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Arm movements and slip severity

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Slip-initiated falls often cause occupational injuries and deaths, especially in older workers. Previous slips and falls research has to a large extent focused on lower extremity reactions, yet arm responses are often part of postural reactions to such perturbations. It is unclear if arm responses play a role in balance recovery, are modulated by the severity of the postural perturbation and/or are a reflex-type response, e.g. reaching for external body support. In this study, the relationship between slip severity and shoulder biomechanics was examined. Subjects (17 younger and 12 older adults) were exposed to two conditions: (1) baseline dry (subjects knew the floor was dry), and (2) unexpected slip (a diluted glycerol solution was spread on the floor to slip the leading/left foot). Bilateral sagittal plane kinematics and kinetics were derived. Slip severity was quantified using a measure of slip hazardousness based on the peak slip velocity (PSV) measured at the heel of the slipping foot. Specifically, if PSV $\geq$ 1 m/s, then the slip was classified as hazardous. Although arm responses were bilateral, only the biomechanics of the shoulder ipsilateral to the slipping foot, specifically moment generation rate, were affected by slip hazardousness. Specifically, a hazardous slip was associated with an extensor moment at the shoulder ipsilateral to the slipping foot, whereas a non-hazardous slip was associated with a flexor moment. Shoulder responses were triggered later than the hip and knee response based on moment onset data. Finally, overall, older adults appeared to generate a greater extensor moment at the shoulder compared to the response seen in the younger group of participants. In conclusion, evidence presented in this study implies that (1) arm responses play a role in balance recovery but also may be protective in nature when experiencing a severe slip, (2) a legs-to-arms response sequence appears to drive the reaction to a slip, and (3) older adults may use their arms as a protective strategy to a greater extent than their younger counterparts.

INTRODUCTION

Injuries due to slips and falls are a significant occupational problem especially in older workers. Falls account for more than 20% of fatal injuries in workers over the age of 65 years old and are the leading cause of deaths in this group of workers (Agnew & Suruda, 1993). Also, almost half the non-fatal injuries in workers over the age of 65 years old are attributed to falls (U.S. Department of Labor - Bureau of Labor Statistics, 2005). Injuries from falls are often severe. Indeed, more than 30% of workers sustaining non-fatal falls-related injuries miss at least 31 days at work (U.S. Department of Labor - Bureau of Labor Statistics, 2005) and falls-related sick leave periods are longer in older workers compared to their younger counterparts (Kemmlert & Lundholm, 2001). The severity of occupational falls-related injuries is in part responsible for the high cost associated with such incidents, i.e. US$6 billion / year (Courtney, Sorock, Manning, & Holbein, 2001). An estimated 24% of the direct cost of all claims filed in 1989-1990 was attributed to falls (Leamon & Murphy, 1995). The problem of falls is expected to become more prominent with the aging trends of the labor force (Toossi, 2005; Saunders, 2005).

Same level falls, the most common type of occupational falls especially in older adults, are often initiated by slipping. Findings of the US National Health Interview Survey questionnaire administered in 1997 suggest that slipping was the most common triggering event precipitating 43% of same level falls, followed by tripping (18%) and loss of balance (14%) (Courtney et al., 2001). Also, in addition to the risk of fall-related injuries and fatalities, slip recovery efforts may contribute to an increased risk of overexertion injuries (Courtney & Webster, 2001).

Slips and falls research has to a large extent focused on lower extremity responses. While arm movements are a prominent component of postural responses to slips, the role of the arms is not fully understood. Such information is important not only to understand potential causes of falls in older adults but also to design occupational environments that minimize the risk of slips and falls. A number of non-mutually exclusive theories have been proposed in an attempt to understand the role of arm responses. For example, the primary role of the arms has been suggested to be (1) reaching for external body support, e.g. hand rails (McIlroy & Maki, 1995; Cejka, Lee, McIlroy, & Maki, 2005) (2) recovering dynamic balance (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Maki & McIlroy, 1997; Misiaszek, 2003; Pozzo, Ouamer, & Gentil, 2001; Romick-Allen & Schultz, 1988; Tang & Woollacott, 1998; Oates, Patla, Frank, & Greig, 2005), (3) preparing for impact onto the ground, i.e. a protective response (Allum et al., 2002; McIlroy & Maki, 1995).

How arm responses are triggered is also subject of debate. Specifically, it is unclear if arm reactions occur at approximately the same time as leg responses, i.e. external sensory cues trigger both leg and arm responses, and/or later than leg reactions in a sequence of leg-to-upper-body postural responses. For example, in response to treadmill deceleration, waist-jolt perturbations and simulated slipping during gait on rollers, shoulder muscles fired at about the same time as leg muscles (Dietz, Fouad, & Bastiaanse, 2001; Misiaszek, 2003; Marigold, Bethune, & Patla, 2003). In contrast, another study found that shoulder muscle activation onsets were considerably later than ankle and knee reactions in response to perturbations administered during standing (Romick-Allen & Schultz, 1988).

Age may impact arm responses to external perturbations. In general, in perturbed stance and gait research, when young and older adults are exposed to the same external perturbation, arm responses are delayed and weaker in the older group of participants (Allum et al., 2002; Tang & Woollacott, 1998). Furthermore, Allum and colleagues reported that the arms moved in different directions in young and older adults when exposed to toes up rotations of the base of support (Allum et al., 2002). Specifically, young subjects directed their arm movements opposite the direction of the platform tilt, but elderly subjects directed their arm movements in the same direction as the platform tilt, perhaps in an attempt to prepare for a fall onto the ground (Allum et al., 2002). This finding suggests a potential different goal of arm responses in young and older adults, perhaps modulated by the perceived severity of the postural perturbation.

The goal of this paper is two fold: (1) to investigate the relationship between slip severity and magnitude/timing characteristics of arm reactions generated in response to unexpected slips in young and older adults; (2) to compare the onset of the arm and leg response to an unexpected slip.

METHODS

Twenty nine subjects (18 F, 11 M) were recruited in two age groups: 17 young (age 20-33) and 12 older (age 55-67) participants. Exclusion criteria included a clinically significant history of neurological, orthopedic and cardiovascular conditions preventing normal gait and balance function.

Prior to data collection, subjects practiced walking to get accustomed to walking while being instrumented with the motion analysis marker set and wearing a safety harness. Subjects were instructed to walk as naturally as possible at a self-selected pace. Subjects were exposed to two experimental conditions: baseline dry (BD) in which subjects walked along a known dry gait pathway. The coefficient of friction between the dry vinyl floor and the shoes provided to the subject was 0.53, as measured with an English XL VIT Slipmeter. Following two or three BD trials, one unexpected slip trial was collected when, unbeknownst to the subject, a slippery contaminant (75% glycerol, 25% water by volume) was spread onto the floor where the subject stepped with his/her left foot, i.e. the slip was always generated at the leading (left) foot. The coefficient of friction of the shoe-floor interface was 0.03 in the slippery condition. Each slip trial was classified as hazardous or non-hazardous based on a cutoff value of 1 m/s in the peak slip velocity measured at the heel of the slipping foot (Moyer, Chambers, Redfern, & Cham, 2006).

A model of the body was constructed to derive upper body biomechanics of interest (Figure 1). Inertial parameters were based on de Leva et al. (de Leva, 1996). Shoulder kinematics were assessed using Euler angles based on the rotation matrices between the local reference frame of each upper arm segment and that of the torso. Inverse dynamic analyses were used to calculate shoulder joint moments using a distal to proximal approach. Shoulder joint moments are reported in the reference frame of the torso, and are normalized to body mass. Although 3D biomechanical data are available, only sagittal plane shoulder kinematics (flexion-extension angle) and kinetics (flexion-extension moment) are reported here.

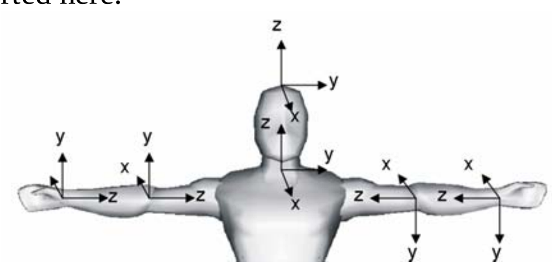

Figure 1. Upper body model comprised of 6 rigid body segments: head, torso, left/right upper arm and lef/right forearm-hand

Sagittal plane shoulder kinetics/kinematics were parameterized to derive the following specific variables of interest:

- Bilateral maximum changes in shoulder angle between the slippery and baseline condition observed in the first half of stance.
- Bilateral onset and generation rate of the corrective moment produced at the shoulder as a result of slipping.

RESULTS

To investigate the association between slip severity and shoulder biomechanics in young and older adults, bilateral shoulder kinematic and kinetic parameters of interest were entered individually in a linear regression model including age group (young/older), slip hazardousness (hazardous / non-hazardous), and their interaction as fixed predictors.

The analysis of the kinematic data revealed no statistical significant effects of slip hazardousness on bilateral changes in shoulder angles between the slippery and baseline condition (Figure 2). Older adults flexed their arm less than their younger counterparts did (Figure 2).

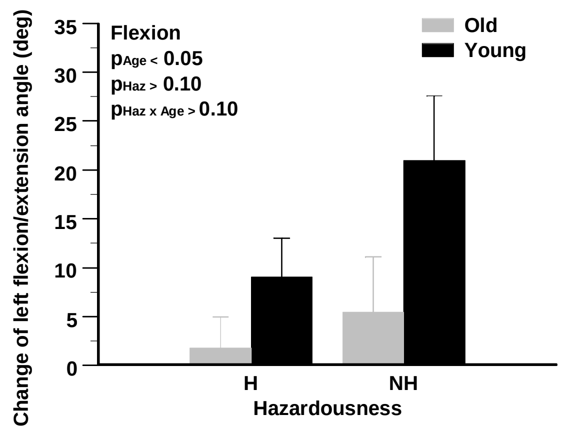

Figure 2. Change of left flexion angle and slip hazardousness. (standard error bars)

The analysis of the kinetic data suggested that subjects who experienced hazardous slips generated a left (ipsilateral to the slipping foot) extensor moment and those exposed to a non-hazardous slip produced a left flexor moment (Figure 3). Furthermore, age effects on left shoulder moment generation rate data suggest older subjects produced moments tending more toward extension, while younger subjects generated moments that tended toward flexion (Figure 3). Finally, effects of slip hazardousness and age on moment onset data were not statistically significant.

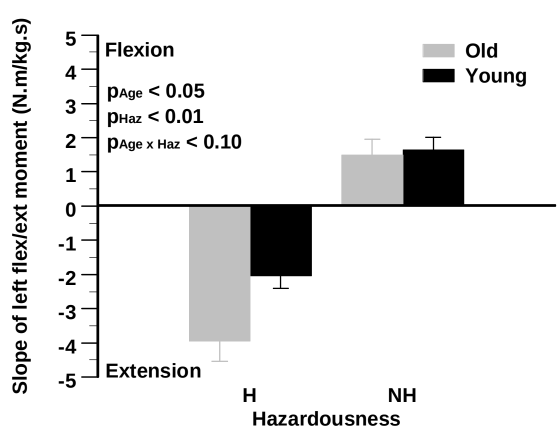

Figure 3. Left flexion moment generation rate and slip hazardousness. (standard error bars).

To compare the reaction time of the hip, knee, and shoulder on the left side of the body (ipsilateral to the slipping foot), a mixed linear model was used, with subject as a random effect, joint (shoulder, knee, hip) as a fixed effect and moment onset as the dependent variable. The results of this analysis indicated that the sagittal plane corrective moment generated by the left shoulder occurs significantly later than that of the left hip and knee moment generated in response to the unexpected slip (Figure 4).

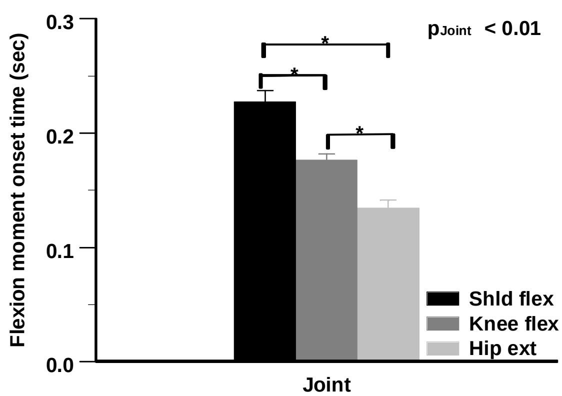

Figure 4. Comparison of reactive moment onsets in the left shoulder, knee, and hip, averaged across all subjects.

DISCUSSION

In summary, although arm responses were bilateral, only left (ipsilateral to the slipping foot) shoulder biomechanics, specifically sagittal plane moment generation rate, were associated with slip hazardousness. This left-right asymmetry implies that arms are at least partially involved in stabilizing the perturbed body. Previous studies have also suggested that arm movements may be protective in nature, e.g. reaching a hand rail for support or protecting the upper body from impacting the floor (Allum et al., 2002; McIlroy & Maki, 1995; Maki & McIlroy, 1997; Cejka et al., 2005). Indeed, extension of the ipsilateral arm that may stem from a fall-breaking strategy was seen in this study as well but only in the hazardous slips. Thus, our findings suggest that arm responses are modulated by the actual or perceived severity of the perturbation.

The slip elicited some response by the right (contralateral to the slipping foot) shoulder, but overall differences in the right limb between dry and slip trials were smaller than in the left arm and these differences were not correlated with slip severity. It can be argued that the right arm was already near full flexion at the time of slip initiation, shortly after left heel contact on the slippery floor, thus hindering any substantial arm elevation response.

Older and young subjects differed significantly in the direction of the shoulder moment generated in response to slip: older subjects generated an extension response and the young participants generated a flexion response. These age-related effects may be due to a difference in the goal of arm use between young and older participants, e.g. older subjects position their arm in an attempt to protect their upper body from floor impact in case of a fall, whereas the young participants use their arms to recover balance. These findings are in agreement with the results of Allum and colleagues who reported differences in the direction of arm movements between young and older adults in response to external perturbations during standing (Allum et al., 2002).

Left shoulder responses were triggered later than left hip and knee responses, supporting Tang and Woollacott's observations of distal-to-proximal slip-related reaction sequences from ankle to trunk (Tang & Woollacott, 1998). Other investigators such as Romick-Allen and Schultz reported such findings (Romick-Allen & Schultz, 1988). These results appear to contradict experimental data suggesting that the response of lower and upper extremities are triggered at about the same time (McIlroy & Maki, 1995; Dietz et al., 2001; Marigold et al., 2003). This apparent contradiction may be due to differences in the perturbation paradigm used in the protocol, e.g. anticipation effects, type of perturbation, etc. and in the way response onset was determined, e.g. EMG's, moment, kinematic. Our findings do not rule out the potential role of the vestibular system in triggering arm responses to slip.

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