Journal of Biomechanics 133 (2022) 110967

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Quantification of reactive arm responses to a slip perturbation

Jonathan S. Lee-Confer [a,b], Nina S. Bradley [a], Christopher M. Powers [a,*]

[a] Musculoskeletal Biomechanics Research Laboratory, University of Southern California, Los Angeles, CA, United States
[b] Verum Biomechanics, Tucson, AZ 85719, United States

ARTICLE INFO

Keywords:
Gait
Slip
Perturbation
Arms
Electromyography

ABSTRACT

The purpose of this study was two-fold: 1) characterize bilateral upper extremity responses during a slip event in both the sagittal and frontal planes, and 2) to examine the utility of using slip onset as the measurement reference for behavioral responses of the upper extremities using EMG latency. Sixteen healthy young adults were exposed to an unexpected slip during walking. Three-dimensional arm kinematics (excursions) and electromyographic onset latencies (bilateral deltoids) were quantified. Thirteen of the 16 participants recovered their balance following the slip perturbation. Of those who recovered, multi-planar arm responses were observed bilaterally. The arm contralateral to the slipping foot demonstrated significantly greater excursion in the frontal plane than the ipsilateral arm ($p < 0.001$), whereas excursions in the sagittal plane did not differ between arms ($p = 0.75$). Further, the frontal plane excursion of the contralateral arm was greater than sagittal plane excursion ($p < 0.001$). The electromyographic onset of deltoid activity was equivalent in both arms (57–76 ms), despite the differences in kinematics. Multi-plane arm motion occurs in response to a slip perturbation. Specifically, frontal plane motion of the arm contralateral to the slipping foot exhibited the greatest amount of excursion.

1. Introduction

Slip-induced falls are a major health care concern as injuries sustained from falls have been reported to result in significant health care costs (Dieleman et al., 2016). The estimated medical costs for older adults who suffered non-fatal injuries from a fall amounted to approximately 50 billion dollars in 2015 (Florence et al., 2018). Given the major health concern and high financial cost of slip and trip incidences, there is interest in understanding how individuals recover from a such events. This information is an important first step in the development of evidence-based fall prevention programs.

Previous researchers addressed how to differentiate fallers from non-fallers during a slip perturbation by investigating lower extremity responses to an unexpected slip event. Specifically, it was reported that successful recovery from a slip is achieved through knee flexor and hip extensor moments of the slipping limb to bring the slip foot back towards the body (Cham & Redfern, 2001). Furthermore, older individuals experiencing a slip have been shown to rely on lower extremity moments generated in both the frontal and sagittal plane, while younger adults rely primarily on sagittal plane moments to successfully regain balance (Liu et al., 2009).

To date, there is limited knowledge regarding arm motions or their significance, as a comprehensive evaluation of arm responses to a slip perturbation during locomotion has not been performed. Studies investigating arm responses during a slip perturbation have reported only sagittal plane kinematics. For example, individuals who experience a slip exhibit a generalized arm elevation strategy (i.e. bilateral arm flexion in the sagittal plane) (Marigold et al., 2003; Nazifi et al., 2020). It was further reported that the arm ipsilateral to the slipping foot may flex or extend, with the later occurring during instances of greater slip severity (Merrill et al., 2017). A theoretical and mathematical model of slipping has suggested that sagittal plane arm motions serve to counter a backwards loss of balance during a slip by decreasing the trunk extension velocity (Troy et al., 2009).

Thus far, studies have not specifically explored arm responses in the frontal plane during a slip. One study reported that 18 of 30 participants exhibited non-sagittal plane arm responses, however the specifics of these motions (i.e. magnitudes, planes of motion) were not reported (Troy et al., 2009). Theoretically, frontal plane motion of the arms during slipping would act to limit lateral displacement of the center of mass to assist in recovery. Evidence in support of this premise is provided by a study that reported medial–lateral perturbations induced by a moving platform with voluntary abduction of the arm contralateral to the direction of the perturbation minimized the lateral excursion of the

---

* Corresponding author at 1540 E. Alcazar Street, CHP-155, Los Angeles, CA 90089, United States.
E-mail address: powers@pt.usc.edu (C.M. Powers).

https://doi.org/10.1016/j.jbiomech.2022.110967
Accepted 17 January 2022

center of mass (Grin et al., 2007).

Not only is there limited knowledge of arm motions during slipping, there also is a lack of information related to arm muscle onset timings as individuals recover from a slip. Further, the interpretation of muscle onset data as determined by electromyography (EMG) is challenging owing to differences in the temporal ranges reported and the types of perturbations employed. For example, a study reported that the average EMG onset latency for the deltoid muscle ranged from 143 to 150 ms in both arms during a slip perturbation (Marigold et al., 2003). On the other hand, a different study reported a deltoid muscle onset of 58 ms following a trip perturbation,(Pijnappels et al., 2010) which is similar to the reported ranges of 65–80 ms during treadmill-induced perturbations (Dietz et al., 2001). Apart from the potential influence of the types of perturbations evaluated, discrepancies in muscle onset timing among studies may be related to the methods used to quantify EMG onset latency. Previous studies that examined neuromuscular latencies during slipping defined slip initiation as the time of foot contact with the floor (Cham & Redfern, 2001; Marigold et al., 2003; Marigold & Patla, 2002). This is potentially problematic as slip initiation has been reported to occur anywhere between 50 and 120 ms following initial contact (Cham & Redfern, 2002; Lockhart & Kim, 2006). It is likely that accounting for individual variability in the onset of slip initiation may result in a more accurate and less variable assessment of neuromuscular responses during a slip perturbation.

Given that multi-plane arm motion likely is important in recovering from a slip event, the purpose of the current study was two-fold: 1) characterize bilateral upper extremity responses during a slip event in both the sagittal and frontal planes, and 2) to examine the utility of using slip onset as the measurement reference for behavioral responses of the upper extremities using EMG latency. Information gained from this study will provide insight into the kinematic responses to a slip perturbation with the intent to better inform slip and fall prevention programs.

2. Methods

2.1. Participants

Sixteen young, healthy participants between the ages of 21 and 35 participated in this study (9 males and 7 females). Prior to participation, all were informed of the nature of the study, and provided written informed consent as approved by the University of Southern California Health Science Campus Institutional Review Board. After providing informed consent, participants completed a medical questionnaire to screen for possible conditions that could jeopardize their safety by participating in the study. Specifically, individuals were excluded from participation if they reported any of the following: neurological or orthopedic conditions that would affect gait, current muscle strains or joint sprains, recent bone fractures, or previous back injuries.

3. Instrumentation

All gait trials were conducted on a 10-meter walkway. Ground reaction forces were recorded at 1500 Hz using an AMTI force plate (46 × 50 cm) imbedded in the middle of the walkway (Model OR6-6 1000 Advanced Mechanical Technology, Inc., Watertown, MA). The force plate was covered with smooth vinyl composition tile (similar to the rest of the laboratory floor). Mineral oil was placed on the tile to reduce the coefficient of friction to induce slipping.

To prevent falls during testing, a fall-arresting body harness (Miller Model 550–64, Dalloz Fall Protection, Franklin, PA, USA) secured with an 8 mm climbing rope was attached to an overhead low-friction trolley. An Omega S-beam load cell (Omega Engineering Inc., Norwalk, CT, US) connected the climbing rope to the trolley system was used to measure the amount of supported bodyweight during the slip perturbation trials. To control for the influence of footwear, participants were provided with a pair of oxford dress shoes with a standard rubber outer sole (Bates Footwear, Richmond, IN, US).

Three-dimensional motion analysis was performed using an 11-camera motion analysis system (Qualisys, Gothenburg, Sweden) collecting at 150 Hz. Seventy-six reflective markers placed over specific anatomical locations were used to quantify upper and lower extremity kinematics. EMG data were collected at 1,500 Hz using bipolar Ag/AgCl surface electrodes with an inter-electrode distance of 22 mm (Noraxon U.S.A. Inc., Scottsdale, AZ, USA). The EMG system had a differential input impedance of greater than 100 MOhm, a common-mode rejection ratio greater than 100 dB.

4. Procedures

Prior to testing, an adjustable fall arresting harness was fitted to the participant. The harness was adjusted so that the hip would not be permitted to drop below a distance equal to 35% of participants' height (Yang & Pai, 2011). Participants were then instrumented with a full body marker set. Reflective joint markers were placed on the L5S1, Xyphoid Process, and C7, and markers were placed bilaterally on the: second toe, fifth metatarsal head, first metatarsal head, lateral and medial malleolus, lateral and medial epicondyles of the femur, greater trochanter, anterior superior iliac spine, iliac crest, posterior superior iliac spine, acromioclavicular joint, anterior and posterior glenohumeral joint, greater tubercle, lateral and medial epicondyle of the humerus, radial and ulnar styloid processes, and the third metacarpal head. Additionally, a head band fitted with four markers was used to track the head, and marker tracking clusters were placed bilaterally on the heel, shank, thigh, upper arm, and forearm. A static calibration trial was obtained to establish the local segmental coordinate system and joint centers.

EMG preparation included cleaning the skin over the lateral aspect of the deltoid muscle (bilaterally) with an alcohol swab. Surface EMG electrodes were secured to the right and left middle deltoids. Electrodes were placed on the muscle belly between the acromion and the lateral epicondyle of the humerus and on the bulge of the deltoid (Hermens et al., 1999).

The lighting in the laboratory was dimmed prior to the walking trials. Participants were permitted multiple practice walking trials to adjust to the harness system and to achieve a consistent walking speed of 1.35–1.5 m/s. Gait speed was monitored using photoelectric light switches. Trials in which the prescribed gait speed was not achieved were discarded and repeated. To avoid anticipatory gait changes to a potential perturbation, care was taken by slightly dimming the lighting so that participants were unaware of which trial the contaminant would be applied (Heiden et al., 2006; Siegmund et al., 2006).

Non-slip practice trials were performed to allow participants to practice achieving the target gait speed. During these practice trials each participant's start position was adjusted so that right foot would consistently land on the force platform. Following the accommodation period, kinematic data were obtained during four non-slip walking trials. Between each trial, participants faced away from the walkway for one minute so that they would be uncertain as to the trial in which a contaminate would be placed on the floor to induce a slip. Loud music was played during each of the one-minute breaks between trials to act as an additional distraction and avoid the participant hearing the application of the contaminant. After obtaining the four non-slip walking trials, the mineral oil contaminate was placed on the tile covering the force plate. Following the slip trial, participants were asked if they had anticipated the slip or if they had seen the contaminant. Any anticipation or observation of the contaminant would have resulted in the subject being excluded from this study. All participants were slipped on their right foot and were only exposed to one slip during the study.

4.1. Data analysis

For purposes of this study, only data from participants who recovered their balance immediately following the slip were used for analysis. The outcome of the slip, recovery or fall, was determined by the load cell. An outcome was classified as a fall if the individual placed more than 30% of their body weight onto the harness system (Yang & Pai, 2011).

Kinematic data were filtered using a second order, 6 Hz, low pass Butterworth filter with zero-lag compensation. Fifteen body segments (head, pelvis, thorax, and bilateral feet, shank, thigh, upper arm, forearm, and hand) were created through a custom designed model template using Visual 3D software (C-Motion, Inc., Germantown, MD, USA). The global coordinate system was defined with Y as the anterior-posterior axis, X as the medio-lateral axis and Z as the vertical axis. The coordinate system for the upper extremities and thorax were based on the work of Wu et al (Wu et al., 2005). Processing of the shoulder angles were calculated using the upper arm relative to the thorax and a Euler sequence of Y-X-Z (frontal, sagittal, transverse plane).

For each arm, the frontal and sagittal plane time-series kinematics from the slip trial were compared to the average time series data of the four non-slip trials. The onset of arm excursion during the slip trial was defined as the point where the arm motion exceeded 1 standard deviation from the average arm motion during the non-slip trials (Fig. 1). Arm excursion was calculated by taking the difference between the arm angle at time of deviation from the baseline trials and the maximum displacement during the slip event as determined by the peak in the curve.

EMG signals were band-pass filtered (20–500 Hz) and full wave rectified. A custom-written Matlab program (Matlab, Natick, MA, USA) was used to calculate a root-mean-square EMG envelope using a 30 ms moving window. The envelope selection was based on previous research showing that an envelope size greater than 30 ms introduces a temporal shift in the signal thereby influencing the determination of EMG onset time (Merletti, 1999).

To determine the onset time of the deltoid muscle activity, the processed EMG data for the four non-slip trials were averaged. The onset of muscle activity was defined as the point at which the EMG from the slip trial exceeded one standard deviation from the average non-slip trial activity for at least 50 ms (Hodges & Bui, 1996). The neuromuscular latencies were calculated using two methods: 1) the time from slip initiation to the onset of muscle activation (SI method), and 2) the time from initial contact with the ground to the onset of muscle activation (IC method).

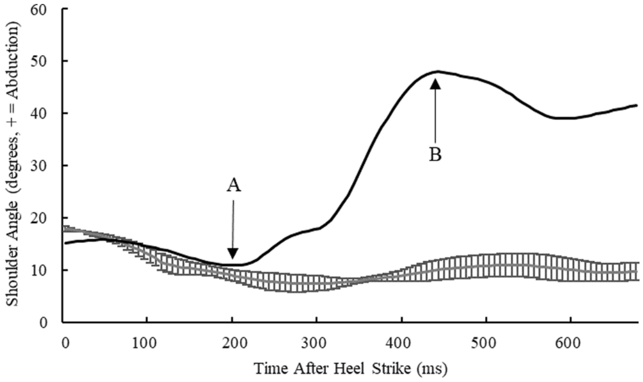

Fig. 1. Illustration of the method used to calculate arm excursion (representative participant). The light gray line is the average arm motion from three non-slip trials with one standard deviation indicated by the shaded region. The black line is the arm motion during the slip trial. Time point “A” defines the moment when the arm angle during the slip trial deviates from the one standard deviation of the baseline trials. Time “B” indicates the arm angle at its’ maximum value. Total arm excursion was calculated by subtracting the arm angle at time point “A” from time point “B”.

To determine slip initiation, the integrated sum of the vertical force data during the four non-slip trials were calculated and averaged. The onset of the slip was defined as the time point when the integrated-sum of the vertical force during the slip trial deviated more than two standard deviations from the averaged integrated-sum of the vertical force of the non-slip trials (Herzog et al., 1989). For the IC method, foot contact was defined as the point at which the ground reaction force exceeded 15 N (Marigold et al., 2003).

4.2. Statistical analysis

Normality of the dependent variables of interest was assessed using Jarque-Bera Test. A two-way ANOVA with repeated measures was performed to test for differences in excursions between the right arm (ipsilateral to the slipping foot) and the left arm (contralateral to the slipping foot) in both the frontal and sagittal planes. Similarly, a two-way ANOVA (arm × method) with repeated measures was performed to compare differences in EMG onset latencies between the right deltoid (ipsilateral arm to the slipping foot) and left deltoid (contralateral arm to the slipping foot) using the two measurement methods for calculating EMG onset latencies. In the case of a significant interaction for either of the ANOVA tests described above, post-hoc pair-wise comparisons were made using Tukey’s Honest Significance Difference (HSD) test. Statistical analyses were performed using SPSS 16.0 software (SPSS, Chicago, IL, USA). Significance levels were set at $p < 0.05$.

5. Results

Of the 16 individuals that participated in this study, three experienced a fall based on the load cell data. As such the results presented below are from the 13 participants who recovered their balance from the slip event. The results of the two-way repeated measures ANOVA revealed a significant arm × plane of motion interaction ($F(1,12) = 24.7$, $p < 0.001$). Post-hoc testing revealed that the arm contralateral to the slipping foot demonstrated significantly greater excursion than the ipsilateral arm in the frontal plane (61.7 ± 26.9 degrees vs. 7.6 ± 7.1 degrees, $p < 0.001$, Fig. 2). There were no significant differences between the contralateral arm and the ipsilateral arm in the sagittal plane (18.2 ± 18.9 degrees vs. 20.5 ± 17.6 degrees, $p = 0.75$, Fig. 3). However, post-hoc testing for within arm comparisons revealed that the arm contralateral to the slipping foot exhibited greater excursion in the frontal plane compared to the sagittal plane (61.7 ± 26.9 degrees vs.

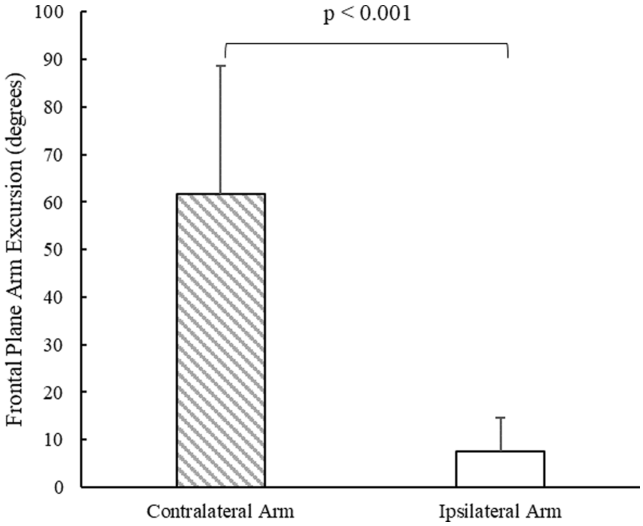

Fig. 2. Comparison of frontal plane excursions of the arms contralateral and ipsilateral to the slipping foot ($n = 13$).

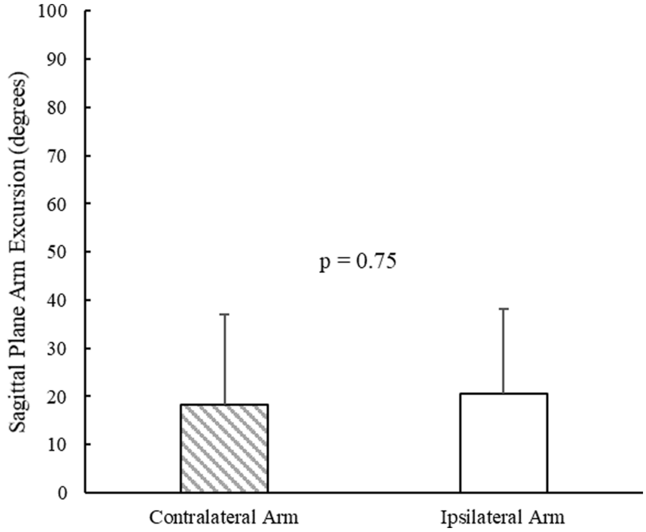

Fig. 3. Comparison of sagittal plane arm excursion (contralateral and ipsilateral) to the slipping foot (n = 13).

18.2 ± 18.9 degrees, $p < 0.001$, Fig. 4). In contrast, sagittal plane excursion was significantly greater than the frontal plane excursion in the ipsilateral arm (20.5 ± 17.6 degrees vs. 7.6 ± 7.1 degrees, $p < 0.01$, Fig. 5).

Differences also were found between the two reference methods for calculating deltoid EMG onset latency (initial foot contact versus the onset of slip). The average time from initial contact to slip initiation was 74 ± 14 ms. The results of the 2-way ANOVA did not reveal a significant arm (ipsilateral, contralateral) × method interaction (F (1,12) = 0.00, p = 0.983) or main effect for arm (p = 0.716). However, the effect of measurement method was significant ($p < 0.001$). When averaged across the ipsilateral and contralateral arms, the deltoid EMG onset latencies for the SI method were significantly shorter than the IC method (64.4 ± 5.9 vs 138.5 ± 11.1, $p < 0.001$, Table 1). Across subjects, the SI method also yielded a smaller total range in deltoid onset latency (19 ms) than the IC method (31 ms). Additionally, the SI method yielded more consistent values across all participants as demonstrated by the lower standard deviations when compared to the IC method.

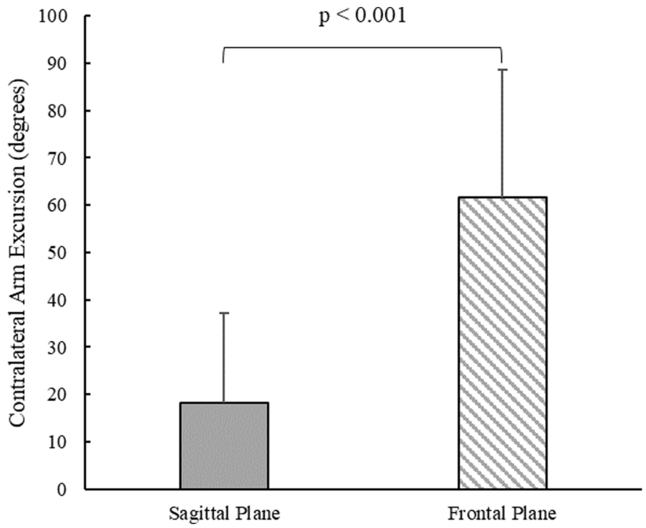

Fig. 4. Comparison of sagittal and frontal plane excursions of the arm contralateral to the slipping foot (n = 13).

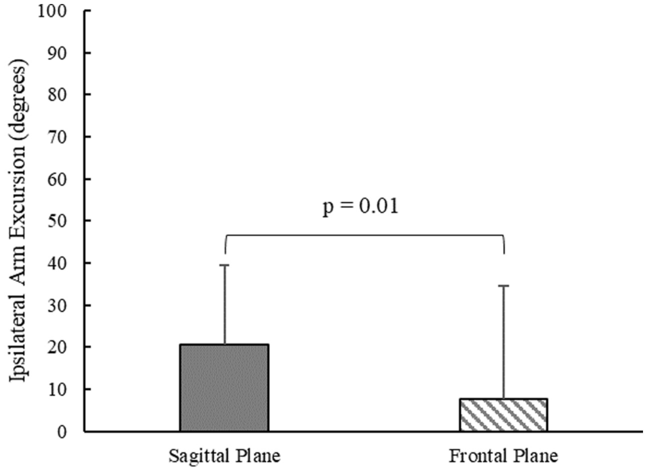

Fig. 5. Comparison of sagittal and frontal plane excursions of the arm ipsilateral to the slipping foot (n = 13).

Table 1
Comparison of the two methods to quantify EMG onset latencies of the deltoid muscles (N = 13). Values represent mean ± SD (range).

	Initial Contact Method	Slip Initiation Method
Right Deltoid (ipsilateral)	139.3 ± 12.1 ms (126–157)	65.1 ± 5.4 ms (58–74)
Left Deltoid (contralateral)	137.8 ± 10.6 ms (127–157)	63.6 ± 6.6 ms (57–76)
Average (ipsilateral and contralateral)	138.5 ± 11.1 ms	64.3 ± 5.9 ms*

*Significantly different when averaged across ipsilateral and contralateral arms ($p < 0.001$).

6. Discussion

The purpose of the current study was to identify and differentiate arm responses during a slip perturbation. We also examined the use of two different measurement methods for quantifying EMG onset of deltoid activity. Bilateral arm responses were observed in all participants during the slip trials and both arms exhibited motions in the sagittal and frontal planes, suggesting that multi-plane arm motion is important in recovering from a slip event. In addition, referencing deltoid muscle activity onset to slip onset as opposed to initial contact resulted in varied onset times and impacted measurement variability.

The largest arm excursions were observed in the frontal plane of the arm contralateral to the slipping foot. On average, this motion was almost three times greater than any other arm response observed. We surmise that this motion plays in important role in reducing the lateral excursion of the center of mass during a slip perturbation. As illustrated in Fig. 6, contralateral arm abduction was accompanied by a lateral trunk lean towards the slipping foot in all participants. We postulate that this motion may have served to reduce frontal plane center of mass excursion and velocity induced by the lateral trunk lean. This premise is consistent with a previous study that reported that contralateral arm abduction during a platform perturbation acts to reduce frontal plane center of mass excursion (Grin et al., 2007). Ultimately, contralateral arm abduction may be important in preventing a laterally directed fall which has been implicated as being a primary cause of fall related hip fractures in the elderly (Greenspan et al., 1998; Nankaku et al., 2005).

In contrast to frontal plane excursions, sagittal plane excursions were similar between the contralateral and ipsilateral arms (18.2 and 20.5 degrees of flexion, respectively). Two studies reported bilateral arm flexion motion in response to a slip perturbation but did not quantitatively compare excursions between arms in their studies (Marigold et al.,

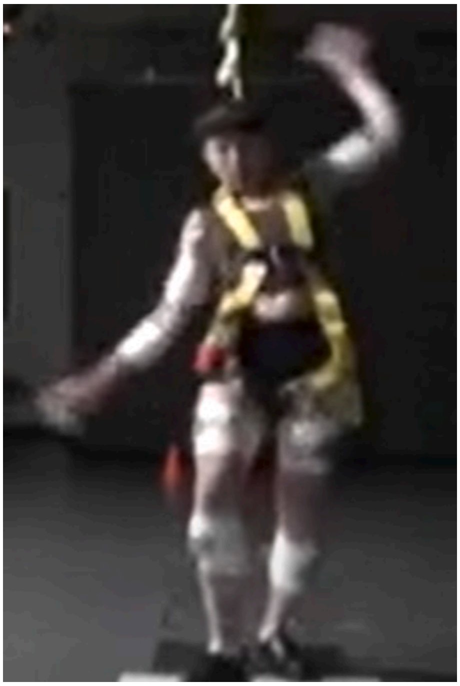

Fig. 6. Snapshot of a participant demonstrating contralateral arm abduction in conjunction with a lateral trunk lean towards the slipping foot (right).

2003, Troy et al., 2009). However, our findings are consistent with Merrill (2017) who reported sagittal plane motion of the arm ipsilateral to the slipping foot (14.8 ± 30.8 degrees). As noted above, Troy (2009) have suggested that the sagittal plane motion reduces backward trunk velocity and the likelihood of losing balance in the sagittal plane.

We evaluated the impact of two methods for measuring EMG onset latencies of the deltoid muscles. Our results using initial contact as the reference point, yielded a latency range of 126 ms to 154 ms which is similar to values reported by Marigold (2003) (143 to 150 ms) who used a similar method. However, EMG onset latencies using the SI method were considerably shorter and yielded a between-subject variability less than half that of IC measures.

The EMG onset latencies using the SI method in the current study are similar to studies that examined reactions to various perturbations during locomotion. In a study involving a trip perturbation, the EMG onset latency of the deltoids was reported to be as short as 58 ms (Pijnappels et al., 2010). A separate study that induced treadmill perturbations during walking and reported that EMG responses of the tibialis anterior and deltoid muscle occurred between 75 and 80 ms (Dietz et al., 2001). The calculation of EMG onset latency using the SI method may provide a more reliable and less variable approximation of neuromuscular responses during a slip than using previously implemented methodologies of initial contact. Given the substantial reduction in between-subject variability using the SI method, we propose that referencing muscle activity onset to onset of slip may be a more valuable measure for future studies examining the relationship between muscle activity and kinematics and/or behavioral strategies.

Falls are more likely to occur when the center of mass moves beyond the base of support. During slipping, successful recovery appears to be dependent on controlling the center of mass excursion such that re-alignment of the body over the slipping foot is possible (Cham & Redfern, 2001). Although it was beyond the scope of the current paper to quantify the specific biomechanical influences of arm motions on slip recovery, it is reasonable to assume that the multi-planar arm motions described here function to assist in minimizing center of mass excursions during slipping. Specifically, our results suggest that frontal plane arm motions during slipping may minimize the loss of balance in the medio-lateral direction thereby improving recovery performance.

The results of current study should be viewed in light of its limitations. First, the Euler sequencing order used to quantify the shoulder angles of the upper arm relative to the thorax can influence angular excursions reported. The Euler sequencing selected for this study was based on preliminary observations of higher degrees of frontal plane motion relative to sagittal plane motion. As such, we used the recommended Euler sequencing for primary abduction motion (Senk & Cheze, 2006). However, care must be taken in comparing our results to studies that used different Euler sequencing for shoulder angle calculations. Second, our participants were young, healthy adults. With this in mind, our findings may not be generalizable to older adults or persons with various clinical conditions (i.e. stroke, etc.).

7. Summary

Multi-plane arm motion occurs in response to a slip perturbation. Specifically, frontal plane motion of the arm contralateral to the slipping foot exhibited the greatest amount of excursion. EMG onset latencies of the deltoid muscles were found bilaterally to occur as early as 57 ms following slip initiation despite differences in arm kinematics. A temporal reference based on onset of the actual slip appears to reduce both measurement magnitude and variability.

CRediT authorship contribution statement

Jonathan S. Lee-Confer: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Nina S. Bradley:** Methodology, Resources, Writing - review & editing, Supervision. **Christopher M. Powers:** Methodology, Resources, Writing - review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Cham, R., Redfern, M.S., 2001. Lower extremity corrective reactions to slip events. Journal of biomechanics 34 (11), 1439–1445. https://doi.org/10.1016/S0021-9290(01)00116-6.

Cham, R., Redfern, M.S., 2002. Heel contact dynamics during slip events on level and inclined surfaces. Safety Science 40 (7–8), 559–576. https://doi.org/10.1016/S0925-7535(01)00059-5.

Dieleman, J.L., Baral, R., Birger, M., Bui, A.L., Bulchis, A., Chapin, A., Hamavid, H., Horst, C., Johnson, E.K., Joseph, J., Lavado, R., Lomsadze, L., Reynolds, A., Squires, E., Campbell, M., DeCenso, B., Dicker, D., Flaxman, A.D., Gabert, R., Highfill, T., Naghavi, M., Nightingale, N., Templin, T., Tobias, M.I., Vos, T., Murray, C.J.L., 2016. US spending on personal health care and public health, 1996–2013. Jama 316 (24), 2627. https://doi.org/10.1001/jama.2016.16885.

Dietz, V., Fouad, K., Bastiaanse, C.M., 2001. Neuronal coordination of arm and leg movements during human locomotion. European Journal of Neuroscience 14 (11), 1906–1914.

Florence, C.S., Bergen, G., Atherly, A., Burns, E., Stevens, J., Drake, C., 2018. Medical costs of fatal and nonfatal falls in older adults. Journal of the American Geriatrics Society 66 (4), 693–698.

Greenspan, S.L., Myers, E.R., Kiel, D.P., Parker, R.A., Hayes, W.C., Resnick, N.M., 1998. Fall direction, bone mineral density, and function: Risk factors for hip fracture in frail nursing home elderly. American Journal of Medicine 104 (6), 539–545. https://doi.org/10.1016/S0002-9343(98)00115-6.

Grin, L., Frank, J., Allum, J.H., 2007. The effect of voluntary arm abduction on balance recovery following multidirectional stance perturbations. Experimental brain research 178 (1), 62–78. https://doi.org/10.1007/s00221-006-0711-4.

Heiden, T.L., Sanderson, D.J., Inglis, J.T., Siegmund, G.P., 2006. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. Gait & posture 24 (2), 237–246. https://doi.org/10.1016/j.gaitpost.2005.09.004.

Hermens, H.J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Hägg, G., 1999. European recommendations for surface electromyography. Roessingh research and development 8 (2), 13–54.

Herzog, Walter, Nigg, B.M., Read, L.J., Olsson, Ewa, 1989. Asymmetries in ground reaction force patterns in normal human gait. Med Sci Sports Exerc 21 (1), 110–114.

Hodges, P.W., Bui, B.H., 1996. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor*. Control 101 (6), 511–519. https://doi.org/10.1016/S0921-884X(96)95190-5.

Liu, J., Lockhart, & Thurmon. 2009. Age-related joint moment characteristics during normal gait and successful reactive-recovery from unexpected slip perturbations. *Gait & Posture*, *30*(3), 276–281. 10.1016/j.gaitpost.2009.04.005.

Lockhart, T.E., Kim, S., 2006. Relationship between hamstring activation rate and heel contact velocity: factors influencing age-related slip-induced falls. Gait & Posture 24 (1), 23–34. https://doi.org/10.1016/j.gaitpost.2005.06.016.

Marigold, D.S., Bethune, A.J., Patla, A.E., 2003. Role of the Unperturbed Limb and Arms in the Reactive Recovery Response to an Unexpected Slip During Locomotion. Journal of Neurophysiology 89 (4), 1727–1737. https://doi.org/10.1152/jn.00683.2002.

Marigold, D., Patla, A.E., 2002. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. Journal of Neurophysiology 88 (1), 339–353. https://doi.org/10.1152/jn.00691.2001.

Merletti, R., Di Torino, P.J.J.E.K., 1999. Standards for reporting EMG data. J Electromyogr Kinesiol 9 (1), 3–4.

Merrill, Z., Chambers, A.J., Cham, R., 2017. Arm reactions in response to an unexpected slip—Impact of aging. Journal of biomechanics 58, 21–26. https://doi.org/10.1016/j.jbiomech.2017.04.011.

Nankaku, M., Kanzaki, H., Tsuboyama, T., Nakamura, T., 2005. Evaluation of hip fracture risk in relation to fall direction. Osteoporosis International 16 (11), 1315–1320. https://doi.org/10.1007/s00198-005-1843-2.

Nazifi, M.M., Beschorner, K., Hur, P., Masani, K., 2020. Angular momentum regulation may dictate the slip severity in young adults. PLoS ONE 15 (3), e0230019. https://doi.org/10.1371/journal.pone.0230019.

Pijnappels, M., Kingma, I., Wezenberg, D., Reurink, G., Van Dieën, J.H., 2010. Armed against falls: the contribution of arm movements to balance recovery after tripping. Experimental brain research 201 (4), 689–699. https://doi.org/10.1007/s00221-009-2088-7.

Senk, M., Cheze, L., 2006. Rotation sequence as an important factor in shoulder kinematics. Clinical Biomechanics 21, 3–8. https://doi.org/10.1016/j.clinbiomech.2005.09.007.

Siegmund, G.P., Heiden, T.L., Sanderson, D.J., Inglis, J.T., Brault, J.R., 2006. The effect of subject awareness and prior slip experience on tribometer-based predictions of slip probability. Gait & posture 24 (1), 110–119. https://doi.org/10.1016/j.gaitpost.2005.08.005.

Troy, K.L., Donovan, S.J., Grabiner, M.D., 2009. Theoretical contribution of the upper extremities to reducing trunk extension following a laboratory-induced slip. Journal of biomechanics 42 (9), 1339–1344. https://doi.org/10.1016/j.jbiomech.2009.03.004.

Wu, G.e., van der Helm, F.C.T., (DirkJan) Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. Journal of biomechanics 38 (5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042.

Yang, F., Pai, Y.-C., 2011. Automatic recognition of falls in gait-slip: a harness load cell based criterion. Journal of Biomechanics 2 44 (12), 2243–2249.