Published in final edited form as:
J Biomech. 2017 June 14; 58: 21–26. doi:10.1016/j.jbiomech.2017.04.011.

Arm Reactions in Response to An Unexpected Slip—Impact of Aging

Zachary Merrill[1], **April J. Chambers**[1], and **Rakié Cham**[1]

[1]Department of Bioengineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Abstract

Slips and falls represent a serious public safety concern in older adults, with the segment of the United States population over the age of 65 accounting for about three quarters of all fall related deaths. The majority of falls in older adults are due to trips and slips. The objective of this study was to investigate how age affects arm reactions generated in response to unexpected slips. Thirty-three participants divided into two age groups (16 young, 17 old) participated in this study. Participants were exposed to two conditions: known dry walking (baseline) and an unexpected slip initiated when stepping onto a glycerol-contaminated floor. The upper extremity parameters of interest included the timing and amplitude of the shoulder flexion moment generated in response to the slip as well as the resulting angular kinematics (trajectories). The analysis of the kinetic data revealed a delayed shoulder flexion reaction to slips in older adults compared to their young counterparts, as well as a greater flexion moment magnitude. Knowledge of such upper body reaction mechanisms to unexpected slips may help to improve balance recovery training in older adults, as well as aid in the implementation of environmental modifications, e.g. handrails, to reduce falls-related injuries.

Keywords

Slipping; upper body reactions; aging

Introduction

Falls are a serious concern in older adults, with the segment of the United States population over the age of 65 years contributing to over 80% of all fall related deaths (Centers for Disease Control, 2014). Within this older population, fall-related injuries account for about $19 billion in annual medical costs (Hanley et al., 2011). Falls are also a hazard in occupational settings. More specifically, in 2014, the Bureau of Labor Statistics estimated

---

Corresponding Author: Zachary Merrill, (412) 624 9261, zfm1@pitt.edu, Department of Bioengineering, 302 Benedum Hall, 3700 O'Hara St., Pittsburgh, PA, 15260.

Conflict of Interest Statement

There are no conflicts of interest to report for any of the authors involved.

that approximately 50% of the total workplace injuries for the over 65 years age group are due to accidental environment related falls, such as trips and slips (Bureau of Labor Statistics, 2014). Falls incidence in the workplace will continue to rise as the labor force ages, with 25% of the workers predicted to be over the age of 55 years in 2022 compared to nearly 12% in 1992 (Toossi, 2013).

Upper limb fractures are among the most common fall-related fractures in older adults, with nearly 90% of humeral fractures being caused by falling, and the incidence of fractures continuously increasing over 45 years old (Kim et al., 2012). This increase in fracture rate is likely due to two factors (1) reduced bone density in older adults, and (2) fundamental differences in the way arms are used when balance is perturbed, leading to more injurious falls in older adults. For example, a shorter body braking time, defined as the period between contacting the ground and stopping motion, which leads to increased peak contact forces when contacting the ground has been reported in older adults (Kim and Ashton-Miller, 2003).

The role of upper extremities in balance recovery during perturbed stance or perturbed gait is important to understand for two main reasons: (1) this information is needed to understand and to reduce the increased incidence of upper extremity fractures in older adults, and (2) identify potential fundamental differences in the way arms are used in response to slips and trips between young and older adults. The following three potential non mutually-exclusive goals of arm responses have been hypothesized in the literature: (1) reaching for an external support, such as a hand rail (King et al., 2009; King et al., 2011, McIlroy and Maki, 1995), (2) contributing to balance recovery by moving the arms to counteract the effect of the perturbation during standing (Allum et al., 2002; Hof, 2007; Maki and McIlroy, 1997; Pozzo et al., 2001) or walking, e.g. moving the arms forward and up to counteract a backward slip during walking (Misiaszek, 2003; Oates et al., 2005; Pijnappels et al., 2010; Roos et al., 2008; Tang and Woollacott, 1998) and (3) preparing for impact with the ground as a protective measure (Allum et al., 2002; Hsiao and Robinovitch, 1998; McIlroy and Maki, 1995; O’Neill et al., 1994; Roos et al., 2008). Arm responses and their contribution to a postural strategy may be modulated by the nature of the perturbation, e.g. direction and severity, and age. More specifically, prior studies have determined that older adults tend to show delayed and smaller magnitude reactions than young adults (Allum et al., 2002; Tang and Woollacott, 1998). Additionally, the two age groups may exhibit arm movements in different directions when exposed to specific types of base of support perturbations such as toes-up rotations during standing (Allum et al., 2002), with the young participants moving their arms in the opposite direction of the platform tilt, and the older participants moving their arms in the same direction as the platform. Another study by Roos et al. (2008) has specifically shown age related differences in arm response to trips, with younger adults using arm elevation presumably to slow trunk angular momentum, and older adults reaching anteriorly for support, suggesting older participants are preparing for impact with the ground.

The specific triggering mechanism of arm responses is also a subject of debate. Specifically, cues affecting both the upper and lower extremities, e.g. vestibular cues or external cues, would cause arm and leg responses to occur simultaneously, but postural cues due to leg reactions would cause the arm reactions to occur after the leg reactions. For example, in studies where perturbations were triggered by treadmill deceleration, waist-jolt application, and a simulated slip on rollers, shoulder muscles activated at about the same time as leg muscles (Dietz et al., 2001; Marigold et al., 2003; Misiaszek, 2003). Another contrasting study found that shoulder muscle activation onsets were noticeably later than leg reactions in response to base of support translations during stance (Romick-Allen and Schultz, 1988), i.e a leg-to-arm postural strategy was used.

The objective of this study is two-fold, as follows:

1. To determine the impact of age on arm responses to unexpected realistic slips. More specifically, the magnitude and timing of shoulder reactive moments and angles will be the primary outcome variables. We hypothesize that older adults will exhibit a delayed response compared to their younger counterparts.
2. To determine if these responses are modulated by the severity of the slips within the younger and older age groups. We hypothesis that arm responses to unexpected slips will vary with the severity of the slip.

Methods

Thirty three participants (N=33), still employed and holding full-time jobs, participated in this study, which was approved by the University of Pittsburgh Institutional Review Board. Written informed consent was obtained prior to any screening and experimental procedures. Two age groups were considered: (1) young adults including 16 participants (7 female) aged 20 to 31 years, and (2) older adults including 17 participants (10 female) aged 50 to 65 years (Table 1). While the older adult group included in this study is younger than typical older adult groups considered in geriatric research, the age groups of interest in this study represent older and young adults that are in the labor force. Participants were subjected to a thorough screening clinical exam and vestibular testing performed by a neurologist expert in vestibular and balance disorders. Exclusion criteria included clinically significant histories or neurological, orthopedic, or cardiovascular conditions that impede normal gait and balance.

The experimental set-up consisted of an 8.5m level vinyl tile walkway specially designed for gait studies, with two forceplates (4060A, Bertec, Inc.) embedded into the floor. Placement of the forceplates was adjusted to maximize the chance of landing each foot on one and only one forceplate (based on mean step length/width of young and middle-aged adults). Vinyl tile sample floors matching the rest of the walkway's flooring material covered the force platforms. Whole body motion was tracked with a 14-camera Vicon system (Vicon Motion Systems Ltd, Oxford, UK). Forceplate and motion capture data were synchronized and sampled at 1080 and 120 Hz, respectively. All subjects wore the same brand and model of polyvinyl chloride (PVC) sole shoes, a common shoe sole material worn in the workplace. For slippery surface conditions, 90 mL of diluted glycerol solution (75% glycerol, 25% water by volume) was uniformly applied onto the leading/left foot – forceplate interface. The coefficient of friction at the shoe-floor interface during the dry trials was 0.53, compared to 0.03 for the glycerol-contaminated trials, as measured with an English XL VIT

Slipmeter (Excel Tribometers, LLC). A harness system with an overhead trolley is used to catch the subject in case of an irrecoverable fall.

We started the testing procedures with a study team member verbally explaining to the subject the overall goal of this study. The subject was reassured that he/she would be caught by the harness in a case of an irrecoverable fall, thus emphasizing the importance of walking as naturally as possible throughout the experiment. Next, subjects were equipped with the safety harness and instrumented with the motion capture markers (body and shoes as detailed in Moyer et al., 2009). Subjects were instructed to walk at a comfortable pace and allowed to practice walking across the walkway. During these practice trials, an experienced researcher adjusted the subject's starting point and instructed him/her to start walking with his/her right or left leg such that he/she contacted the leading forceplate with the left foot. Once a natural gait is achieved under these conditions (typically 3–5 practice trials are needed), data collection begins. Prior to each trial (dry and slippery), the subject was asked to walk to his/her starting line, face away from the walkway, wait for 1–2 minutes while listening to loud music, distracting him/her from a possible contaminant application on the floor. At the end of the waiting period, the lights were dimmed to prevent the identification of the floor's slipperiness condition. The subject was reminded to walk naturally at a self-selected pace prior to each trial, then he/she turned around and walked while looking straight ahead at the opposite wall. The participants were exposed to two environmental conditions: (1) dry floor (baseline condition), and (2) unexpected slippery floor. Three to five baseline dry trials were collected followed by the unexpected slippery condition. Because the same testing procedures were used for each trial, the subject was not aware of the location or timing of the unexpected slip trial, thus minimizing potential anticipation effects. For more details related to the experimental research, the reader is referred to prior research by the study team (Beschorner and Cham, 2008; Cham and Redfern, 2001; Cham and Redfern, 2002; Chambers and Cham, 2007; Chambers et al., 2013; Chambers et al., 2014; Moyer et al., 2006; Moyer et al., 2009; O'Connell et al., 2016).

The left (ipsilateral to the slipping foot) angular trajectory of the shoulder and the reactive shoulder moment (magnitude and timing characteristic) in the sagittal plane were of interest. The reason for the focus on the left upper extremity is that the right shoulder is fully flexed at the time of slip initiation (left heel contact onto the slippery area). Specific outcome variables of interest that were derived include the timing and peak magnitude of the shoulder reactive moment and the slip-related deviation of the shoulder flexion angle from the baseline trajectory (Table 2). Flexion angles were determined with a 3D Euler decomposition of the upper arm relative to the torso (based on reflective markers on the shoulder, elbow, and torso), and moments were determined using a custom 3D kinetic model. For details regarding the derivation of these outcome variables, the reader is referred to the doctoral work of Moyer (2006). During severe slips, participants may have slipped beyond the force plate area or used the harness for support later during the slip. The kinematic and kinetic data were considered only prior to these times. Additionally, there were no nearby supports (such as handrails) for the participants to attempt to grasp.

The onset and peak timing and magnitude measurements for the reactive moment and angular deviation were determined by simultaneously plotting the baseline dry and slipping trials for each angle (example in Figure 1), and selecting the point at which the slip trial parameter began to deviate from the baseline dry measurement (onset timing) following slip initiation (Sandrian, 2006), as well as the maximum value reached during the response to the slip (timing and magnitude of the peak following the onset). For the purposes of the plot comparison, both the baseline and slip trials were time-normalized to stance duration during normal gait (baseline/dry). Timings were reported in seconds following left heel contact, i.e. initiation of the slip. After locating the onset and peak reaction times for sagittal plane moment and angle deviation, the onset and peak values for each were determined as the difference between the slip parameter and baseline parameter at the given reaction point. The onset and peak reaction values were reported for the angle in degrees, and for the normalized moment in N m kg^{-1}.

Slip severity is assessed using the peak slip velocity (PSV) measured at the heel of the slipping foot (Moyer et al., 2006). More specifically, PSV is determined from the total heel shear velocity, determined as the resultant of the medial-lateral and anterior-posterior velocities of the heel marker on the slipping foot. The peak slip velocity is determined as the first local maximum after heel strike (Moyer et al., 2006) (Figure 2).

Two main linear statistical analyses were conducted to (1) determine the age-related differences using a t-test between the two age groups, and (2) to determine if slip severity modulates arm reaction in young and older adults, using a regression analysis. In the first set of analyses, the dependent measure was one of the primary outcome measures of interest (Table 3), and the predictor variable was age group (young/older). Statistical significance was set at 0.05. In the second set of analyses, each outcome variable of interest included in Table 3 was linearly regressed against slip severity. These analyses were conducted within age group of participants due to the age-related differences found in the first set of analyses, using peak slip velocity as a continuous predictor. Once again, statistical significance was set at 0.05.

Results

Overall, the study participants demonstrated a variety of kinetic and kinematic slip responses, with the majority (64%) having shoulder flexion moments and angles. Representative responses of flexion and extension responses are shown in Figure 3. For both of the examples shown, the participants demonstrated shoulder response angles in the same directions as their shoulder response moments. Of the participants that showed shoulder moments and angles occurring in opposite directions, 12% had flexion moments paired with extension response angles, and 15% had extension moments paired with flexion response angles.

Statistically significant age-related differences in a number of shoulder kinematic and kinetic variables were found. Specifically, the onset of arm reactions was delayed by an average of 60 ms in older adults (based on kinetic data, Table 3) compared to young adults. The peak reactive shoulder moment was also delayed by an average of 110 ms in older adults compared to their young counterparts (Table 3, $p<0.05$). This finding translated into an approximate 200 ms average delay in the peak reactive shoulder kinematics in older adults compared to young adults (Table 3, $p<0.05$).

In addition, an average shoulder extension moment was generated in younger adults, whereas in older adults an average shoulder flexion moment was generated in response to a slip (Table 3). These differences in average moment values may be due to the greater number of older adults who generated a flexion moment compared to young adults. More specifically, the majority of older adults (nearly 90%) generated a flexion moment in response to the slip perturbation, in contrast to younger participants who generated a flexion moment in only about 60% of the slips (Table 4). These age-related differences were observed despite the slip severity being similar between young and older adults ($p>0.1$).

The second set of analyses conducted within age group (due to the age-related differences presented in the first set of analyses) was focused on determining whether arm reactions are modulated by how severely an individual slips (PSV). Significant effects of PSV on a number of arm reaction variables were found in the young age group. More specifically, increasing PSV was associated with earlier deviation of the angular shoulder trajectory in the slip response compared to baseline data (Figure 4, $p=0.032$ and Pearson's $r=0.54$). Also, more severe slips were associated with greater peak slip extension moment (Figure 4, $p=0.028$ and Pearson's $r=0.55$). In contrast to young participants, older participants did not modulate their arm reactions with slip severity ($p>0.1$).

Discussion

The findings of this study demonstrate fundamental timing and magnitude differences in arm responses to slips between young and older adults. More specifically, first, the arm responses were delayed in older adults compared to young adults. Second, while the majority (nearly 90%) of older adults generated a shoulder flexion moment in response to slips, about 40% of the young participants generated an extension moment. Third, young adults modulated their arm responses with slip severity in contrast with older adults who did not. Despite the fact that older adults walked slower than young adults, slip severity was similar between the two age-groups.

The delayed arm responses in older adults may lead to an increase in injury risk for two reasons: (1) the likelihood of successfully recovering balance or reaching for support after a slip will be reduced if responses in general are delayed (Maki and McIlroy, 2006), and (2) quick arm responses are key to minimize the consequences of a possible impact onto the floor (DeGoede et al., 2003; Kim and Ashton-Miller, 2009; Lattimer et al., 2016; Lee and Ashton-Miller, 2014). Delayed reactions in older adults may be a result of a number of age-dependent factors including reduced slip sensation, slow central processing and reduced motor conduction. Our findings agree with prior published reports related to the timing of upper extremity responses to balance perturbations. For example, compared to the findings of Allum et al (2002), which found that older adults showed shoulder reactions delayed by 20–30 ms, the results of this study showed a delay of nearly 60 ms, based on kinetic measures. Allum (2002) used EMG data as the measure of response time, while we used moments (EMG data not available), thus the difference between the two studies are most likely due to electromechanical delay.

Young adults modulated their arm responses with slip severity. More specifically, the shoulder extensors' activity increased with slip severity. Because this extensor activity is measured as the response (reactive) moment, it appears that as slip severity increases, the younger group attempts to brace for impact with the ground due to an increased likelihood of falling. Previous studies have shown that the extension moments demonstrated by this younger group may have a preventative intent, such as reaching for support or breaking the fall (Allum et al., 2002; Maki and McIlroy, 1997; McIlroy and Maki, 1995).

Overall, an average extension moment was generated at the shoulder in young adults in contrast to a flexion moment in the older group. While the average slip severity was similar in young and older adults, there were similar occurrences of severe (PSV > 1.0 m s^{-1}) slips in the young participants (56%) compared to 53% in the older participants (Moyer et al., 2006). As mentioned previously, PSV had a significant effect on peak moment, with increasing PSV being correlated with a shift toward shoulder extension moments. This evidence points toward increasing slip severity causing an arm reaction aimed toward breaking the fall by contacting the ground with the hands first, while less severe slips induce flexion reactions that may help recover balance.

Because older adults tend to display delayed reactions to unexpected slips, potential methods of reducing fall and injury risk include environmental modifications such as handrails or other sources of support in high slip risk areas, and training specifically tailored towards regaining balance following a perturbation. Previous research has shown that training programs focused on balance recovery in older adults can lead to quicker movement to grasp a handrail to avoid falling (Maki et al., 2008; Mansfield et al., 2010; McKay et al., 2013). In addition to perturbation-based training, other research has shown that with sufficient instruction and practice, individuals can be trained to essentially override their automatic responses to recover balance, and instead attempt to fall safely (Weerdesteyn et al., 2007).

A number of limitations to this study are worth noting. First, while all participants were employed full time at the time of testing, information on their specific job type (i.e. desk job or manual labor) was not collected. Furthermore, we know that participants were healthy, however overall physical activity level was not assessed. Finally, while nearly all of the participants were right handed (31 of the 33), the handedness of each of the participants was not taken into account when determining which foot to slip. Slips were induced on the left foot for all participants. Potential future work could consider which arm is dominant in each participant, and induce a slip only on the dominant on non-dominant side of the body.

Acknowledgments

Funding source: NIOSH R01 OH007592.

We would like to thank Joseph M. Furman, MD, PhD, a neurologist expert in balance and vestibular disorders. Dr. Furman conducted a thorough clinical exam and vestibular testing to exclude conditions that may impede balance and gait.

References

Allum JH, Carpenter MG, Honegger F, Adkin AL, Bloem BR. Age dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. Journal of Physiology. 2002; 542(Pt 2):643–663. [PubMed: 12122159]

Beschorner K, Cham R. Impact of joint torques on heel acceleration at heel contact, a contributor to slips and falls. Ergonomics. 2008; 51:1799–1813. [PubMed: 18937108]

Centers for Disease Control and Prevention, National Center for Injury Prevention and Control Web-based Injury Statistics Query and Reporting System. 2014. Retrieved from https://www.cdc.gov/injury/wisqars/index.html

Cham R, Redfern MS. Lower extremity corrective reactions to slip events. Journal of Biomechanics. 2001; 34:1439–1445. [PubMed: 11672718]

Cham R, Redfern MS. Changes in gait when anticipating slippery floors. Gait and Posture. 2002; 12:159–171.

Chambers AJ, Cham R. Slip-related muscle activation patterns in the stance leg during walking. Gait and Posture. 2007; 25:565–572. [PubMed: 16876417]

Chambers AJ, Harchick EA, Cham R. Shoe-floor frictional requirements during gait after experiencing an unexpected slip. IIE Transactions on Occupational Ergonomics and Human Factors. 2014; 2(1): 15–26.

Chambers AJ, Perera S, Cham R. Changes in walking characteristics of young and older adults when anticipating slippery floors. IIE Transactions on Occupational Ergonomics and Human Factors. 2013; 1(3):166–175.

De Goede KM, Ashton-Miller JA, Schultz AB. Fall-related upper body injuries in the older adult: a review of the biomechanical issues. Journal of Biomechanics. 2003; 36:1043–1053. [PubMed: 12757814]

Dietz V, Fouad K, Bastiaanse CM. Neural coordination of arm and leg movements during human locomotion. European Journal of Neuroscience. 2001; 14:1904–1914.

Grabiner MD, Bareither ML, Gatts S, Marone J, Troy KL. Task-specific training reduces trip-related falls risk in women. Medicine and Science in Sports Exercise. 2012; 44(12):2410–2414.

Hanley A, Silke C, Murphy J. Community-based health efforts for the prevention of falls in the elderly. Clinical Interventions in Aging. 2011; 6:19–25. [PubMed: 21472088]

Hof AL. The equations of motion for a standing human reveal three mechanisms for balance. Journal of Biomechanics. 2007; 40:451–457. [PubMed: 16530203]

Hsiao ET, Robinovitch SN. Common protective movements govern unexpected falls from standing height. Journal of Biomechanics. 1998; 31:1–9.

Kim KJ, Ashton-Miller JA. Biomechanics of fall arrest using the upper extremity: Age differences. Clinical Biomechanics. 2003; 18(4):311–318. [PubMed: 12689781]

Kim KJ, Ashton-Miller JA. Segmental dynamics of forward fall arrests: A system identification approach. Clinical Biomechanics. 2009; 24:348–354. [PubMed: 19250726]

Kim SH, Szabo RM, Marder RA. Epidemiology of humerus fractures in the United States: Nationwide emergency department sample, 2008. Arthritis Care & Research. 2012; 64(3):407–414. [PubMed: 22162357]

King EC, Lee TA, McKay SM, Scovil CY, Peters AL, Pratt J, Maki BE. Does the “eyes lead the hand” principle apply to reach-to-grasp movements evoked by unexpected balance perturbations? Human Movement Sciences. 2011; 30:368–383.

King EC, McKay SM, Lee TA, Scovil CY, Peters AL, Maki BE. Gaze behavior of older adults in responding to unexpected loss of balance while walking in an unfamiliar environment: a pilot study. Journal of Optometry. 2009; 2:119–126.

Lattimer LJ, Lanovaz JL, Farthing JP, Madill S, Kim S, Arnold C. Upper limb and trunk muscle activation during an unexpected descent on the outstretched hands in young and older women. Journal of Electromyography and Kinesiology. 2016; 30:231–237. [PubMed: 27541386]

Lee Y, Ashton-Miller AJ. Age and gender effects on the proximal propagation of an impulsive force along the adult human upper extremity. Annals of Biomedical Engineering. 2014; 42(1):25–35. [PubMed: 23979475]

Maki BE, Cheng KC-C, Mansfield A, Scovil CY, Perry SD, Peters AL, McKay S, Lee T, Marquis A, Corbeil P, Fernie GR, Liu B, McIlroy WE. Preventing falls in older adults: New interventions to promote more effective change-in-support balance reactions. Journal of Electromyography and Kinesiology. 2008; 18:243–254. [PubMed: 17766146]

Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: the "change-in-support" strategy. Physical Therapy. 1997; 77(5):488–507. [PubMed: 9149760]

Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. Age and Ageing. 2006; 35-S2:ii|2–ii|8.

Mansfield A, Peters AL, Liu BS, Maki BE. Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: A randomized controlled trial. Physical Therapy. 2010; 90:476–491. [PubMed: 20167644]

Marigold DS, Bethune AJ, Patla AE. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. Journal of Neurophysiology. 2003; 89(4):1727–1737. [PubMed: 12611998]

McIlroy WE, Maki BE. Early activation of arm muscles follows external perturbation of upright stance. Neuroscience Letters. 1995; 184(3):177–180. [PubMed: 7715841]

McKay SM, Fraser JE, Maki BE. Effects of uni- and multimodal cueing on handrail grasping and associated gaze behavior in older adults. Accident Analysis and Prevention. 2013; 59:407–414. [PubMed: 23896044]

Misiaszek JE. Early activation of arm and leg muscles following pulls to the waist during walking. Experimental Brain Research. 2003; 151:318–329. [PubMed: 12783148]

Moyer, BE. PhD dissertation. University of Pittsburgh; 2006. Slip and fall risks: pre-slip gait contributions and post-slip response effects.

Moyer BE, Chambers AJ, Redfern MS, Cham R. Gait parameters as predictors of slip severity in younger and older adults. Ergonomics. 2006; 49(4):329–343. [PubMed: 16690563]

Moyer BE, Redfern MS, Cham R. Biomechanics of trailing leg response to slipping—Evidence of interlimb and intralimb coordination. Gait & Posture. 2009; 29(4):565–570. [PubMed: 19196513]

News Releases. U.S. Bureau of Labor Statistics; U.S. Department of Labor; 2014. Non-fatal occupational injuries and illnesses requring days away from work, 2013.

O'Connell C, Chambers AJ, Mahboobin A, Cham R. Effects of slip severity on muscle activation of the trailing leg during an unexpected slip. Journal of Electromyography and Kinesiology. 2016; 28:61–66. [PubMed: 27023486]

O'Neill TW, Varlow J, Silman AJ, Reeve J, Reid DM, Todd C, Woolf AD. Age and sex influences on fall characteristics. Annals of Rheumatic Diseases. 1994; 53:773–775.

Oates AR, Patla AE, Frank JS, Greig MA. Control of dynamic stability during gait termination on a slippery surface. Journal of Neurophysiology. 2005; 93:64–70. [PubMed: 15295010]

Pijnappels M, Kingma I, Wezenberg D, Reurink G, van Dieen JH. Armed against falls: the contribution of arm movements to balance recovery after tripping. Experimental Brain Research. 2010; 201:689–699. [PubMed: 19949781]

Pozzo T, Ouamer M, Gentil C. Simulating mechanical consequences of voluntary movement upon whole-body equilibrium: the arm-raising paradigm revisited. Biological Cybernetics. 2001; 85(1):39–49. [PubMed: 11471839]

Romick-Allen R, Schultz AB. Biomechanics of reactions to impending falls. Journal of Biomechanics. 1988; 21(7):591–600. [PubMed: 3410862]

Roos PE, McGuigan MP, Kerwin DG, Trewartha G. The role of arm movement in early trip recovery in younger and older adults. Gait & Posture. 2008; 27:352–356. [PubMed: 17561398]

Sandrian, PN. MS Thesis. University of Pittsburgh; 2006. Arm movements during slipping.

Tang PF, Woollacott MH. Inefficient postural responses to unexpected slips during walking in older adults. Journals of Gerontology: Series A, Biological Sciences and Medical Sciences. 1998; 53(6):M471–M480.

Toossi, M. Monthly labor review. U.S. Bureau of Labor Statistics; 2013. Labor force projections to 2022: The labor force participation rate continues to fall.

Weerdesteyn V, Laing AC, Robinovitch SN. Automated postural responses are modified in a functional manner by instruction. Experimental Brain Research. 2007; 186:571–580.

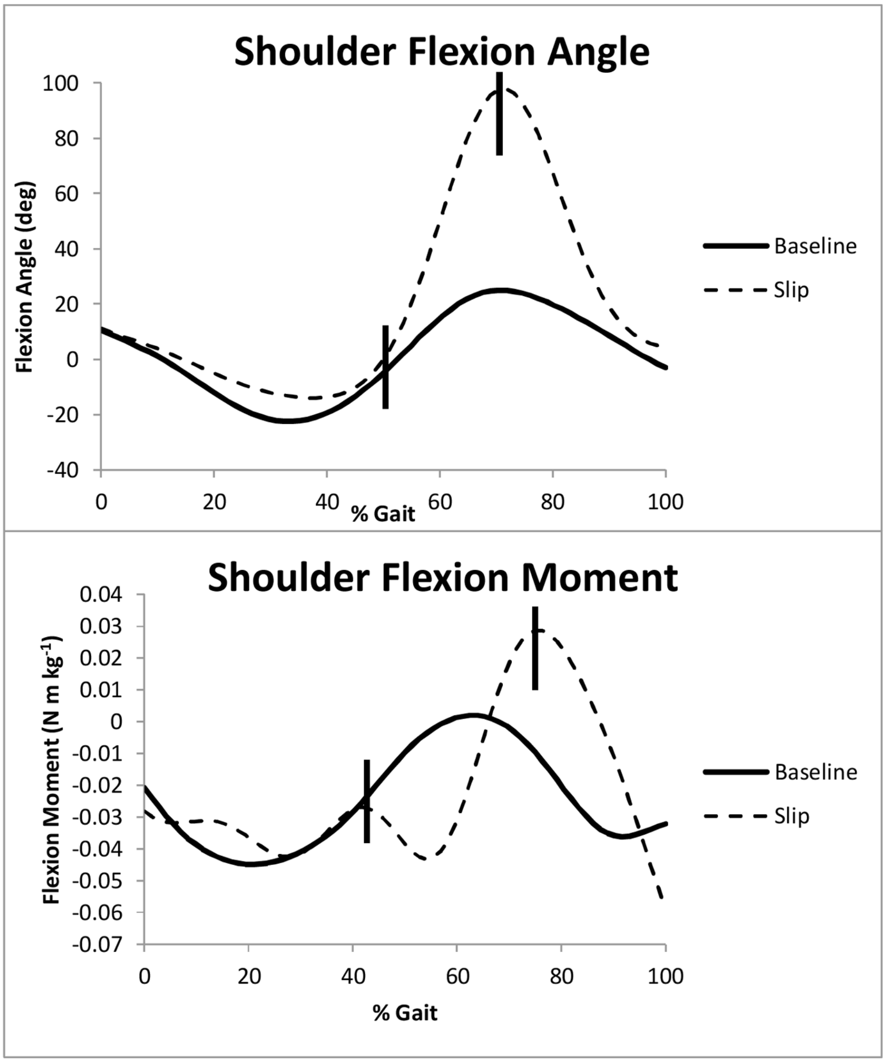

Figure 1.

Example of individual shoulder flexion angle trajectory (top) and shoulder reactive flexion moment (bottom) for the baseline dry trial (solid line) and slippery trial (dashed line) collected from the same participant, specifically from a younger male participant. Time on the x-axis is normalized to stride time during the baseline dry trial, with 0% being heel strike and 100% being the next heel strike on the same foot. The first vertical bar on each plot marks the response onset, and the second bar marks the peak value during slip reaction. Positive values (angle and moment) represent a flexion reaction.

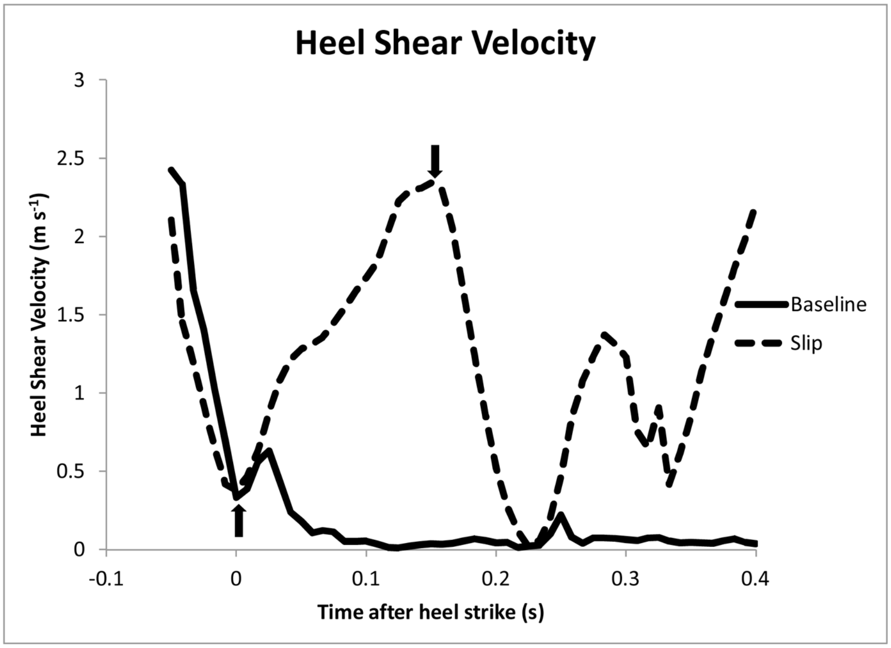

Figure 2.

Example of heel shear velocity trajectory for a younger male, and determination of the peak slip velocity during a slip. Time = 0s refers to the instant of heel strike. The location of the peak slip velocity (PSV, second arrow) is determined as the first local maximum of heel shear velocity after heel strike (first arrow). In this specific slip, the subject slip with a PSV of about 2.4 m/s occurring about 150 ms after heel strike.

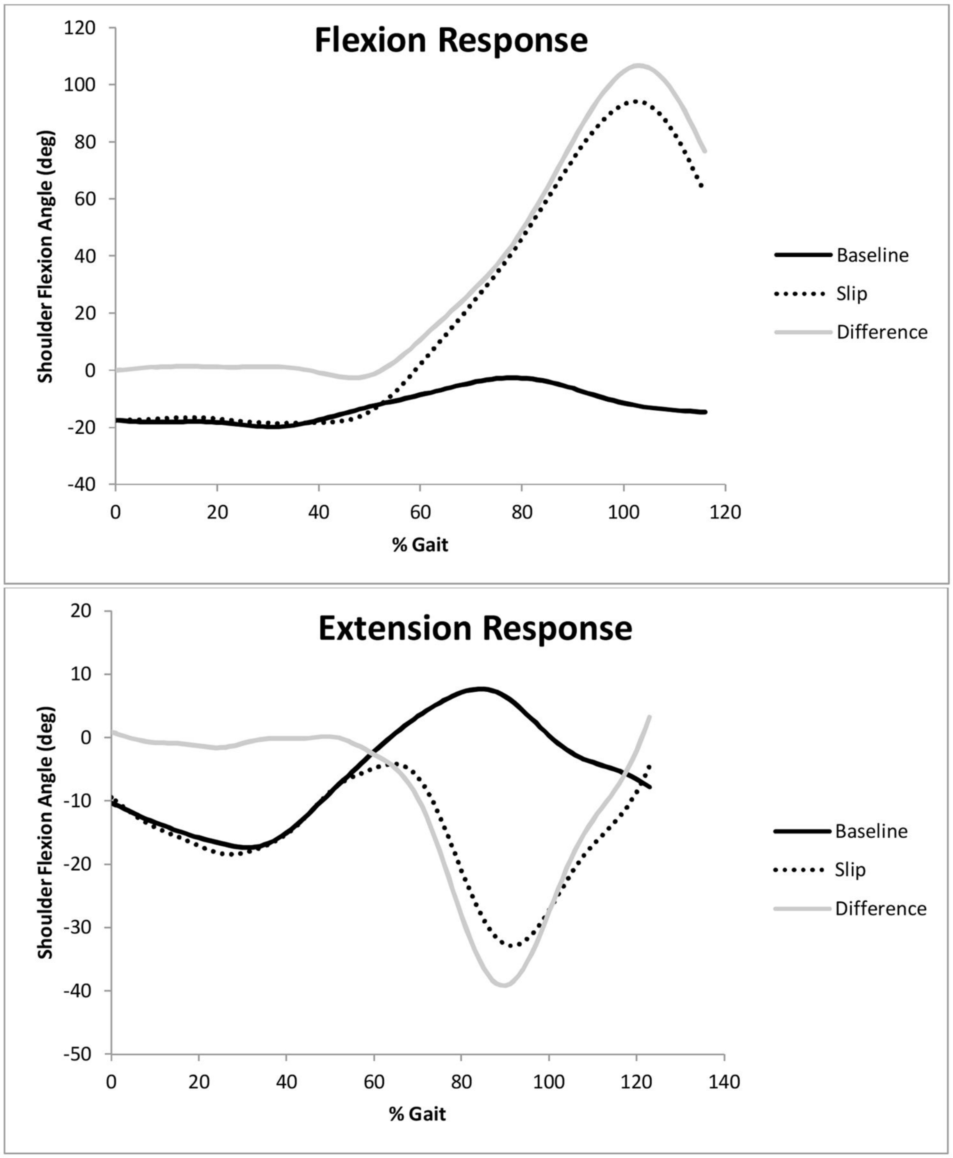

Figure 3.

Example of individual subject responses for flexion (top) and extension (bottom) reactions, both of younger female participants. Positive angles indicate shoulder flexion. The participant with the flexion response exhibited minimal arm motion during normal gait (solid line), with a large response due to the slip (dashed line). The participant demonstrating the extension reaction showed a normal range of sagittal plane motion during normal gait (solid line), with a large extension response to the slip (dashed line). For both plots, the solid line represents the baseline sagittal plane angle, while the dashed line represents the sagittal plane angle during the slip. The solid grey line is the difference (slip – baseline). Time on the x-axis is normalized to stride time during the baseline dry trial, with 0% being heel strike and 100% being the next heel strike on the same foot.

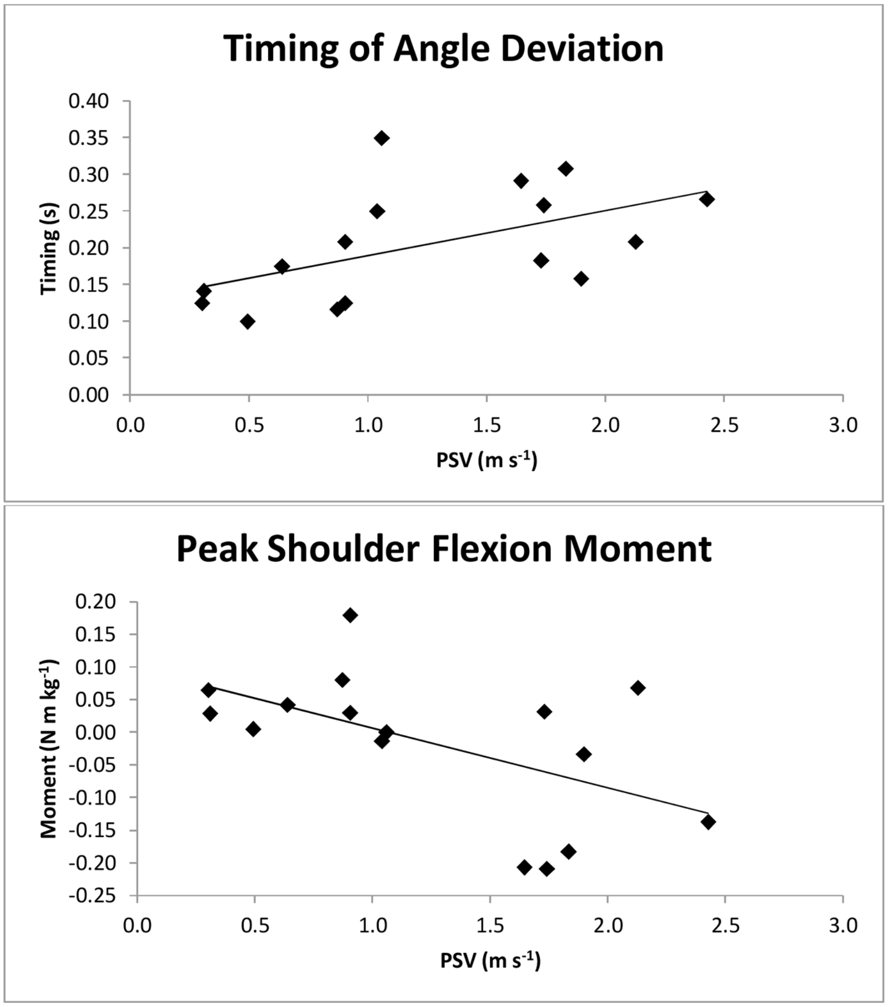

Figure 4.

Peak flexion moment and angle deviation timing plots for the young group. With increasing slip severity, as measured by the peak slip velocity (PSV), the angle response timing increased, while the sagittal plane reaction moment moved toward the negative (extension) direction.

Table 1

Participant demographic information stratified by age group and gender.

Age Group	**Gender**	**Age (years)** ***Mean ± S.D. [Min – Max]***	**Stature (cm)** ***Mean ± S.D. [Min – Max]***	**Body Mass (kg)** ***Mean ± S.D. [Min – Max]***	**BMI (kg m^{-2})** ***Mean ± S.D. [Min – Max]***	**Right Handed (N)**
Older (N = 17)	Female (N=10)	54.9 ± 2.9 [52 – 60]	163.3 ± 4.0 [157 – 169.5]	77.8 ± 12.3 [55.5 – 94.4]	29.2 ± 4.6 [21.1 – 36.9]	10
	Male (N=7)	56.3 ± 6.8 [50 – 65]	176.6 ± 4.1 [172 – 182]	84.4 ± 14.6 [61 – 106]	27.0 ± 4.4 [20.6 – 32.4]	7
Young (N=16)	Female (N=7)	24.4 ± 3.7 [20 – 31]	165.5 ± 5.4 [158.5 – 173.5]	64.2 ± 13.2 [52.5 – 88.4]	23.4 ± 4.2 [19.5 – 31.9]	6
	Male (N=9)	23.4 ± 1.9 [21 – 26]	179.1 ± 5.8 [170 – 187]	73.0 ± 11.0 [55.5 – 88.2]	22.7 ± 2.6 [18.9 – 26.6]	8

The mean ± standard deviation (S.D.) and the range [minimum (Min) – maximum (Max)] values are provided.

Table 2

Definitions of left shoulder parameters determined.

Parameter	Definition
KINEMATIC VARIABLES	
Timing of angle deviation	Time at which the sagittal plane angle during the slip begins to deviate from the angle observed during baseline gait.
Timing of peak angle deviation	Time at which the sagittal plane angle during the slip response reaches its maximum deviation.
Peak deviation angle	Difference in sagittal plane angle between the slip response and baseline gait at the timing of peak angle deviation.
KINETIC VARIABLES	
Reaction Onset	Time at which sagittal plane moment during the slip begins to deviate from the moment observed during baseline gait.
Timing of peak reactive moment	Time at which the sagittal plane moment during the slip response reaches its maximum deviation.
Peak reactive moment	Difference in sagittal plane moment between the slip response and baseline gait at the timing of peak reactive moment deviation.

Table 3

Comparison of key biomechanical variables between age groups.

Parameter	Young	Older	page
KINEMATIC VARIABLES			
Timing of angle deviation (s)	0.20±0.08	0.28±0.05	0.0005
Timing of peak angle deviation (s)	0.41±0.13	0.60±0.14	0.0001
Peak deviation angle (degrees)	14.8±30.8	29.4±31.3	> 0.1
KINETIC VARIABLES			
Reaction Onset (s)	0.15±0.08	0.21±0.05	0.02
Timing of peak reactive moment (s)	0.35±0.11	0.46±0.10	0.003
Peak reactive moment (N m kg^{-1})	−0.02±0.11	0.07±0.08	0.011
OTHER			
Gait speed (m s^{-1})	1.41±0.18	1.23±0.13	0.003
Peak slip velocity (m s^{-1})	1.25±0.67	1.09±0.34	> 0.1

Values are shown as mean ± standard deviation.

Table 4

Characteristics (direction of moments and kinematics) of arm responses generated when exposed to unexpected slips. Results are shown for young (A) and older (B) adults. The moments and angles shown are for the peak reaction values (should flexion moment and angle) observed over the course of the response.

A) Young Adults

		Angle	
		Flexion (75%)	**Extension (25%)**
Moment	Flexion (62%)	56% (N=9)	6% (N=1)
	Extension (38%)	19% (N=3)	19% (N=3)

B) Older Adults

		Angle	
		Flexion (82%)	**Extension (18%)**
Moment	Flexion (88%)	70% (N=12)	18% (N=3)
	Extension (12%)	12% (N=2)	0