Journal of Biomechanics 49 (2016) 2734–2740

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
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Balance and recovery on coronally-uneven and unpredictable terrain

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ARTICLE INFO

Article history:
Accepted 7 June 2016

Keywords:
Uneven terrain
Unpredictable terrain
Balance recovery
Angular momentum
Angular impulse

ABSTRACT

Stepping on coronally-uneven and unpredictable terrain is a common gait disturbance that can lead to injurious falls. This study identified the biomechanical response to a step on coronally-uneven and unpredictable terrain through observation of participants traversing a walkway with a middle step that could be blinded to participants, and positioned either 15° inverted, 15° everted, or flush. The isolated disturbance was intended to simulate stepping on a rock, object, or other transient coronal disturbance and allow for observation of the subsequent balance recovery. Gait balance was affected by the disturbance, and was measured by the range of coronal whole-body angular momentum, which compared to unblinded flush, increased during blinded eversion, and decreased during blinded inversion. Analysis of external coronal moments applied to the body about the center-of-mass by the disturbed and recovery legs suggested the disturbed leg contributed more to differences in the range of coronal angular momentum, and thus more to balance recovery. The stepping strategy for the disturbed and recovery steps was measured by mediolateral foot position, and appeared to have been mostly affected by anticipatory actions taken by participants before stepping on the blinded terrain, and not by the terrain angle. In contrast, on the disturbed step, distinct differences between blinded inversion and eversion in the coronal moments of the hip and ankle suggested the hip and ankle joint moment strategies were important for adapting to the terrain angle. A clinical implication of this result was interventions that augment these moments may improve gait balance control on coronally-uneven and unpredictable terrain.

1. Introduction

The majority of U.S. adult falls occur during walking and are usually caused by extrinsic factors such as uneven terrain (Finlayson and Peterson, 2010; Li et al., 2006; Niino et al., 2000). When uneven terrain is obscured (e.g., low light, plant cover) it becomes unpredictable (Bauby and Kuo, 2000; Marigold and Patla, 2008). Uneven and unpredictable terrain are common in the outdoors where falls are three times as likely to cause injury (CDC, 2015; Kelsey et al., 2012), and one of four outdoor falls occur in the coronal plane (Li et al., 2006). Despite the prevalence and consequences of coronal falls, the dynamics of gait on coronally-uneven and unpredictable terrain are not fully understood.

Balance is often measured by metrics related to coronal plane whole-body system dynamics. Step width variability (Owings and Grabiner, 2004), lateral margin between whole-body center of mass (COM) and base of support (Hof et al., 2007), coronal angle between whole-body COM and center of pressure (Chen and Chou, 2010), and range of whole-body coronal angular momentum (RCAM) (Silverman and Neptune, 2011) are metrics that can differentiate between stable and unstable walkers. These metrics can also measure the effects of gait pathologies or experimental gait disturbances (Hof et al., 2010; McAndrew et al., 2010; Segal and Klute, 2014; Vistamehr et al., 2014). An insightful measure to assess coronal plane gait balance is coronal angular momentum because it is thought to be highly regulated by the nervous system (Herr and Popovic, 2008) and related to Clinical Test of Sensory Organization and Balance and Tinetti Balance Test outcomes (Allum et al., 2001).

Three coronal plane strategies that may aid balance during normal and disturbed gait involve the ankle (inversion/eversion), the hip (abduction/adduction), and stepping (mediolateral foot placement) (MacKinnon and Winter, 1993). Activation of the peroneus longus and

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http://dx.doi.org/10.1016/j.jbiomech.2016.06.014
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brevis muscles, which produce eversion moments about the ankle, has been observed during unexpected inversion (Nieuwenhuijzen and Duysens, 2007; Linford et al., 2006). Lateral translational disturbances applied to the base of support have evoked the use of hip and stepping strategies, evidenced by alterations in trunk angle and step width (McAndrew et al., 2010; Oddsson et al., 2004). The mediolateral stepping strategy, in which foot placement is adjusted over a succession of steps, has been observed during walking on unpredictable terrain and after an induced error in foot placement (Thies et al., 2007; Segal and Klute, 2014). The relative importance of these biomechanical strategies in balance recovery after a step on an uneven surface remains unknown.

The purpose of this study was to identify the biomechanical response to a step on coronally-uneven and unpredictable terrain. A novel experimental method was used to blind healthy adults walking to three different terrain conditions: 15° inverted, 15° everted, or flush. Coronal angular momentum, ankle and hip joint coronal moments over stance, and mediolateral foot placement were measured for undisturbed, disturbed, and recovery steps. These observations were used to determine the relative contributions of the ankle, hip, and stepping strategies during balance recovery.

2. Methods

2.1. Participants

Ten healthy adults (9 male, age: 44.0 ± 18.7 years, height: 1.74 ± 0.11 m, mass: 76.3 ± 15.1 kg, walking speed: 1.2 ± 0.1 m/sec) with no self-reported musculoskeletal or gait disorders completed the protocol. The governing Institutional Review Boards approved the study procedures and all participants provided informed consent.

2.2. Instrumentation

A custom walkway with handrails (length: 6.0 m, width: 1.5 m) was constructed with five embedded force plates to capture ground reaction forces (GRFs) and centers of pressure (COPs) which were applied to a whole-body model (Winter, 2009). The outermost plates (model BP400600, AMTI, Watertown, USA) were static and flush with the floor, while the center plate (model 9286AA, Kistler, Winterthur, CHE) provided the disturbance. The center plate could be rigidly positioned flush with the walkway or in a 15° inverted or 15° everted position (Fig. 1). Calibration confirmed minimal GRF and COP errors in all coordinate directions (root mean squared error < 10 N for GRF, and < 3 mm for COP) (Collins et al., 2009a). GRFs and COPs of the portable force plate for each position were transformed to be relative to the global coordinate system.

The condition of the disturbance was blinded (visually obscured) to participants by a 0.5 mm opaque latex cover that had negligible stiffness. The ± 15° angle of the force plate was chosen to maximize the observable effect of the disturbance while minimizing risk to participants. Similar magnitude inversions and eversions have been used without injury in a prior study (Curtze et al., 2011) whereas greater angles (i.e., 30° inversion) have been used to study ankle sprains (Linford et al., 2006). The single step on coronally-uneven and unpredictable terrain was intended to simulate stepping on a rock, small object, or other coronal plane disturbance and then allow observation of balance recovery, as opposed to observation of the steady-state behavior of cross-slope walking.

A 12-camera MX motion capture system (Vicon Motion Systems, Oxford, GBR) recorded marker trajectories at 120 Hz and force plate data at 1200 Hz. A digital, 4th order, low-pass Butterworth filter was applied with cutoff frequencies of 25 Hz for kinetic data and 6 Hz for kinematic data.

2.3. Whole-body model

A 15-segment, modified Plug-In Gait (Vicon Motion Systems Ltd, Oxford, GBR) (Ferrari et al., 2008), whole-body model was developed in Visual 3D (C-Motion, Germantown, USA). Head and hands were modeled as ellipsoids, the pelvis as a cylinder, and all other segments as truncated cones. Seventy-one spherical, 14 mm diameter markers tracked body segments. Modifications to the standard Plug-In Gait model included tracking of the femur and humerus with marker clusters (Cappozzo et al., 1997), tracking of the shank with markers on the tibial tuberosity and fibular head, and a marker on the humerus medial epicondyle. Hip joint centers were calculated based on regression equations (Bell et al., 1990) using the inter-ASIS (anterior superior iliac spine) distance of the pelvis.

2.4. Protocol

Trials consisted of participants walking at their self-selected speed after being fit with appropriately sized, study-provided, walking shoes (model M577, New Balance, Boston, USA) across the walkway and stepping on the disturbance with their dominant foot. Side dominance was determined by asking participants which foot they used to kick a ball. The first set of trials were unblinded and performed in the flush, inverted, and everted condition, five times each, in the listed order. Before each unblinded condition, participants walked across the walkway a few times to establish familiarity and proper foot positioning. For blinded trials, the opaque cover was installed and the disturbance condition was switched in a random order between each trial while participants waited in a separate room. This process was repeated ~15 times, five times for each condition of the disturbance (flush,

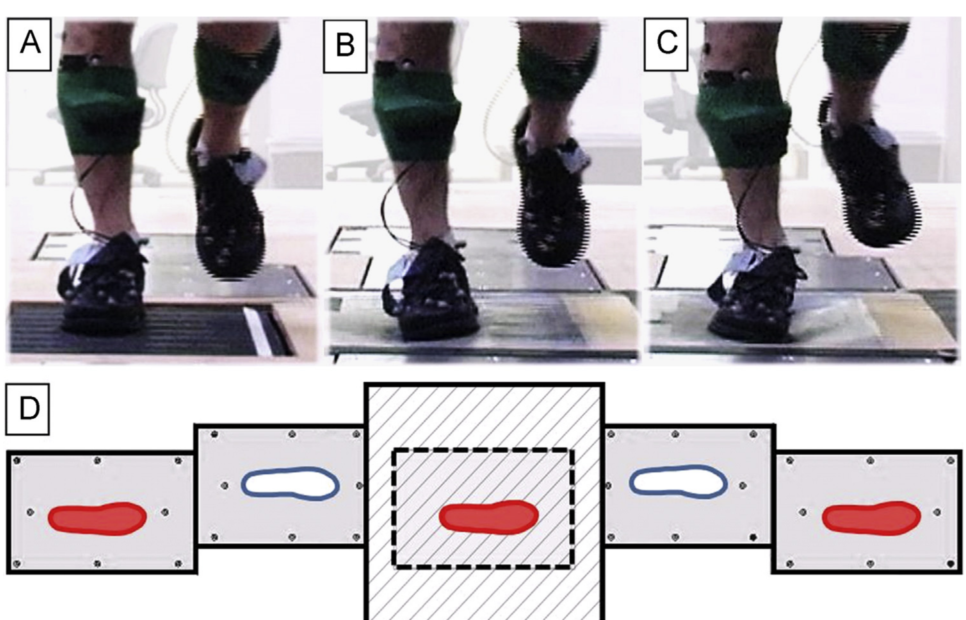

Fig. 1. Experimental setup for a right foot dominant participant. Interaction with disturbance device in three conditions: (A) unblinded flush, (B) blinded inversion, and (C) blinded eversion, (D) top view of the walk way showing the disturbance device (dashed-rectangle), static force plates (solid-rectangles), and footprints of the disturbed (filled) and recovery (outlined) legs. For blinded trials, an opaque membrane was installed in the cross-hatched area.

inverted, and everted). Only trials with single foot contact were included in the analysis. Unblinded flush served as the baseline condition for undisturbed gait and comparison with blinded inversion and blinded eversion conditions. Blinded flush was used post-hoc to aide in blinding effect interpretation.

2.5. Analysis metrics

Gait balance was measured by RCAM. Whole-body coronal angular momentum was calculated as the sum of the coronal angular momentum of each segment about the whole-body COM relative to the longitudinal axis of the lab (parallel with the travel direction of participants) and normalized to body height, mass, and walking speed (Silverman and Neptune, 2011). To capture the full RCAM induced by the transient disturbance, the range was calculated between mid-stance of the lead-in step, and mid-stance of the recovery step. This time period is referred to as the disturbance gait period.

Differences in the external coronal angular impulses (CAI) (Kobayashi et al., 2014) of each leg were used to determine their roles during the disturbed gait period. The external CAIs were calculated as the time integral of the external coronal moment (normalized to body mass) each leg imparted on the whole-body COM (Eq. (1)). For each trial, the external CAI integration bounds corresponded to the maximum and minimum values of coronal angular momentum (Fig. 2). If either leg was used to adapt to the terrain, its external CAI would differ between conditions. Additionally, the magnitude of each leg's external CAI would determine its relative contribution to the RCAM (Eq. (1)),

$$CAM|_{t1}^{t2} = \int_{t1}^{t2} M_{EXT_{DIST}}dt + \int_{t1}^{t2} M_{EXT_{REC}}dt \quad (1)$$

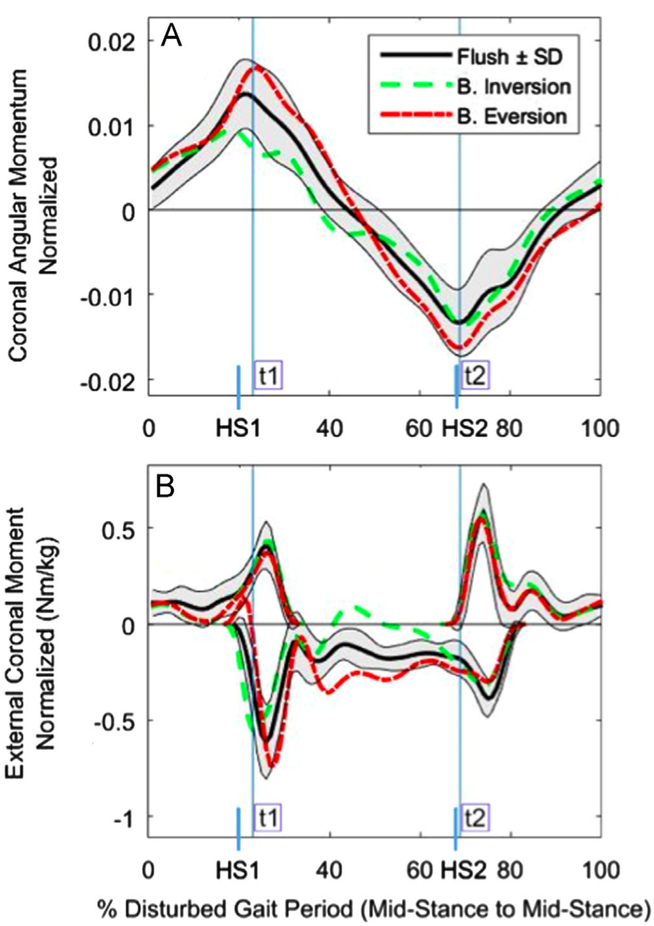

Fig. 2. (A) Mean coronal angular momentum (normalized to body height, mass, and walking speed) of each condition plotted over the disturbed gait period. (B) Mean external coronal moment from each leg (normalized to body mass) plotted over the disturbed gait period. Disturbed leg moment exists in the negative vertical axis, and recovery leg moment exists in the positive vertical axis. For both plots: vertical lines denote average times of maximum ($t1$) and minimum ($t2$) coronal angular momentum for all conditions (equivalent to average integration bounds for external coronal angular impulses); average disturbed (HS1) and recovery (HS2) heel strikes denoted on horizontal axis. Blinded abbreviated to B.

where the absolute value of the left hand side is the un-normalized RCAM when time points t_1 and t_2 correspond to the maximum and minimum values of the coronal angular momentum during the disturbance gait period (Fig. 2). The right hand side is the sum of the un-normalized external CAI of the disturbed leg ($\int_{t1}^{t2} M_{EXT_{DIST}}dt$) and the recovery leg ($\int_{t1}^{t2} M_{EXT_{REC}}dt$) over the same period of time, where M_{EXT} is the external moment applied by each leg.

Recovery mechanisms of the disturbed leg were analyzed for the disturbed step, and recovery mechanisms of the recovery leg were analyzed for the lead-in and recovery steps. To evaluate use of the ankle and hip coronal joint moment strategies, coronal moments of each joint were integrated over each of the stance phases to produce a joint-level CAI for each joint for each step, which were normalized to body mass. Mediolateral foot positions (MLFP) for each of the three steps were used to evaluate the stepping strategy. MLFP was measured as the mediolateral distance from the whole-body COM to the ankle joint center, normalized to body height. MLFP was measured at first shoe contact with a force plate, or for blinded conditions, the opaque cover. When appropriate, metrics from left foot dominant participants were negated, making ankle invertor and hip adductor moments of the disturbed leg positive.

2.6. Statistical methods

A two-way, mixed-effects ANOVA test with interaction effects was applied to all metrics using Matlab (Mathworks, Natick, USA). If significance at an alpha level of 0.05 was detected for the condition effect, post-hoc pairwise comparisons were made using Tukey's honestly significant difference test. Correlation analyses determined potential contributions of the ankle, hip and stepping strategies to the external coronal moment provided by the disturbed and recovery legs. External CAI's were compared to the corresponding legs' hip CAI, ankle CAI, and MLFP at each step using Pearson's correlation coefficient (ρ).

3. Results

A minimum of four repeated measures for all conditions were recorded with no adverse events, with less than 8% of trials for any condition being rejected due to misplaced steps. All participants completed at least three strides before contacting the disturbance. During inversion and eversion, participants encountered an average step down of 2.7 cm before contacting the force plate. Walking speeds, disturbed stance time, and disturbed gait period were not significantly different between conditions (unblinded flush, blinded inversion, blinded eversion) (Table 1).

The RCAM was not equal between conditions ($p<0.001$) with a 21% larger ($p<0.001$) mean range for blinded eversion, and a 10% smaller ($p<0.001$) mean range for blinded inversion, compared to unblinded flush (Table 2). For all conditions, maximum and minimum mean coronal angular momentum occurred within 0.1 sec of the mean disturbed step heel strike (HS1) and the mean recovery step heel strike (HS2), respectively (Fig. 2A). At HS1, the peak coronal angular momentums of all three conditions appear different, while at HS2, only that of the blinded eversion condition appears different from the other conditions.

The external CAI of the disturbed leg ($p<0.001$) was not equal for all conditions (Table 2) with differences detected between all conditions ($p<0.001$). However, the external CAI of the recovery leg did not exhibit a significant condition effect (p=0.067)

Table 1
Statistical results for temporal metrics. Bolded p-values considered significant. Abbreviations: (SD) standard deviation, (B) blinded.

Metric	Units	p-Val.	Mean (SD)		
			Flush (n=55)	B. Inversion (n=51)	B. Eversion (n=51)
Walking speed	m/s	0.855	1.000 (0.684)	1.005(0.753)	0.992(0.758)
Disturbed stance time	s	0.053	0.707 (0.072)	0.677(0.080)	0.693(0.077)
Disturbed gait period	s	0.226	1.150 (0.106)	1.114 (0.113)	1.122 (0.112)

Table 2
Statistical results for balance and recovery metrics. Bolded *p*-values considered significant. Abbreviations: (SD) standard deviation, (B) blinded, (F) flush, (BI) blinded inversion, (BE) blinded eversion, (RCAM) range of coronal angular momentum, (CAI) coronal angular impulse, (MLFP) mediolateral foot position.

Metric	Units	*p*-Val.	Mean (SD)			Pairwise *P*-Values		
			Flush (n=55)	B. Inversion (n=51)	B. Eversion (n=51)	F to BI	F to BE	BI to BE
RCAM	None	< **0.001**	0.029 (0.007)	0.026 (0.007)	0.035 (0.008)	< **0.001**	< **0.001**	< **0.001**
Disturbed leg external CAI	m^2/s	< **0.001**	−0.102 (0.027)	−0.052 (0.041)	−0.148 (0.047)	< **0.001**	< **0.001**	< **0.001**
Recovery leg external CAI	m^2/s	0.067	0.028 (0.016)	0.036 (0.026)	0.025 (0.016)	N/A	N/A	N/A
Lead-in step ankle joint CAI	m^2/s	0.128	0.037 (0.034)	0.034 (0.028)	0.029 (0.027)	N/A	N/A	N/A
Disturbed step ankle joint CAI	m^2/s	< **0.001**	−0.050 (0.027)	−0.172 (0.030)	0.056 (0.030)	< **0.001**	< **0.001**	< **0.001**
Recovery step ankle joint CAI	m^2/s	0.660	0.034 (0.031)	0.032 (0.036)	0.034 (0.032)	N/A	N/A	N/A
Lead-in step hip joint CAI	m^2/s	0.203	0.378 (0.062)	0.362 (0.068)	0.366 (0.060)	N/A	N/A	N/A
Disturbed step hip joint CAI	m^2/s	< **0.001**	−0.383 (0.069)	−0.391 (0.069)	−0.327 (0.091)	**0.034**	< **0.001**	< **0.001**
Recovery step hip joint CAI	m^2/s	0.056	0.396 (0.063)	0.372 (0.070)	0.386 (0.070)	N/A	N/A	N/A
Lead-in step MLFP	None	0.856	0.042 (0.010)	0.043 (0.012)	0.042 (0.009)	0.845	0.976	0.940
Disturbed step MLFP	None	**0.002**	0.041 (0.010)	0.036 (0.009)	0.037 (0.010)	< **0.001**	**0.001**	0.793
Recovery step MLFP	None	< **0.001**	0.041 (0.009)	0.032 (0.011)	0.034 (0.012)	< **0.001**	**0.001**	0.573

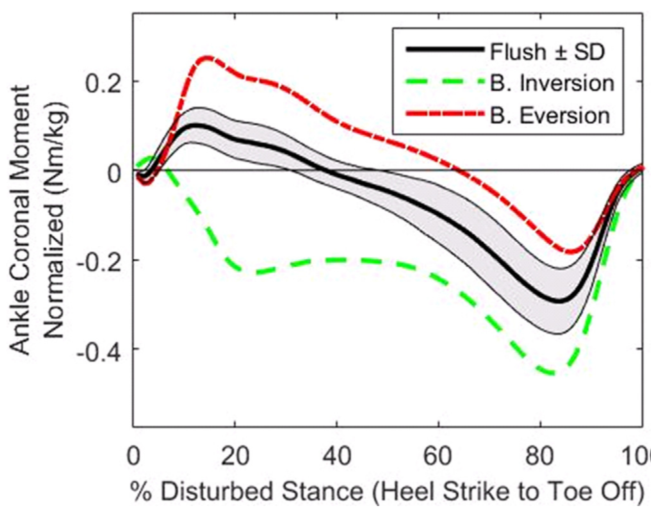

Fig. 3. Mean ankle coronal moment (normalized to body mass) for each condition plotted over the disturbed stance. Positive values correspond to invertor moments. Blinded abbreviated to B.

(Table 2). External coronal moment magnitudes appear largest immediately after heel strike (Fig. 2B). For all conditions, the mean external CAIs of the disturbed leg were 44–492% larger than the recovery leg (Table 2).

On the disturbed step, the ankle joint CAI exhibited significant pairwise differences between all three conditions (Table 2). Compared to unblinded flush, the mean disturbed step ankle joint CAI was 244% more negative for blinded inversion ($p < 0.001$) and 212% more positive for blinded eversion ($p < 0.001$) with the ankle coronal moment curves exhibiting similar differences (Table 2 and Fig. 3). No significant condition effect was detected for the lead-in (p=0.128) and recovery (p=0.660) steps' ankle joint CAI (Table 2). The disturbed step had the strongest correlation between the ankle CAI and the corresponding leg's external CAI ($\rho = -0.680$, $p < 0.001$) (Table 3).

On the disturbed step, the hip joint CAI exhibited significant pairwise differences between all conditions ($p \leq 0.034$) (Table 2), with an increased adduction moment for blinded eversion and a reduced adduction moment for blinded inversion compared to unblinded flush. However, compared to the ankle coronal moment (Fig. 3), the hip coronal moment differences between conditions (Fig. 4) appear less pronounced. No significant condition effect was detected for the lead-in (p=0.203) and recovery (p=0.056) steps' hip joint CAI (Table 2). The disturbed step had the strongest correlation between the hip joint CAI and the corresponding leg's external CAI ($\rho = -0.568$, $p < 0.001$) (Table 3).

The mean MLFP differed between conditions for the disturbed (p=0.002) and recovery ($p < 0.001$) steps (Table 2). For both steps, the blinded MLFP means were significantly smaller (by 7–9 mm for disturbed step and by 12–16 mm for recovery step) than unblinded flush ($p \leq 0.001$). Additionally, both the disturbed and recovery steps exhibited no pairwise differences in MLFP between blinded inversion and blinded eversion ($p \geq 0.573$). No significant condition effect was detected for the lead-in step MLFP (p=0.856) (Table 2). The disturbed step had the strongest correlation between MLFP and the corresponding leg's external CAI ($\rho = -0.363$, $p < 0.001$) (Table 3).

4. Discussion

4.1. Interpretation

The purpose of this study was to identify the biomechanical response to a step on coronally-uneven and unpredictable terrain. A unique experimental protocol enabled this analysis on ten healthy adults.

The uneven disturbance affected gait balance, as shown by pairwise differences in RCAM between all conditions (Table 2). Additionally, it appears blinded inversion and eversion had coronal angular momentum peaks that differed from unblinded flush on the disturbed step heel strike, while only blinded eversion had a peak that differed from unblinded flush on the recovery step heel strike (Fig. 2A). This suggests blinded eversion was more disturbing to gait balance, and accordingly, the difference between blinded eversion RCAM and unblinded flush is twice the difference between blinded inversion RCAM and unblinded flush. Participant RCAM for unblinded flush was higher than reported for stable walkers in previous work (mean=0.023) (Silverman and Neptune, 2011); however, this may be explained by whole-body model differences, such as the inclusion of arms in this study's model. Compared to unblinded flush, blinded eversion had a 21% higher RCAM, a delta similar to that between non-amputee (more stable) and amputee (less stable) walkers (Miller et al., 2001; Silverman and Neptune, 2011), suggesting blinded eversion meaningfully reduced gait balance.

In the case of blinded inversion, the RCAM decreased, which is an interesting result as previous work has shown steady-state gait disturbances to increase RCAM. It is possible that blinded inversion still destabilized participants' gait, and that balance metrics, such as RCAM, must be interpreted differently depending on whether the disturbance is steady-state or transient. In a transient disturbance, if

Table 3
Pearson correlation coefficient (ρ) results between recovery mechanism metrics of each step and the external coronal angular impulse (CAI) of the corresponding leg during the disturbed gait period. Bolded p-values considered significant. Abbreviation: (MLFP) mediolateral foot position.

Step	Correlation between stance leg's external CAI and corresponding leg's:					
	Ankle joint CAI		Hip joint CAI		MLFP	
	ρ	p-Value	ρ	p-Value	ρ	p-Value
Lead-in	−0.206	**0.018**	0.135	0.125	0.237	**0.007**
Disturbed	−0.680	< **0.001**	−0.568	< **0.001**	−0.363	< **0.001**
Recovery	−0.304	< **0.001**	0.158	0.072	0.339	< **0.001**

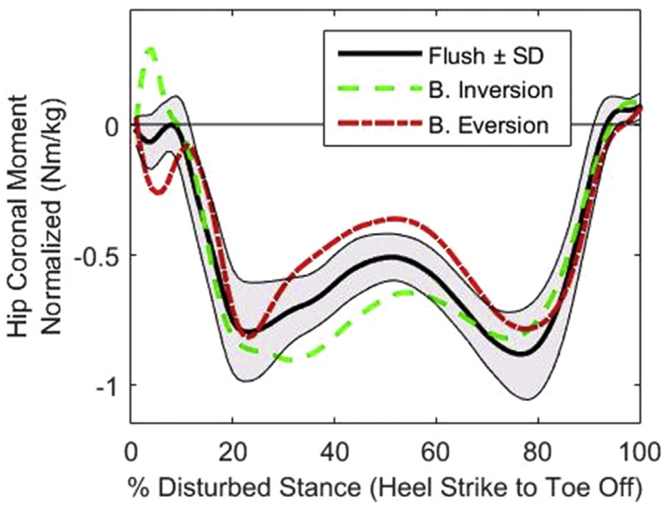

Fig. 4. Mean hip coronal moment (normalized to body mass) for each condition plotted over the disturbed stance. Positive values correspond to adductor moments. Blinded abbreviated to B.

coronal angular momentum is highly regulated (Herr and Popovic, 2008), then any disturbance from an individual's nominal steady-state (RCAM for the flush condition in this study) could be interpreted as a decrease in gait balance.

Compared to the recovery leg, the disturbed leg exhibited greater adaption as only its CAI exhibited a condition effect as well as pairwise differences between conditions (Table 2). Additionally, the magnitude of the external CAI of the disturbed leg was 44–492% larger than that of the recovery leg, suggesting the disturbed leg had a greater contribution to the RCAM, and thus a greater role in recovery. These observations are consistent with those establishing the importance of the disturbed leg in recovery from unpredictable trips (Pijnappels et al., 2004).

On the disturbed step, the ankle CAI had significant pairwise differences between all conditions (Table 2), indicating the coronal ankle joint strategy was used during stance on the disturbance. The mean peak values (0.09 Nm/kg, and −0.32 Nm/kg) of the coronal ankle moment for unblinded flush were both within 22% of the range of peaks previously reported (~0.05 Nm/kg, and ~−0.25 Nm/kg) (Bruening et al., 2012). In response to blinded inversions, there was an ankle evertor moment (corresponding to a medial COP shift (Hof, 2007)), consistent with electromyography studies showing evertor muscle activation during unexpected inversions (Linford et al., 2006; Nieuwenhuijzen and Duysens, 2007). In response to blinded eversions, there was an invertor moment (corresponding to a lateral COP shift (Hof et al., 2007)). The ankle CAI and disturbed leg external CAI had a relatively strong correlation ($\rho = -0.680$, $p < 0.001$), substantiating previous observations of the ankle's importance during the stance phase of disturbed gait (MacKinnon and Winter, 1993).

The coronal hip joint strategy of the disturbed leg was also important in recovery, as suggested by significant pairwise differences in the hip joint CAI between all conditions on the disturbed step (Table 2). The shape and magnitude of the coronal hip moment for unblinded flush agree with previous findings for straight line walking, with a mean peak abductor moment (75 Nm) within 25% of the mean peak value previously reported (~60 Nm) (MacKinnon and Winter, 1993). In the case of blinded inversion, the hip joint had significantly more abduction, which is consistent with previous findings highlighting the activation of abductors in unexpected inversions of the ankle (Beckman and Buchanan, 1995). The hip CAI and disturbed leg external CAI had a relatively strong correlation ($\rho = -0.568$, $p < 0.001$), substantiating model predictions of the hip's importance in modulation of coronal angular momentum (Neptune and McGowan, Revised Manuscript in Review).

The ankle and hip moments observed in the disturbed stance appear to work together. The synergy between these two joints has been reported (Beckman and Buchanan, 1995; MacKinnon and Winter, 1993), and is seen on the disturbed step in the form of similar correlation coefficients between each of these joints' CAIs and the disturbed leg's external CAI (Table 3). Additionally, on the disturbed step, the hip and ankle joint CAIs have a positive change for inversion, and a negative change for eversion. These changes, when coupled with existing findings relating joint moments to trunk accelerations (Nott et al., 2010), may explain RCAM differences observed on uneven terrain. On inverted terrain, more negative hip and ankle moments, which correspond with more positive trunk acceleration, may have reduced the RCAM, and vice versa in the case of eversion.

The participants' stepping strategy appears to have been influenced by whether the disturbed step was blinded. Both the disturbed and recovery step MLFPs were smaller for blinded inversion and eversion when compared to unblinded flush, but were not different between blinded inversion and eversion. The smaller disturbed step MLFP may have been a preparatory strategy for the disturbance's potential step down (~2.7 cm), a common feature of both types of uneven terrain, but not of the flush terrain. This step down created differences in vertical GRFs between conditions. The impact of these differences on whole-body coronal angular momentum may have been reduced by the smaller disturbed step MLFP, which reduced the lateral moment arm about which the vertical GRFs were applied. This reduction would decrease the external moment about the whole-body COM and corresponding change in whole-body angular momentum. During the disturbed gait period, the whole-body COM appears to have shifted towards the recovery leg for all the blinded conditions (Fig. 5). This preparatory behavior has been previously observed in participants as a strategy to improve balance when stepping onto an anticipated disturbance (Marigold and Patla, 2002), and likely contributed to the smaller recovery step MLFP for blinded inversion and eversion.

In contrast to the similar stepping strategy used for blinded inversion and eversion onto the disturbance, distinct differences between these two conditions existed for the ankle and hip joint

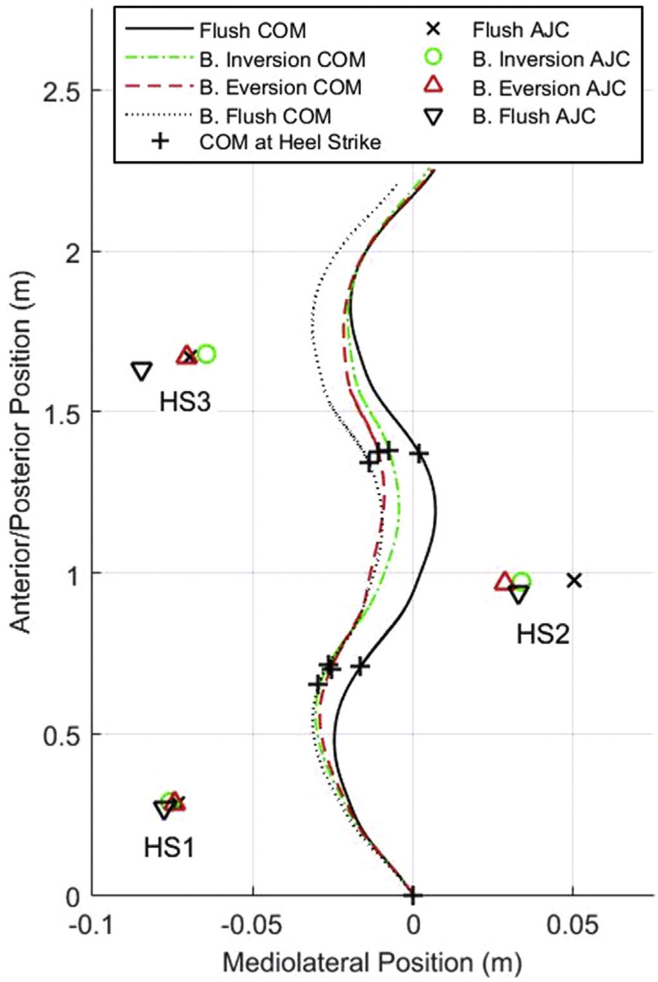

Fig. 5. Mean center of mass (COM) path during stance-phase of lead-in, disturbed, and recovery steps, with ankle joint center (AJC) locations shown at each heel strike (HS1, HS2, HS3, respectively). All positions normalized to the COM position at heel strike of lead-in step (shown at (0,0)). Blinded abbreviated to B.

strategies. This suggests that during the disturbance, modulation of the ankle and hip coronal joint moments played an essential role in adapting to the direction of the uneven terrain, while an indiscriminate stepping strategy was used to help reduce the disturbance's impact on gait balance. This notion is supported by the hip and ankle joint CAI having stronger correlation coefficients with the disturbed leg's external CAI than MLFP (Table 3).

4.2. Implications

The findings of this study quantify key strategies healthy ambulators use to maintain balance on coronally-uneven and unpredictable terrain. Interventions which augment the ankle and hip recovery moments, such as supportive footwear (Ottaviani et al., 1995), or ankle (Sekir et al., 2006) and hip strengthening exercises, may reduce falls on uneven terrain.

4.3. Limitations

A limitation of this study was the slight step down that occurred during inversion and eversion conditions. Another limitation was the focus on coronal plane metrics. It is possible that sagittal and transverse plane adaptions were also used to recover from coronally-uneven and unpredictable terrain and should be considered in future work. Finally, analysis of additional balance metrics (e.g., COM trajectory) and other disturbance conditions (blinded flush, unblinded inversion, and unblinded eversion) may further the understanding of uneven terrain balance recovery.

Conflict of interest

All products identified in this article were independently purchased through commercial channels. No commercial party having a direct financial interest in the results of the research reported in this article has or will confer a benefit on the authors or on any organization with which the authors are associated.

Acknowledgments

This work was funded by the Department of Veterans Affairs, Rehabilitation Research and Development Service, Grants A9243C, RX001840, and A9248-S. In addition, Janice Pecoraro recruited participants, and Krista Sanchez assisted with data collection.

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