Journal of Biomechanics 95 (2019) 109269

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Effect of arm motion on postural stability when recovering from a slip perturbation ☆

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ARTICLE INFO

Article history:
Accepted 13 July 2019

Keywords:
Perturbation
Stability
Gait
Falls
Upper extremity
Angular momentum
Slip
Arm swing

ABSTRACT

The aim of this study was to examine the effects of various arm swing on postural stability and recovery responses to an unexpected slip during treadmill walking. Fifteen healthy young adults (23.4 ± 2.8 years old) participated in this study. The CAREN-Extended system was used to simulate unexpected slip perturbations in a safe environment while walking symmetrically and asymmetrically with various arm swings (normal, bound, released). Whole-body angular momentum (range), peak trunk angular velocities, step width and stance time were extracted before and after perturbations (when recovering from slip). All participants were able to recover their balance after two strides and no falls occurred. There were significant differences ($p < 0.05$) in most gait parameters between pre- and post-perturbations. Arm conditions had significant effects on all gait parameters during both pre- and post-perturbation except for stance time. Compared to symmetric walking, walking asymmetrically before a perturbation led to larger step width and stance time among the different arm conditions both before and after the perturbations. Despite the presence of significant effects of different arm and walking conditions on most gait parameters during pre- and post-perturbation, participants were able to implement stabilization strategies to prevent fall even when they were prevented from using their normal arm swing, in both symmetric and asymmetric walking. While our results indicate that perturbations were mild to moderate in magnitude, investigations with elderly and faller populations are needed to examine their susceptibility to these arm and walking conditions when trying to regain postural balance.

1. Introduction

Falls are the leading cause of non-fatal injury in the United States (McAndrew et al., 2010; Madehkhaksar et al., 2018), which increases costs for health care and diminish quality of life (Deandrea et al., 2010; Madehkhaksar et al., 2018). Most falls occur after a loss of balance while walking and following an unexpected perturbation such as a slip (Madehkhaksar et al., 2018; Maki et al., 2008). Understanding of how humans control balance and recovery responses after a slip is fundamental to help reduce the incidence of falls (Marigold et al., 2003). Arm swing during walking or after perturbations have been shown to enhance gait stability (Ortega et al., 2008; Meyns et al., 2013) and decrease energy expenditure (Collins et al., 2009; Ortega et al., 2008; Bruijn et al., 2010). Furthermore, the regulation of foot placement on the ground when walking is also an important contributor to gait stability (McAndrew et al., 2010).

In typical gait, the arm and leg motions are anti-phase to counteract the angular momentum of the legs. Bruijn et al. proposed that walking without arm motion prior to a perturbation, but allowing arm motion during the recovery phase could be optimal. During normal walking, the absence of arm motion would increase the inertia of the trunk and improve its resistance to perturbations; in contrast, the lack of arm swing following a perturbation would lead to less effective recovery strategies compared to walking with normal arm swing (Bruijn et al., 2010). Still, little is known about the influence of different arm movements on gait stability immediately prior to, and when recovering from, a sudden perturbation, such as a slip.

Margin of stability, an indicator of dynamic stability (Hof et al., 2007; Hof et al., 2010) that characterizes the relationship between the extrapolated position of the COM and the base of support

☆ All authors were fully involved in the study and preparation of the manuscript and the material within has not been and will not be submitted for publication elsewhere except as an abstract.

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https://doi.org/10.1016/j.jbiomech.2019.07.013
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(Young et al., 2012) has been shown to increase in challenging walking conditions (Hak et al., 2012; Hak et al., 2013a). In response to continuous perturbations, people walk with wider, faster, and shorter steps and exhibit increased step-to-step variability (Young et al., 2012; McAndrew et al., 2010; Madehkhaksar et al., 2018; Roeles et al., 2018; Espy et al., 2010; Hak et al., 2013a). Such perturbations also result in greater variability of the trunk position and velocity, which indicates a need for greater control of the torso, especially in the medial-lateral direction (McAndrew et al., 2010). In a recent study, Inkol et al., (2019) evaluated upper body postural responses following first and repeated exposure to sudden slip perturbation in eleven healthy young adults (Inkol et al., 2019). They found that the first exposure to sudden perturbation affected the gait variable the most compared to the rest of perturbation. Moreover, young individuals would recover postural stability and adapt very quickly to sudden perturbation (Inkol et al., 2019). In another study, Roeles et al. (2018) found no significant difference in response to continuous perturbations and recovery responses between young individuals and very fit and healthy older adults (Roeles et al., 2018).

Previous research has shown that trunk stabilisation and interlimb coordination require greater neural control during asymmetric walking compared to symmetric activities (MacLellan, et al., 2013; McFadyen et al., 2009). Yet it remains uncertain whether these adaptations in gait-related parameters and to dynamic stability also occur after sudden perturbations during asymmetric walking with restricted arm motion.

Another useful descriptor of human gait is whole-body angular momentum (WBAM) which is kept near zero during normal walking in order to maintain dynamic balance and avoid falling (Herr and Popovic, 2008; Pijnappels et al., 2004; Pijnappels et al., 2010). Previous findings showed that WBAM must be swiftly regulated to recover postural stability and prevent falls after a perturbation (Pijnappels et al., 2004; Silverman et al., 2012). However, the effects of asymmetric walking with restricted arm motions have not yet been studied.

The main objective of this study was to quantify the effect of various arm swing and walking conditions on gait stability when recovering from a sudden slip perturbation. More specifically, we measured the effects of arm motions on the recovery of postural stability following a slip, and determined the strategies to recover postural stability following a slip while walking symmetrically and asymmetrically. We hypothesized that following an unexpected slip perturbation, healthy young adults would recover postural stability and adapt more quickly when they were allowed arm motion during the recovery phase and when they were perturbed in symmetric gait conditions.

2. Methodology

A convenience sample of 15 young and healthy individuals (eight men, seven women) was recruited from the University of Ottawa. The participant's mean age was 23.4 ± 2.8 years, height was 170.2 ± 8.1 cm, and weight was 72.3 ± 13.5 kg. Participants had no history of upper or lower extremity orthopedic injury or any neurological condition which could affect their gait. Moreover, they had no experience with treadmill induced perturbations. The study was approved by the Institutional Review Board (University of Ottawa) in accordance with the declaration of Helsinki and all participants provided written informed consent.

2.1. Data collection

3D motion analysis was completed using a virtual park scenario within the CAREN-Extended System (Motek Medical, Amsterdam, NL). The CAREN-Extended system combines a six degree-of-freedom motion platform with embedded dual-belt instrumented treadmill, 12 camera Vicon motion capture system, 180-degree projector screen, and safety harness. Platform motion was tracked by three markers, and a set of 57 markers (Wilken et al., 2012; Sinitski et al., 2015) was used to track full body kinematics. Kinematic data were collected at 100 Hz and ground reaction force (GRF) data were collected at 1000 Hz. Participants were fitted with a safety harness which did not interfere with movement and was attached to an overhead structure to prevent any possible falls. Participants were allowed to rest whenever necessary to minimize fatigue. The 3 arm conditions in this study were:

a) ***Normal***: Normal arm motion.
b) ***Bound***: Arms were tied at their sides, across the midpoint of their forearms.
c) ***Released***: Subjects were instructed to walk without arm swing unless it was necessary to maintain/recover balance (eg. in the event of a perturbation).

2.2. Perturbations

Participants performed symmetric (treadmill speed = 1.2 m/s for both legs) or asymmetric (treadmill speed for left leg = 1.2 m/s, and for right leg = 0.96 m/s) walking for approximately 15 s, in order to achieve a comfortable walking speed. Once steady-state conditions had been reached, a total of five slips were induced during each trial. To minimize potential anticipation effects, the order of the perturbations was randomized, and each perturbation was cued by the system operator at a random time after the participant had recovered from the previous perturbation, approximately 15 s. When the operator cued a perturbation, it was dynamically triggered the next time the heel of the swing foot passed the heel of the stance foot. For a slip, the treadmill belt on the perturbed side began accelerating at 1.5 m/s^2 for 0.75 s before decelerating at the same rate for the same time to finish at the set treadmill speed of 1.2 m/s. Note that due to system limitations, the treadmill returned to symmetric speeds following a perturbation under asymmetric conditions. In this study, all perturbations were performed on the right side. Participants completed six trials, one for every combination of arm swing (normal, bound, or released) and gait condition (symmetric or asymmetric).

2.3. Data analysis

Vicon Nexus (Nexus 2.6, Oxford, UK) was used to process markers and GRF data before exporting to Visual3D v6 (C-Motion, Germantown, MD) for 3D kinematic and kinetic calculations. A 4th order, low-pass Butterworth filter with a 10 Hz cut-off frequency was used to filter marker data. WBAM range, peak trunk angular velocities, center of mass (COM) and spatiotemporal gait parameters (step width, stance time) were extracted before and when recovering from a slip. WBAM, center of mass (COM), trunk angular velocities, and both feet positions were exported from Visual3D. Subsequently, the exported data was analyzed using custom scripts (https://dx.doi.org/10.5281/zenodo.2652550) in Julia (Bezanson et al., 2017) to produce spatiotemporal gait data (step width, and stance times), COM range, WBAM range, and peak trunk angular velocities for each stride. All measures were calculated for the 5 strides immediately prior to and the 5 strides following a perturbation; the results of all 5 strides prior to the perturbation were averaged. Data were analyzed using SPSS 23.0 and statistical significance was set at $\alpha = 0.05$. The normality of variables was verified by the Shapiro-Wilk test. A two-way repeated measure ANOVA was used to find the effect of arm swing, walking condition and their interactions on each variable. Both a one-way repeated measures ANOVA with a Bonferroni adjustment for multiple comparisons and a paired samples *t*-test were used to compare pre- and post-perturbation among the various arm swing and walking conditions. To evaluate learning effects, steady-state and all perturbations (1 to 5) were compared using a one-way repeated measures ANOVA.

3. Results

Overall, all participants were able to recover their balance following the sudden slips. The assessment of the five strides after perturbations showed significant difference ($p < 0.05$) between the first two strides and the third thru fifth strides for most of the gait variables evaluated in this study as shown in Appendix A. As seen in Table 1, significant differences were found in most of the gait parameters between pre- and post-perturbations ($p < 0.05$). Moreover, evaluating all gait parameters in the first stride after perturbations showed no significant differences between the first and the rest of perturbations, therefore the first strides in all five perturbations were averaged for each combination of conditions.

3.1. Pre- and post-perturbation

Pairwise comparisons showed that the range of WBAM increased considerably in the sagittal and frontal planes post-perturbation with various arm swings and walking conditions ($p < 0.001$) (Table 1, Appendix B). In the bound arm condition, WBAM range was reduced compared to normal arm swing only in the sagittal plane, both pre- and post-perturbation (Table 1). Peak trunk angular velocities also significantly increased in all planes post-perturbation in all conditions ($p < 0.001$); the largest changes in trunk angular velocity occurred after perturbation in horizontal plane when the arms were bound ($p < 0.001$). Moreover, center of mass (COM) ranges of motion were smaller in both the AP and ML directions in the restricted arm condition compared to normal arm swing (Table 1). There was no significant difference in step width between pre- and post-perturbation except in the released condition in symmetric and asymmetric walking ($p < 0.05$). The results also showed that the stance time was decreased significantly post-perturbation ($p < 0.001$).

3.2. Effect of arm and walking condition

The two-way repeated measures ANOVA showed that the arm conditions had significant effects on WBAM range in all 3 planes of motion both pre- and post-perturbation (Table 2A); post-hoc tests (Table 2B) showed significant differences between the normal arm swing and the two other conditions (released and bound) primarily in pre-perturbation. Arm conditions had significant effects on trunk angular velocity in the frontal ($F(2,28) = 8.73$, $p < 0.001$) and horizontal ($F(2,28) = 4.08$, $p = 0.028$) planes during pre-perturbation (Table 2A, Appendix C). However, post-perturbation, arm conditions had significant effects on trunk angular velocity in the sagittal ($F(2,28) = 4.20$, $p = 0.026$) and horizontal ($F(2,28) = 22.10$, $p < 0.001$) planes; moreover, there was no significant difference between the normal arm swing and the released condition both in pre- and post-perturbation for all three planes (Table 2B). Arm conditions also had significant effects on step width only during pre-perturbation ($F(2,28) = 5.69$, $p = 0.008$) (Table 2A). Arm conditions had no significant effects on stance time during pre- and post-perturbation.

Walking conditions had a significant effect on WBAM range in the sagittal plane (Table 2A) during pre-perturbation ($F(1,14) = 50.02$, $p < 0.001$) and post-perturbation ($F(1,14) = 29.62$,

Table 1
Comparison between pre- and post-perturbations in symmetric and asymmetric walking for whole-body angular momentum range and peak trunk angular velocity in the anterior-posterior (AP), medial-lateral (ML) and vertical (VT) directions and step width and stance time. Center of Mass (COM) range data presented for post-perturbation.

		Mean (SD) Pre-perturbation						Mean (SD) First Stride Post-perturbation					
		Normal		Bound		Released		Normal		Bound		Released	
		Symmetric	Asymmetric	Symmetric	Asymmetric	Symmetric	Asymmetric	Symmetric	Asymmetric	Symmetric	Asymmetric	Symmetric	Asymmetric
Step width (cm)		19.45 (3.64)	20.68 (4.37)	20.60 (3.75)	21.52 (4.24)	19.88 (3.23)	20.75 (3.92)	20.72 (2.59)	21.63 (3.12)	21.24 (3.30)	21.65 (3.20)	21.15 (3.30)[†]	21.91 (3.47)[†]
Stance Time (s)		0.70 (0.04)	0.75 (0.05)	0.69 (0.04)	0.73 (0.06)	0.70 (0.04)	0.75 (0.06)	0.46 (0.06)[‡]	0.49 (0.07)[‡]	0.46 (0.07)[‡]	0.48 (0.08)[‡]	0.45 (0.07)[‡]	0.50 (0.08)[‡]
Whole-Body Angular momentum ranges (m/s)[*]	AP	0.044 (0.006)	0.050 (0.007)	0.040 (0.005)	0.045 (0.006)	0.040 (0.006)	0.047 (0.007)	0.075 (0.013)[‡]	0.067 (0.012)[‡]	0.068 (0.013)[‡]	0.063 (0.014)[‡]	0.074 (0.012)[‡]	0.062 (0.011)[‡]
	ML	0.033 (0.008)	0.034 (0.010)	0.040 (0.009)	0.039 (0.010)	0.035 (0.008)	0.038 (0.010)	0.051 (0.014)[‡]	0.052 (0.014)[‡]	0.056 (0.012)[‡]	0.060 (0.012)[‡]	0.055 (0.015)[‡]	0.054 (0.014)[‡]
	VT	0.014 (0.004)	0.013 (0.004)	0.019 (0.004)	0.018 (0.004)	0.018 (0.005)	0.019 (0.004)	0.015 (0.005)	0.015 (0.004)[†]	0.016 (0.006)[†]	0.017 (0.005)	0.017 (0.005)	0.018 (0.006)
Trunk Angular Velocity (Peak) (deg/s)	AP	26.2 (5.6)	25.7 (5.6)	24.3 (4.5)	25.9 (4.6)	25.0 (5.0)	25.7 (5.1)	46.9 (15.6)[‡]	47.3 (10.9)[‡]	42.2 (10.8)[‡]	42.4 (10.4)[‡]	45.4 (15.2)[‡]	43.1 (13.9)[‡]
	ML	13.8 (3.1)	16.3 (4.8)	17.6 (2.9)	18.3 (3.8)	14.3 (3.0)	15.8 (4.0)	28.8 (7.3)[‡]	32.9 (11.4)[‡]	29.0 (7.1)[‡]	29.9 (7.3)[‡]	29.3 (6.0)[‡]	28.3 (7.4)[‡]
	VT	39.7 (7.0)	43.9 (8.5)	42.7 (8.2)	43.3 (11.0)	39.1 (8.0)	40.0 (8.8)	70.8 (14.0)[‡]	67.5 (12.4)[‡]	100.6 (23.9)[‡]	101.1 (25.3)[‡]	83.7 (22.0)[‡]	80.1 (19.1)[‡]
COM (cm)	AP							3.91 (1.76)	4.27 (2.08)	3.40 (1.52)	3.89 (1.96)	3.78 (2.48)	3.62 (1.34)
	ML							6.92 (3.62)	6.10 (3.49)	5.45 (4.10)	5.86 (3.63)	6.05 (4.42)	6.00 (2.73)
	VT							6.02 (2.54)	5.52 (3.00)	5.89 (3.36)	5.78 (2.98)	6.01 (2.58)	6.02 (2.51)

[*] Whole-body angular momentum was normalized in magnitude by body mass (kg) and body height (m).
[‡] $P \leq 0.001$.
[†] $0.001 < P < 0.05$.

Table 2
Effect of different arm and walking conditions on pre- and post-perturbation. **A:** Two-way repeated measure ANOVA results; **B&C:** One-way repeated measure ANOVA results.

A			Stance Time		Step Width		Trunk Angular Velocity (Peak)						Whole-Body Angular Momentum (Range)						COM (Range)		
			P-value Pre	P-value Post	P-value Pre	P-value Post	P-value (Pre-perturbation)			P-value (Post-perturbation)			P-value (Pre-perturbation)			P-value (Post-perturbation)			P-value (Post-perturbation)		
							AP	ML	VT	AP	ML	VT	AP	ML	VT	AP	ML	VT	AP	ML	VT
		Arms	0.066	0.714	**0.01**	0.59	0.33	**0.001**	**0.028**	**0.026**	0.428	**0.000**	**0.000**	**0.000**	**0.000**	**0.033**	**0.003**	**0.002**	0.055	**0.034**	0.319
		Walking	**0.000**	**0.000**	**0.01**	**0.02**	0.21	**0.030**	0.160	0.815	0.289	0.388	**0.000**	0.284	0.058	**0.000**	0.242	0.235	0.101	0.662	0.181
		Arms*Walking	0.348	**0.036**	0.44	0.69	0.17	0.239	0.249	0.838	0.114	0.649	0.329	**0.007**	**0.032**	0.064	**0.041**	0.154	0.232	0.234	0.359
B		Arm condition																			
Walking condition	Symmetric	Normal vs Bound	0.306	1.000	**0.023**	0.836	0.400	**0.003**	0.334	0.181	1.000	**0.001**	**0.009**	**<0.001**	**<0.001**	**0.017**	0.116	0.496	0.072	**0.001**	1.000
		Normal vs Released	1.000	0.977	0.533	0.931	0.888	1.000	1.000	1.000	1.000	0.117	0.057	**0.040**	**<0.001**	1.000	0.143	0.084	1.000	0.144	1.000
		Bound vs Released	0.600	0.620	0.355	1.000	0.558	**0.004**	0.140	0.868	1.000	**0.034**	0.656	**0.001**	0.065	0.072	1.000	1.000	0.930	0.549	1.000
	Asymmetric	Normal vs Bound	0.141	0.700	0.070	1.000	1.000	0.337	1.000	0.169	0.838	**<0.001**	**0.001**	**<0.001**	**<0.001**	0.642	**0.001**	**0.026**	0.547	1.000	1.000
		Normal vs Released	1.000	1.000	1.000	1.000	1.000	1.000	0.185	0.792	0.229	0.057	**0.001**	**0.001**	**<0.001**	0.195	1.000	**0.016**	**0.015**	1.000	0.515
		Bound vs Released	0.197	0.168	0.091	1.000	1.000	0.030	0.188	1.000	1.000	**0.001**	0.127	0.726	1.000	1.000	**0.043**	0.617	0.915	1.000	0.987
C		Walking condition																			
Arm condition	Normal	Symmetric vs Asymmetric	**<0.001**	**0.011**	**0.011**	0.078	0.562	**0.016**	0.012	0.921	0.074	0.306	**<0.001**	0.212	**0.007**	**<0.001**	0.301	0.422	0.108	0.078	0.091
	Bound	Symmetric vs Asymmetric	**<0.001**	**0.011**	**0.024**	0.273	**0.031**	0.393	0.789	0.924	0.487	0.885	**<0.001**	0.310	**0.001**	**0.029**	**0.009**	0.367	0.091	0.389	0.656
	Relax	Symmetric vs Asymmetric	**<0.001**	**<0.001**	**0.016**	0.130	0.402	0.135	0.549	0.552	0.600	0.429	**<0.001**	**0.035**	0.427	**<0.001**	0.414	0.123	0.597	0.942	0.959

$p < 0.001$). The two-way repeated measures ANOVA and post-hoc results showed that walking conditions had no significant effect on peak trunk angular velocity post-perturbation in all three planes (Table 2). However, walking conditions had significant effects on stance time and step width during both pre- and post-perturbation (Table 2A).

There was a significant interaction between arm and walking conditions on WBAM range during pre-perturbation in the frontal ($F(2,28) = 6.06$, $p = 0.007$) and horizontal ($F(2,28) = 3.90$, $p = 0.032$) planes (Table 2A, Appendix C), and a significant interaction post-perturbation between arm swing and walking conditions was found in the frontal plane ($F(2,28) = 3.60$, $p = 0.041$). There were no significant interactions between arm and walking conditions on trunk angular velocity (all planes) and step width during either pre- or post-perturbation. The results showed a significant interaction between arm and walking conditions on stance time post-perturbation ($F(2,28) = 3.75$, $p = 0.012$) (Table 2A).

4. Discussion

In this study, we assessed the effect of various arm swing and walking conditions on gait parameters before and after recovering from sudden slip perturbations in young individuals. While there were significant differences in most of the gait parameters after the perturbations, participants efficiently adapted the gait pattern to unexpected slips even when they were prevented from using their arms.

Madehkhaksar et al. (2018) suggested that evaluating gait parameters over a series of gait cycles after perturbations is a responsive measure of gait adaptations (Madehkhaksar et al., 2018). Therefore, we evaluated gait variables over the five strides following perturbations. No significant differences were found after the first two strides, which suggest that young individuals had fully recovered postural stability two strides following a sudden perturbation. Conditions in which the arms were available following the perturbation (normal and released arm conditions) used larger step width in the first 2 strides. Interestingly, when the arm motion was restricted, the statistical analyses showed no differences between step width before and after perturbations or within the five strides following the perturbation (Appendix A). These results seem counterintuitive, as we expected the bound condition to be more challenging and lead to a larger step width to quickly regain balance as reactive recovery responses are essential in sustaining dynamic stability (Marigold et al., 2003). The combined analyses of the WBAM and the CoM presented in the following paragraphs suggest that participants had to implement more drastic postural strategies to regain balance when arm motion was restricted.

Similarly to studies suggesting that arm swing before and after perturbations could affect gait parameters (Ortega et al., 2008; Meyns et al., 2013; Bruijn et al., 2010), our results showed that the different arm conditions had significant effects on most of gait parameters pre- and post-perturbations. Bruijn et al. (2010) recommended walking without arm swing prior to the perturbation, but allowing arm motion during the recovery phase could be optimal to increase postural stability (Bruijn et al., 2010). This condition was simulated using the released condition, in which participants were instructed to hold their arms still unless arm movement was necessary to maintain or regain balance, presumably in the event of a perturbation. As expected, prior to perturbations, the released and bound conditions showed similar differences in angular momentum compared to walking with normal arm motion. The absence of arm motion pre-perturbation caused a smaller angular momentum in the sagittal plane and larger values in both the frontal and horizontal planes. While the behavior of WBAM range in the sagittal plane is in line with the recommendation by Bruijn et al. (2010), results in the frontal and horizontal planes are not (Bruijn et al., 2010). Our results showed a slight advantage in the released condition due to higher angular momentum in the frontal and horizontal planes prior to perturbations. Results in the sagittal plane suggest that when participants were not allowed to move their arms, they may have tightened their control of the torso, which would reduce the WBAM range. Post-perturbation, angular momentum showed no difference between released and normal arm conditions except for the horizontal plane during asymmetric walking (0.018 vs 0.015 m/s) (Table 1, 2). This was consistent with the increased trunk angular velocity ($p = 0.057$) in the horizontal plane during asymmetric walking with released arms compared to walking with normal arm swing (80.1 vs 67.5 deg/s) (Table 1, 2).

The results showed that the perturbations led to increased WBAM range in all arm conditions both in the sagittal and frontal planes. However, following perturbations, WBAM range in the bound arm condition was significantly ($p < 0.017$) smaller compared to normal arm condition in the sagittal plane. This suggests that angular momentum might have been more strictly controlled as a strategy to maintain postural balance. It seems that young healthy participants are able to control WBAM range in the sagittal plane to compensate for the absence of arm motion both before and after a mild to moderate perturbation. This could have prevented them from falling or experiencing a larger postural instability, as WBAM must be quickly controlled to recover postural stability and avoid falls after a perturbation (Pijnappels et al.,2004, Silverman et al., 2012). This is also consistent with the smaller CoM range of motion (Table 1) in both the AP and ML directions when the arms were bound as compared to normal arm swing. This tighter control of the CoM in the bound arms condition, could explain why the participants did not need to increase step width when regaining balance. Therefore, it is possible that while regaining balance without modifying the base of support is possible during mild to moderate slip perturbations, this strategy might not be possible following perturbations of larger magnitude. The effect of arm motion during perturbations of larger magnitude remains to be assessed.

WBAM in frontal plane was smaller with the normal and released arm conditions post-perturbation, most likely to increase postural stability which is consistent with the findings of Ortega et al that arm swing has a stabilizing effect on steady-state gait in the mediolateral direction (Ortega et al., 2008). Previous research has shown that the ability to control postural stability in the ML direction is an important factor in the recovery of dynamic postural balance and requires active control (Hilliard et al., 2008; O'Connor and Kuo, 2009; Chatterjee, 2010).

Moreover, the biggest changes in peak trunk angular velocity were seen in the horizontal plane between the bound condition and both normal and released arm conditions in symmetric and asymmetric walking. For instance, in symmetric walking with bound arms, peak trunk angular velocity reached to 100.6 ± 23.9) deg/s which was significantly larger than normal arm swing (70.8 ± 14.0) deg/s) and released conditions (83.7 ± 22.0) deg/s). These findings showed the positive effects of arm swing in recovering a stable gait pattern after a perturbation, which is consistent with the recommendation of Bruijn et al. (2010).

Step width was larger in the asymmetric walking compared to symmetric walking. This is consistent with previous studies showing that during steady-state, more challenging walking conditions, such as asymmetric walking, have higher cognitive demands (Hof et al., 2007; Young et al., 2012; Hak et al., 2013b; MacLellan et al., 2013; McFadyen et al., 2009). Following an asymmetric slip, all arm conditions displayed a reduced WBAM range in sagittal plane and showed an increased step width when compared to symmetric conditions. As the perturbation is a greater challenge to postural stability than asymmetric gait, reducing the WBAM range in the sagittal plane and reducing the displacement of the CoM in both the AP and ML directions, could be an optimal postural strategy to control postural balance and avoid falling.

During asymmetric walking treadmill speed for the right leg was 20 percent slower than symmetric walking (0.96 m/s) which could be one of the reasons for increase stance time during asymmetric walking. After perturbation, stance time was decreased; this could help the subjects to regain their postural stability.

4.1. Limitation

Results from this study are only generalizable to young and healthy individuals. The level of fitness of our participants was not assessed and therefore could be a limiting factor in this study. Future research is needed to investigate the effect of arm motion and asymmetric walking following a perturbation in elderly population and fallers as factors such muscle strength and the ability to efficiently respond to perturbations could affect the recovery responses which are critical for preventing falls (Maki and McIlroy, 2006; Roos et al., 2008; Pijnappels et al., 2008). All perturbations were performed on the right side as most of the subjects (14 out of 15) were right leg dominant. The effect of various arm swing and walking conditions on gait parameters when perturbation performs on non-dominant side remains to be assessed.

5. Conclusion

Understanding of how humans control balance and recovery responses after a slip is fundamental in falls research and thus may help to reduce the incidence of falls. In this study, perturbation introduced by transiently desynchronizing the treadmill belts speed and right treadmill belt speed increased (70 percent) at the moment of heel strike. Various arm swing conditions had significant effects on most of gait parameters during pre- and post-perturbation. However, none of the participants fell following the perturbations which indicate that perturbations were mild to moderate in magnitude and participants were able to implement stabilization strategies to prevent fall. Future investigations on elderly population and fallers are needed to better determine the effects of arm swing and asymmetric walking on gait parameters after a sudden slip.

Funding

This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC, #493045-2016 and 2016-04928).

Declaration of Competing Interest

The authors declare no conflicts of interest. This funding source had no involvement in: study design; data collection, analysis and interpretation of data; the writing of the report; or in the decision to submit the article for publication.

Acknowledgement

The Authors would like to thank Courtney Bridgewater, and Cezar Mezher for their assistance with data collection.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.07.013.

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