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Effects of slip severity on muscle activation of the trailing leg during an unexpected slip

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ABSTRACT

Falls and injuries due to falls are a major health concern, and accidental slips are a leading cause of falls during gait. Understanding how the body reacts to an unexpected slip can aid in developing intervention techniques to reduce the number of injuries due to falls. In this study, muscle activation patterns, specifically those of the trailing (non-slipping) limb, were studied in unexpected slips of 24 young and 24 middle-aged adults. The typical reaction of the trailing limb is swing phase interruption in an attempt to arrest the slip. Variables examined were the reactive muscle activation onset, peak electromyography (EMG) magnitude, and time-to-peak of the vastus lateralis and medial hamstring of the trailing limb. Statistical analysis was performed to determine the effects of slip severity, quantified by peak slip velocity, and age on outcome variables. As slip severity increased, the reactive activation onset of the medial hamstring was significantly faster and there was a trend approaching significance for the onset of the vastus lateralis. Additionally, the peak magnitude and time-to-peak of the vastus lateralis increased with slip severity. No significant effects of age were found on any of the output variables. These findings may aid in development of perturbation-based paradigms, as it may be possible to "tune" the postural control system to generate an appropriate response to unexpected slips.

1. Introduction

Slips, trips and falls are among the leading causes of non-fatal injuries in the workplace, with nearly 300,000 cases reported in the United States in 2013 leading to a median of 11 missed workdays (Nonfatal occupational injuries and illnesses requiring days away from work, 2014). Additionally, of all fatal occupational injuries, 17% were caused by slips, trips and falls (Fatal occupational injuries by event or exposure, 2015). Slips, trips and falls in older working adults are more severe than their younger counterparts. Specifically, older working adults (ages 55–64 years) missed a median of 14 days for nonfatal occupational injuries and illnesses compared to their younger counterparts (ages 25–34 years) who missed a median of 6 workdays. Falls account for the most nonfatal injuries in older workers (Nonfatal occupational injuries and illnesses requiring days away from work, 2014).

When an unexpected slip occurs, the body must produce a quick and coordinated corrective response to recover balance and prevent falling. In the stance/slipping limb, the activity of the knee flexors and hip extensors increase in an attempt to arrest the slipping motion of the foot and to move the body forward over the supporting trailing limb (Moyer et al., 2009; Chambers and Cham, 2007). During severe slips, a compensatory step of the trailing limb, also referred to as swing phase interruption, has been reported in the literature (Bhatt et al., 2005; Kojima et al., 2008; Marigold et al., 2003; Maki et al., 2006). Compensatory stepping of the trailing limb is a critical component of postural recovery strategies as it has been shown to improve balance by arresting the backward movement of the center of mass and/or preventing its vertical drop due to gravity (Bhatt et al., 2005). Additionally, stepping of the trailing foot provides a larger base of support to increase stability. For these reasons, more recent falls prevention efforts have focused on perturbation-based paradigms (Mansfield et al., 2010; Crenshaw and Grabiner, 2014; Mansfield et al., 2015).

While the dynamics of the stance/slipping limb during slip has been relatively well studied, less is known about the trailing limb's role in corrective action during slip. Previous work has shown intra-limb coordination during slip response whereby the

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kinematics of the trailing limb are temporally in synch with those of the slipping limb (Moyer et al., 2009). Kinematic response of the trailing limb ranges from minimal interruption of gait during non-hazardous slips to an interruption of the swing phase of gait in severe slips, suggesting that these reactions are modulated by slip severity (Moyer et al., 2009). The magnitude and temporal characteristics of the underlying mechanisms controlling the use of a compensatory step in response to a slip are not well understood. For example, in a simulated slip study in young healthy adults, Marigold et al. reported a large variability in the activation of the muscles in the trailing limb interrupting its swing phase (Marigold et al., 2003). More specifically, the biceps femoris, rectus femoris and the tibialis anterior produced a quick reactive response between 150 and 160 ms after an unexpected slip, while the medial gastrocnemius had a delayed reaction around 250 ms (Marigold et al., 2003).

Understanding the mechanisms that modulate compensatory step reactions is important to efforts focused on reducing the risk of falls using perturbation-based intervention paradigms. In particular, if the temporal and magnitude characteristics of effective compensatory step reactions can be identified, then perturbation-based intervention paradigms can target these characteristics that may be affected by age and/or disease. The overarching hypothesis of this study is that stepping reactions are modulated by the severity of the perturbations, which would be indicative of the flexibility of the postural control system to generate an appropriately "tuned" postural recovery strategy. Increased slip severity has been shown to generate a faster activation of the muscles of the stance/slipping limb. During hazardous slips, the vastus lateralis muscle of the slipping limb had a delayed reaction when compared to non-hazardous slips (Chambers and Cham, 2007). It remains unknown if this slip severity modulation also occurs in the trailing-limb muscles.

The objective of this study is to determine if muscle reactions needed to interrupt swing phase of the trailing limb during a real-life slip are modulated by slip severity. The focus of this study is on the thigh muscles in the trailing limb due to their prominent role in compensatory stepping reactions, specifically lowering the foot onto the floor (Tang and Woollacott, 1998). The hypothesis is that an increased slip severity will generate a faster and more powerful reaction in the muscles of the trailing limb. The effects of age on muscular response will also be examined, with the hypothesis that middle-aged adults will react more slowly and less powerfully than young adults. This study targets middle-aged adults (and not older adults as defined in the general population) for two reasons: (1) our population of interest are older workers, and (2) age-related changes in compensatory step reactions can occur in relatively young and healthy older adults (McIlroy and Maki, 1996); also gait stability and muscle strength begin to decline in adults as young as 40–50 years old (Terrier and Reynard, 2015; Lindle et al., 1997). A better understanding of how the muscles of the trailing limb respond during unexpected slips can aid in developing interventions and training protocols, which have been shown to be effective in reducing fall risk in older adults (Pai et al., 2010; Yang et al., 2014; Bhatt et al., 2006; Parijat and Lockhart, 2012; Shimada et al., 2004; Gillespie et al., 2009).

2. Methods

Forty-eight individuals from two age groups, young (aged 20–35 years) and middle-aged (aged 50–65 years, were recruited for participation in this study. Basic participant information is summarized in Table 1. Participants in both groups were similar in stature ($p > 0.05$); however, the middle-aged group had a significantly larger body mass than the young group ($p = 0.001$). Eligible participants were overall healthy and able to stand or walk for at least 2 h. Additionally, due to equipment safety restrictions, maximum height and mass for participants were set at 1.93 m and 113.4 kg, respectively. Exclusion criteria included self-reported orthopedic, neurological, pulmonary and cardiovascular abnormalities clinically hindering normal balance and gait. Additionally, individuals with proprioception deficits, balance and vestibular conditions were excluded through examination by a neurologist expert in balance disorders. Written informed consent approved by the University of Pittsburgh Institutional Review Board was obtained prior to participation.

Table 1
Subject sample characteristics: mean (SD) [range].

	Young ($N = 24$, 10 female)	Middle-age ($N = 24$, 12 female)
Age (years)	23.75 (2.83) [20–31]	57.13 (2.83) [50–65]
Mass (kg)	68.92 (10.09) [52.5–88.2]	81.81 (14.22) [55.5–111.8]
Stature (m)	1.73 (0.08) [1.59–1.82]	1.69 (0.08) [1.57–1.82]

Participants walked along an 8.5 m vinyl tile pathway wearing standard polyvinyl chloride shoes and a safety harness. Gait kinematics were recorded at 120 Hz using a Vicon motion capture system equipped with eight infrared cameras (Vicon, UK). Reflective markers were placed on key anatomical landmarks in order to reproduce accurate body motions, including four markers placed on the lateral aspect of each foot (heel, mid-foot, fore-foot and toe) to track stepping reactions. Bilateral ground reaction forces were collected at 1080 Hz via two Bertec force plates (Bertec, USA) positioned approximately halfway along the walkway and offset such that the left foot would hit the first force plate and the following step of the right foot would land on the second force plate. Electromyography (EMG) data were recorded from the vastus lateralis and medial hamstring of the trailing swing limb. Prior to electrode placement, skin was abraded and cleaned with an alcohol swab and if necessary, hair was shaved off of the area. Electrodes were fixated to skin using double sided tape and additional wrapping around the thigh ensured minimal movement artifacts. Electrodes were positioned over the muscle belly with an inter-electrode distance of 3 cm. Accurate electrode placement was established by maximum voluntary contraction tests. Data was collected using bipolar Ag/AgCl surface EMG electrodes and an 8-channel telemetered Noraxon Telemyo EMG system (Noraxon, USA) sampled at 1080 Hz with a hardware band-pass filter of 10–500 Hz.

During gait trials, lights were dimmed to prevent participants from detecting contaminants. Participants were instructed to walk at a comfortable self-selected pace while focusing on an eye-level target on the opposite wall. Prior to data collection, participants practiced walking along the track while researchers varied the participants starting location. This was done to ensure that each foot would strike a force plate, with the left foot hitting the leading force plate that would later be contaminated during the unexpected slip condition. Data collection began after the participant was consistently hitting both force plates. Several, typically 8–10, practice dry conditions were collected until each foot of the participant correctly hit its assigned force plate. To ensure normal gait, participants were told that the first few trials would be non-slippery and not to worry about slipping. It should be noted, however, that the consent process included informing participants that there may be slippery contaminants to which they would not be alerted. Prior studies utilizing the same slipping protocol and instructions have shown that kinematic gait patterns prior to heel strike onto the contaminated floor during the slip trial are similar to those of the baseline trials, thus confirming that subjects are walking normally (Cham and Redfern, 2001). Between trials, participants would turn away from the track and listen to music for