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Short communication

Regulation of whole-body frontal plane balance varies within a step during unperturbed walking

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ABSTRACT

This study sought to determine whether the need to actively control lateral balance is consistent within a step. Variability of the frontal plane COM-Ankle angle was calculated over 50 strides at discrete gait events for twenty-one healthy young adults to quantify active control of lateral balance within a step. Frontal plane COM-Ankle angle variability was found to vary significantly between all gait events, decreasing progressively within a step. This suggests that active control of lateral balance varies significantly within a step and that the greatest degree of active control occurs at heel-strike. The increased active control of lateral balance during heel-strike indicates a degree of preparation to ensure sufficient lateral balance control prior to more challenging events. These results provide insight into the mechanisms of lateral balance control and how to assess and treat locomotor balance control impairments.

1. Introduction

Balance control is critical for successful bipedal locomotion [1]. Its maintenance in the medial-lateral direction is reported to require greater active control than movements in the sagittal plane [2,3]. Step width variability is frequently used to assess the control of lateral balance during locomotion [2,4–8]. In these studies, step width variability decreased when subjects walked with supplementary lateral assistance (i.e. canes), and increased when these were removed or additional challenges were introduced (i.e. decreased afferent feedback). This suggests that decreased step width variability signifies a reduced need to actively control lateral balance, while an increase indicates a greater need to actively control lateral balance.

While these results demonstrate that differences in step width variability indicate the extent to which active control of lateral balance is required, step width does not change within a step. This restricts balance control evaluation to step-to-step behavior, ignoring a number of strategies that can be used within a step to maintain lateral balance [9]. The consistency with which lateral balance is actively controlled within a step remains unknown. The potential exists to increase the resolution with which lateral balance control is assessed, and improve our understanding of how balance control is affected by locomotor impairments, altering how interventions are designed and evaluated.

The purpose of this study was to determine whether active control of lateral balance is consistent within a step. The frontal plane COM-Ankle angle [10] was used to quantify lateral balance within a step. This metric describes lateral foot placement with respect to whole-body center-of-mass (COM), a key determinant of lateral balance control [9,11]. We hypothesized that the need to actively control lateral balance would vary within a step, as evidenced by significant differences in frontal plane COM-Ankle angle variability (SD) at discrete points within a step.

2. Methods

2.1. Participants

Inclusion criteria were age between 18 and 50, and the ability to walk continuously for 20 min on a treadmill without assistance. Exclusion criteria were self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions. All protocols were approved by Institutional Review Boards. Written informed consent was obtained prior to enrollment. Demographics including age, height, weight, gender, self-selected walking speed (SSWS) and limb dominance [12] were recorded.

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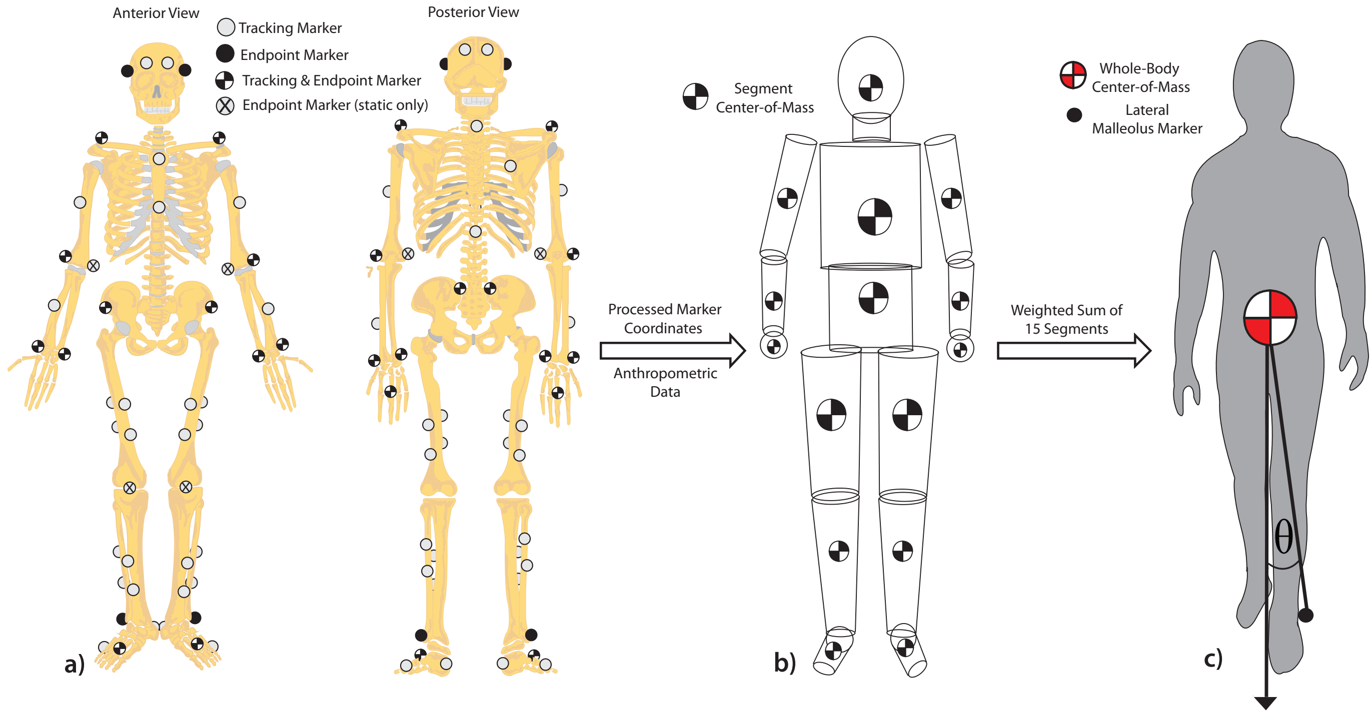

Fig. 1. (a) Whole-body marker set. (b) Processed marker coordinates and anthropometric data were combined to build a 15-segment whole body model. The feet, shanks, thighs, upper arms, and forearms were modeled as cones; the pelvis and thorax/abdomen were modeled as cylinders; the head/neck and hands were modeled as an ellipsoid and spheres, respectively. (c) Whole-body COM position was estimated from the weighted sum of all 15 body segments and used in conjunction with the lateral malleolus position to calculate the frontal plane COM-Ankle inclination angle.

Table 1
Participant characteristics.

	Height (m)	Weight (kg)	Age (years)	Gender[a]	SSWS (m/s)	Dominant leg[b]
Mean (SD)	1.73 (0.11)	70 (14)	31 (7)	11 M, 10 F	1.52 (0.12)	19 R, 2 L
Range	1.58–1.91	49–103	24–50		1.23–1.67	

[a] M: male; F: female.
[b] R: right; L: left.

2.2. Experimental protocol

Fifty-seven reflective markers were placed on participants' bony landmarks (Fig. 1A). Participants walked at a speed of 0.7 m/s on a Bertec split-belt instrumented treadmill (Bertec, Columbus, OH), calibrated with a published technique [13]. Following 15 min of treadmill acclimation [14], 50 consecutive strides of marker coordinate data were collected (120 Hz) using a 12 camera motion-capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from treadmill force platforms (1200 Hz).

2.3. Data processing

Marker coordinates were filtered (4th order Butterworth, 6 Hz low-pass cut-off) [15] and combined with anthropometric data adapted from Dempster [15] to build a 15 segment whole-body model (Fig. 1B) in Visual 3D (C-Motion, Germantown, MD). Whole-body COM position was calculated using the weighted sum approach. Using custom MATLAB™ (MathWorks, Natick, MA) code the frontal plane COM-Ankle angle [10] was calculated for all frames of data as the angle between a line connecting the whole-body COM to the ankle marker and a vertical line through the whole-body COM (Fig. 1C). Discrete values were then obtained from the 50 recorded strides at pre-defined gait events within a step. In chronological order these included ipsilateral heel-strike, peak medial-lateral COM velocity (pCOMV), contralateral toe-off and ipsilateral mid-stance. Timing of each gait event was obtained from processed GRF data (4th order Butterworth, 25 Hz low-pass cut-off) in Visual 3D, with the exception of the pCOMV which was identified as the maximum medial-lateral whole-body COM velocity per step [16]. The standard deviation (SD) of frontal plane COM-Ankle angle was calculated for each gait event, across all 50 strides, for each participant. Metric variability (SD) was used to infer the extent to which lateral balance was actively controlled [2,4–8] during each gait event.

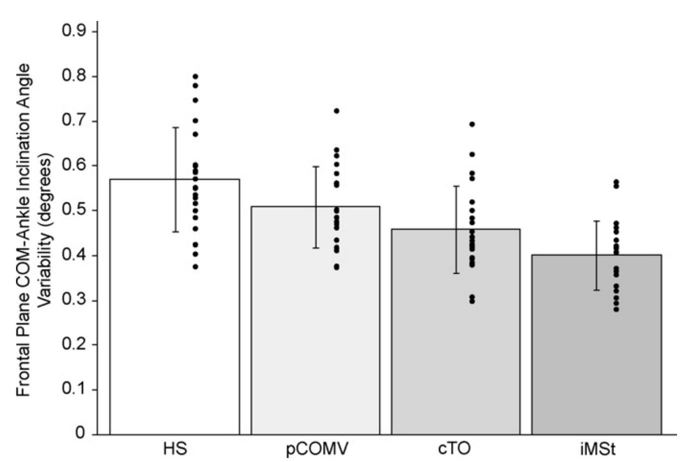

Fig. 2. Level of active control of lateral balance throughout a step. Bars represent the average variability (SD) of the frontal plane COM-Ankle inclination angle at each gait event. Dots represent individual subject variability (SD) of the frontal plane COM-Ankle inclination angle. Active control of lateral balance decreased significantly between each gait event ($p < 0.001$) (HS: heel-strike; pCOMV: peak COM-ML velocity; cTO: contralateral toe-off; iMSt: ipsilateral mid-stance).

2.4. Statistical analysis

Repeated measures ANOVA (SPSS Inc., Chicago IL) was performed to identify differences in frontal plane COM-Ankle angle variability between gait events. When main effects were significant, the two-tailed α-level (0.025) was adjusted for multiple comparisons (six comparisons) using a Bonferroni correction (adjusted $\alpha = 0.0042$).

3. Results

Twenty-one healthy adults participated in the study (Table 1). Results for the dominant and non-dominant legs were equivalent; therefore only dominant leg data are presented. Frontal plane COM-Ankle angle variability differed significantly between all gait events ($p < 0.001$) (Fig. 2), being greatest at heel-strike and decreasing progressively during a step (Fig. 2).

4. Discussion and conclusions

This study sought to determine whether the need to actively control lateral balance is consistent within a step. The frontal plane COM-Ankle angle variability, used to infer the degree of active control, was found to vary significantly between all gait events, decreasing progressively within a step (Fig. 2). Previous studies [2,4–8], have interpreted increased metric variability to indicate greater active control of lateral balance. Our findings suggest that active control over lateral balance varies significantly within a step, with the greatest degree of active control at heel-strike. This supports previous findings that heel-strike was the most critical point for maintaining lateral balance control during gait [9]. Rather than merely controlling lateral movements during weight acceptance, greater active control of lateral balance at heel-strike may reflect preparation to ensure adequate lateral balance prior to upcoming gait events which challenge balance control (i.e. pCOMV). This would reduce the need to maintain a high degree of active control later in stance when balance control strategies are less efficient [3,9].

These results directly impact the assessment and treatment of locomotor balance control impairments. Assessing locomotor balance control within a step may help detect phase specific impairments, and provide more specific interventions. For example, excessive active control of lateral movements at heel-strike may signify difficulty generating corrective frontal plane moments during stance. Alternatively, increased active control of lateral balance after heel-strike may indicate ineffective foot placement strategies. Interventions could be tailored to address phase-specific impairment(s) with the expectation of restoring active lateral balance control within a step to unimpaired levels. Lack of visual flow during treadmill walking and slow walking speed may have influenced the results; however the acclimation period was intended to reduce such limitations.

Our results suggest that active control of lateral balance varies within a step. These findings are important for the assessment and treatment of balance control impairments.

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Conflict of interest statement

The authors attest to having no conflict of interest regarding this submitted work.

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