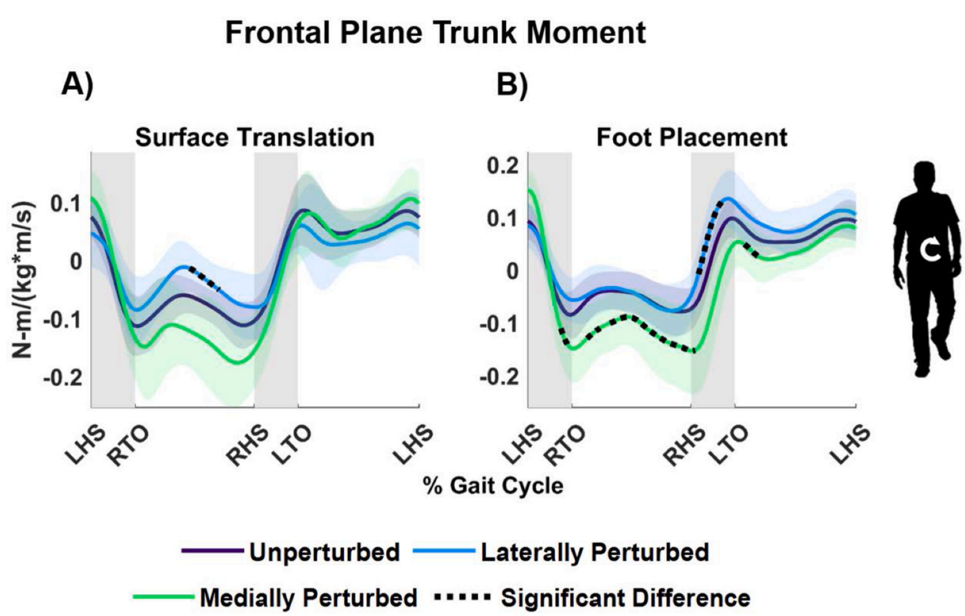

Fig. 5. The frontal plane moment between the trunk and pelvis segments in the trunk reference frame during unperturbed steps and after A) surface and B) foot placement perturbations. A moment rotating the trunk towards the left side of the body is positive. Dotted lines indicate a significant difference between the perturbed and unperturbed moments.

present study may not have necessitated a stepping response. Only medial foot placement perturbations, which caused the largest change in angular momentum, caused a slight increase in step width during the recovery gait cycle. For the other perturbations, it appears that ankle, hip, and/or trunk strategies were sufficient to address the balance disturbance and a change in step width was not required.

While lateral hip and ankle strategies are well-established responses to balance perturbations (e.g. [29]), upper body responses are not as well understood. A lack of trunk control has been shown to predict poor balance performance [37] and the trunk accounts for a large portion of whole-body angular momentum in the frontal plane [2,21]. In the present study, the trunk moment during single leg stance acted to rotate the trunk away from the perturbed leg, counteracting the increase in angular momentum towards the perturbed side following medial foot placement perturbations (Figs. 2 and 5). This same trend was observed after medial surface translations but was not significant. No change in trunk moment occurred after lateral foot placement perturbations, which were not detrimental to balance control. These results are consistent with previous work showing that upper body contributions to balance control, which complemented hip and ankle strategies, increased as the difficulty of the balance task increased (i.e. participants walked on narrower beams) [4]. We also found that trunk muscles contribute to changes in step width after foot placement perturbations [6]. Interestingly, despite the limited effect of surface translations on whole-body angular momentum, the trunk moment was less negative after lateral surface translations and trended more negative after medial surface translations during single leg stance. These responses likely occurred because after the surface translations, the trunk continues to move in the direction of the perturbation. This movement elicits a moment in the opposite direction to counteract that motion. These results highlight the important role of the trunk in balance control regardless of the type of perturbation.

The primary limitation of this study is that different subjects participated in the foot placement and treadmill surface perturbation studies, and therefore within-subject comparisons could not be made. However, because there were no significant differences in age, height, mass, walking speed or baseline balance control between the two groups, we believe both groups used balance response strategies representative of healthy young adults. While there was a difference in unperturbed step width between the groups, we do not believe these step width differences would substantially affect our primary conclusions. Another limitation is the small sample size of perturbed steps. However, despite the limited number of steps analyzed, we observed clear trends in balance responses. Moreover, we studied perturbations during single leg stance due to the high magnitude of angular momentum and the instability of clinical populations during that time [22], but these results may not generalize to balance perturbations that occur elsewhere in the gait cycle, such as those earlier in the gait cycle that allow more time for a stepping response [14]. Another limitation is that the foot placement perturbation magnitudes were on average 3.5 cm, while the surface translations were only 3.0 cm. However, it is unlikely that an additional 0.5 cm of translation from surface translations would significantly alter our results. Finally, we have attempted to design perturbations that could occur during real-world situations, such as errors in foot placement while navigating a crowded path or the unsteady surface of a moving bus. However, these balance perturbations may not successfully emulate real-world situations, as evidenced by the difficulty in translating perturbation-based training to a real-world fall reduction [16]. Thus, more work is needed to determine how individuals incorporate sensory information to maintain balance on natural terrain and in the presence of unexpected perturbations.

In summary, the effects of a medial surface perturbation in late stance were less disruptive to balance than medial foot placement perturbations, while lateral perturbations did not disrupt balance in either group. Although both types of perturbations had similar timing and magnitude, mediolateral surface translations allowed the whole body to translate with the platform, while the foot placement perturbations resulted in a whole-body rotational effect. Lateral hip, ankle, and trunk strategies were used to maintain balance after medial foot placement perturbations, while a trunk strategy was primarily used after surface translations. These results have implications for developing perturbation-based balance training interventions, as treadmill surface perturbations may not produce the desired responses strategies to help reduce fall risk in clinical populations.

CRediT authorship contribution statement

Lydia G. Brough: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Richard R. Neptune:** Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

There is no conflict of interest regarding the publication of this manuscript.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.12.018.

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