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Slip-related muscle activation patterns in the stance leg during walking

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Abstract

Falls precipitated by slipping are a serious public health concern especially in the elderly. Muscular responses generated during slipping have not been investigated during gait on contaminated floors. This study compared slip-related muscular responses (reactive and proactive) in young and older adults and examined if characteristics of muscular activation patterns during normal gait impact slip severity on contaminated floors. Electromyographic recordings were made from the major shank and thigh muscles in the stance leg of 11 young and nine older adults. Three experimental conditions were included: (1) known dry floors (baseline), (2) unexpected contaminated floor, (3) alert dry (subjects uncertain of the floor's contaminant condition). Muscular responses to unexpected slips, similar in both age groups, included the activation of the Medial Hamstring (~175 ms) followed by the onset of the Vastus Lateralis (~240 ms). The power and duration of responses were scaled to slip severity. The Vastus Lateralis latency was delayed in severe slips. When experiencing a severe slip, young adults demonstrated a longer, more powerful response compared to older adults. Subjects who normally walk with greater ankle muscle co-contraction were predisposed to experience less severe slips when encountering an unexpected slippery floor. Finally, anticipation of a slippery surface resulted in more powerful muscular activity and muscle co-contraction at the ankle and knee compared to baseline gait, as well as earlier onsets and longer durations in the posterior muscles' activation. These findings may provide a greater understanding of the higher incidence of falls in the elderly.

Keywords: Slip; Muscle activity; Gait; Proactive responses; Reactive responses

1. Introduction

Slips and falls are a major cause of serious injury and death in the United States [1]. The incidence rate of falls and their consequences, including serious injuries, disability and death increase with age [2,3]. Falls initiated by slips are specifically cited in risk factors for fractures [4].

In order to avoid a fall after an unanticipated hazardous slip (slip velocity measured at the heel greater than 1 m/s) [5], the body must generate a quick, effective corrective response to re-establish dynamic balance while continuing locomotion (reactive strategies). Slip-initiated reactive strategies consist of a primary response with corrective moments initiated about 200 ms after heel contact onto the slippery surface, specifically a flexion and extension moment generated at the knee and hip joint, respectively. This is followed by a secondary response consisting of a knee extension moment and hip flexion moment [6]. Marigold noted a similar temporal pattern in muscle activations during the initial exposure to rollers [7]. The primary response helps bring the slipping foot back near the body [6], while the secondary reaction is thought to be a compensatory reaction to avoid knee buckling and continue gait. In the same study, the ankle was found to generate no moment in severe slips [6].

Proactive strategies, defined as balance control mechanisms that take place before the body encounters a potential disturbance, may also be important in fall prevention interventions [8,9]. The underlying theory of such a

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therapeutic approach, referred to as systems model theory, indicates that balance is based not only on "feedback" reflexes (reactive strategies) but also on motor skills that adapt with training and prior experiences [10,11]. Thus, in the context of the systems model theory, the classification of gait/balance and mobility as motor skills suggests that postural control deficits can be improved by targeting proactive strategies in falls-related interventions. While there is some support for the idea that older adults are fully capable to learn, adapt and be trained to optimize recovery reactions generated in response to an external perturbation [9,12], others do not agree [13]. Proactive strategies generated when anticipating a slippery floor include shortened step length [14], reduced foot-floor angle [7,15,16] and changes in knee and hip joint moments [15]. These adaptations can result in an overall reduction in slip potential [15,17].

EMG analysis has been used to study the neuromuscular characteristics of reactions elicited in response to base of support translations, sometimes intended to simulate a slip during walking. Recent evidence suggests that there exists a more active control of the hip and knee compared to the ankle during a forward translation of the base of support [18]. Tang reported that both the lower leg and thigh muscles demonstrated earlier onset, higher magnitude, and longer activations compared to normal gait [8,19,20]. Muscle activity in the stance/slipping leg has not been investigated during a naturally occurring slip on contaminated floors.

In light of the research gap regarding muscle activity recordings during a naturally occurring slip, especially in the older adults, and the importance of reactive and proactive strategies to prevent a slip-initiated fall, three objectives were set in this study as follows:

- *Objective 1 (reactive strategies):* To quantitatively describe the temporal and power characteristics of muscle activation patterns generated in response to an unanticipated slip in the stance (slipping) leg in young and older adults.
- *Objective 2 (initial conditions):* To examine whether specific temporal and power aspects of EMG recordings during normal/baseline gait increases the risk of hazardous slips.
- *Objective 3 (proactive strategies):* To investigate the proactive activation muscle patterns generated in anticipation of a slippery floor in the stance leg in young and older adults.

2. Methods

2.1. Subjects

Twenty healthy adults divided into two age groups (young/older) were recruited for participation in this study (Table 1). Written informed consent approved by the University of Pittsburgh Institutional Review Board was obtained prior to participation. Exclusionary criteria included neurological, orthopedic, cardiovascular, pulmonary abnormalities as well as any other difficulties hindering normal gait.

Table 1
Subject sample characteristics

	Mean (S.D.) [range]	
	Young (*N* = 11)	Old (*N* = 9)
Age (years)	23.27 (1.95) [20–26]	60.44 (3.50) [55–66]
Weight (kg)	70.53 (13.82) [58.18–105.45]	72.33 (14.44) [45.54–86.82]
Stature (m)	1.71 (.06) [1.64–1.86]	1.64 (.08) [1.54–1.79]

2.2. Equipment

Participants walked along a vinyl tile pathway while full body motion and bilateral ground reaction forces were sampled at 120 and 1080 Hz, respectively [5]. EMG data were recorded from the muscles in the stance (left/leading/slipping) leg, including the Vastus Lateralis (VL), Medial Hamstring (MH), Tibialis Anterior (TA) and Medial Gastrocnemius (MG) at 1080 Hz using a Noraxon Telemyo 8-channel electromyography system with a hardware band pass filter (10–500 Hz). Proper electrode placement was confirmed using an exertion test. Participants were equipped with a safety harness to prevent them from hitting the ground in case of an irrecoverable balance loss. Participants wore the same brand and model of polyvinyl chloride soled shoes.

2.3. Protocol

Participants were instructed to look straight ahead and walk naturally at a self-selected comfortable pace across an 8.5 m walkway. The lights were dimmed just enough to minimize unwanted reflections and detection of a contaminant. Next, subjects were allowed to practice walking as the researcher varied the starting point to ensure proper foot contact. Prior to each trial, participants faced away from the walkway and listened to loud music for one minute, distracting them from the possible application of a contaminant. Participants then turned and walked forward while data were recorded.

The participant was informed that the first few trials would be non-slippery to ensure natural gait. Two to three dry trials were collected, "baseline dry" (BD). Then, without the participant's knowledge, the diluted glycerol solution (75% glycerol:25% water) was applied, by the same researcher ensuring uniformity, to the second force plate (4 m from the start) and another gait trial was conducted, "unexpected slip" (US). The slip index of the dry tile was .55, while the contaminant was .03, as measured with the English XL slip meter device. After the US, the subject was informed that there was a possibility of the contaminant being applied again but no further specific information was revealed. Five additional dry trials were collected, ''alert dry'' (AD); only the first two trials were used in this analysis.

2.4. Data processing

Heel contact (HC) and toe off (TO) were identified from ground reaction forces. EMGs were rectified and filtered at

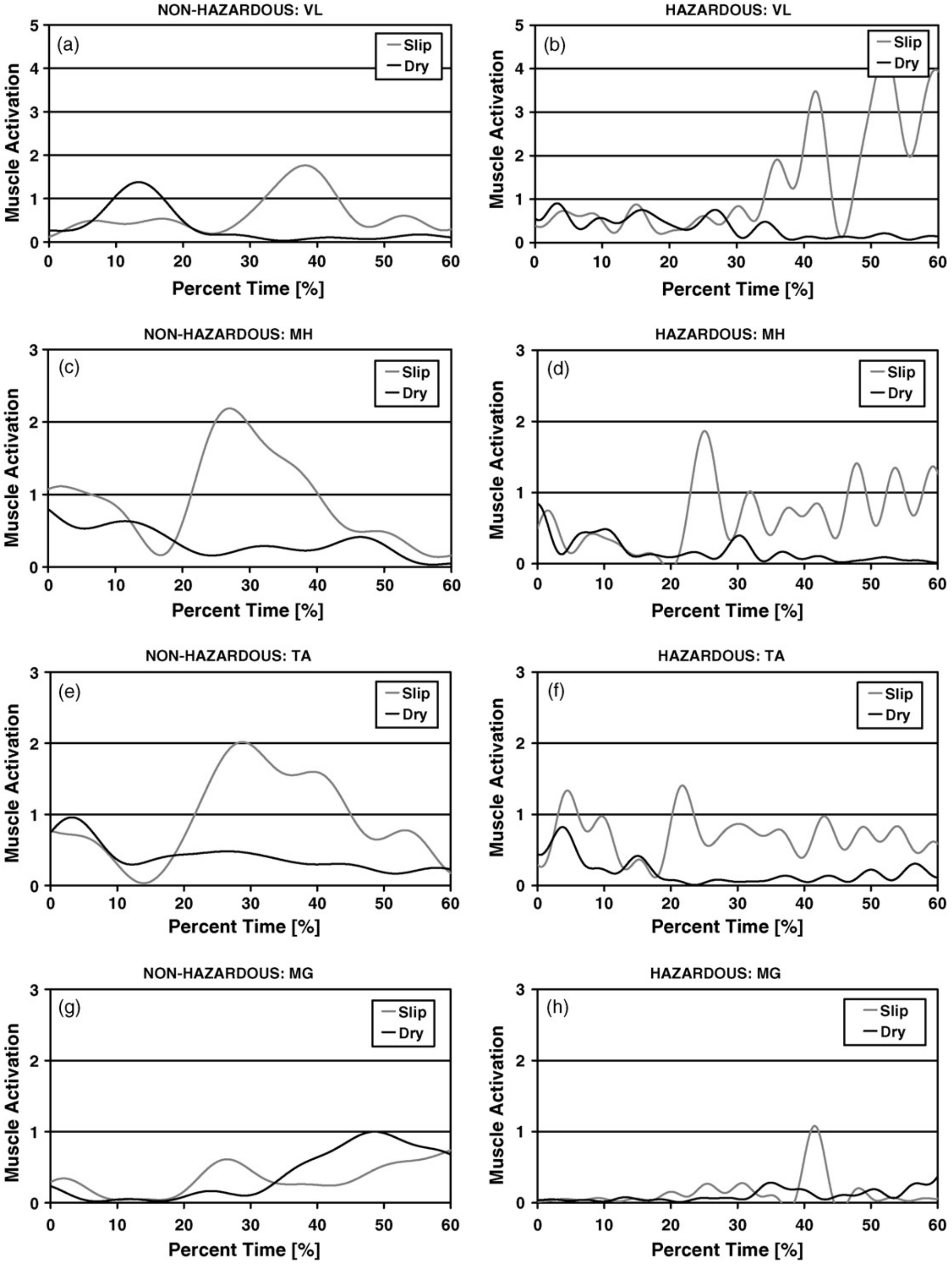

Fig. 1. Typical muscle activation patterns during a non-hazardous slip (gray) and one baseline dry gait trial (black). (a) VL, (c) MH, (e) TA, (g) MG. and during a hazardous slip (gray) and one baseline dry gait trial (black). (b) VL, (d) MH, (f) TA, (h) MG. Muscle activity was filter at 10 Hz for illustration purposes, magnitude normalized to the peak during baseline gait and time normalized to stance with HC being 0% and TO as 100%. The end of the non-hazardous and hazardous slip, when the heel stopped moving, was recorded at 27.4% and 54.4% into stance, respectively. The power and duration of muscle activity increased during both hazardous and non-hazardous slips. The initial reaction to an unexpected slip consisted of the activation of the MH, TA, MG and VL, in this order. Additionally, note the delayed VL activation during a hazardous slip.

50 Hz using a phaseless elliptical filter then time normalized with respect to the stance leg with 0% being HC and 100% as TO (the mean (S.D.) stance duration was 834 (341) ms). Slip trials were time normalized using the stance duration of the previous BD trial. Each EMG channel was peak normalized within subject using the average maximum calculated across the BD conditions during the gait cycle [21].

Dependent variables in the dry trials, i.e. BD and AD conditions: muscle activity onsets and durations were determined using a threshold of two standard deviations above activity during a typically quiet period of the gait cycle and visually confirmed. The power of muscle activity was determined from the integrated EMG (iEMG), calculated by taking the integral from onset to cessation, and normalized to the duration of activation. Co-contraction index (CCI) was calculated based on the integrated (from −20% to 20% into stance, with HC being 0%) ratio of the EMG activity of antagonist/agonist muscle pairs (TA/MG and VL/MH) using the following equation proposed by Rudolph et al. [22]:

$$\mathrm{CCI} = \int_{i=-20\%}^{i=20\%} \frac{\mathrm{Lower\,EMG}_i}{\mathrm{Higher\,EMG}_i} \times (\mathrm{Lower\,EMG}_i + \mathrm{Higher\,EMG}_i)$$

Dependent variables in the contaminated trials, i.e. US conditions: contaminated trials were categorized into non-hazardous (NH) and hazardous (H) by considering the peak velocity of the heel during a slip. Peak slip velocity (PSV) was identified as the first local maximum horizontal velocity after 50 ms from HC using the velocity of the slipping heel virtual marker which was reconstructed using the relative position to additional heel markers present during dynamic trials [5]. Hazardous slips were defined as having a PSV greater than 1.0 m/s. The last trial of the BD condition was subtracted from the US trial within subject providing a difference in muscle activation during slipping. Reactive onset, termed latency, and cessation were determined using a threshold of two standard deviations above the difference activity in between the US and BD trial before HC onto the slippery surface. The latency and cessation points were visually confirmed and duration was calculated. To calculate the power of the muscular response, the difference in the activity between the US and BD trials was integrated between the latency and cessation times and normalized to the duration of reaction.

3. Results

3.1. Objective 1: Reactive strategies

General observations: Young and older adults experienced hazardous slips at similar rates: 64% (7/11) for younger subjects and 67% (6/9) for older subjects. The power and duration of the activity of all muscles considered in this study increased during slips compared to baseline dry (as typically shown in Fig. 1).

To determine the sequence of muscle activations utilized in a reactive strategy, a linear across-muscle regression analysis was conducted on the latency using age group (young/old), hazard (H/NH), muscle and their interaction effects as independent variables. The initial reaction to an US consisted of the activation of the MH (21.9% stance, 175 ms), TA (24.2% stance, 189 ms), MG (26.1% stance, 219 ms) and VL (29.1% stance, 239 ms). Post hoc testing revealed two significant differences in latency: (1) MH was activated significantly sooner than VL and MG and (2) VL was activated after MH and TA (Fig. 2). In other words, the knee flexors were activated significantly sooner than the knee extensors.

An additional across-muscle regression analysis was conducted on the duration and reactive power of the muscular response to slipping with the same independent variables as described in the previous paragraph. Hazardous slips were characterized by longer durations and increased reactive power compared to non-hazardous slips ($p = .0113$ and $p = .0001$, respectively, Fig. 1). Additionally, muscular reactions generated in response to hazardous slips were longer and more powerful in young adults compared to older adults ($p = 0.0230$ and 0.0288, respectively).

To investigate differences between age groups and H/NH slips, within-muscle regression analyses were conducted on EMG using age group, hazard (H/NH) and their interaction effect as independent variables. Interestingly, adults that experienced hazardous slips activated their VL significantly later than those who experienced non-hazardous slips (Table 2). Young adults showed longer durations compared to older adults (significant findings in TA as shown in Table 2). Finally, both MH and TA showed significant increases in the power of the response during hazardous slips (Table 2).

3.2. Objective 2: initial conditions

To investigate differences in EMG characteristics during BD gait between participants that experienced hazardous and non-hazardous slips, linear regression analyses were conducted on the BD EMG variables (onset, duration and ankle/knee muscle CCI) using hazard (N/NH), age group (young/old) and

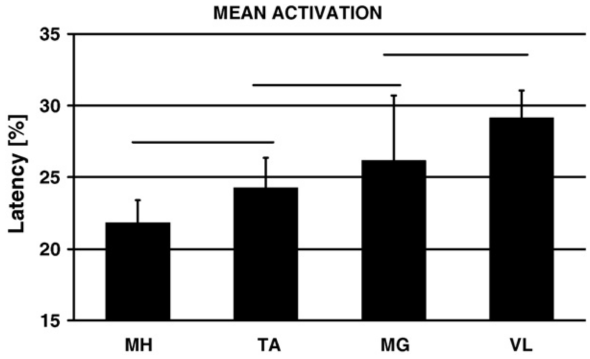

Fig. 2. Mean activation latencies of postural reaction in percent time of stance leg muscles in response to an unexpected slip. Non-significant results of post hoc Tukey tests are provided (−). S.E. bars given. The knee flexors were activated significantly sooner than the knee extensors.

Table 2
Mean (S.E.) reactive muscular activation generated in response to an unexpected slip with respect to normalized time [%]; raw time [ms]

Muscle EMG variable	Young		Older		Statistics
	NH	H	NH	H	p-Value*
VL					
Latency	24.12(0.85)%; 157(6) ms	31.96(0.98)%; 216(9) ms	26.65 (1.31)%; 204 (5) ms	33.80(0.69)%; 326 (22) ms	$p_{\text{hazard}} = 0.0004$
Duration	37.09(3.26)%; 246 (25) ms	36.37(2.85)%; 239(15) ms	35.48 (3.84)%; 283 (45) ms	25.35 (1.94)%; 233(17) ms	
Power	0.65(0.19)	2.17(0.73)	0.59 (0.02)	1.27(0.22)	
MH					
Latency	22.27(0.73)%; 146(6) ms	20.90(0.99)%; 139 (4) ms	21.90(1.24)%; 167 (4) ms	22.27 (0.28)%; 221 (18) ms	
Duration	26.61 (4.07)%; 180(33) ms	47.67(5.32)%; 312 (27) ms	24.58(5.89)%; 205 (59) ms	36.52 (1.50)%; 375(41) ms	
Power	0.51 (0.08)	1.29(0.35)	1.30(0.44)	1.38(0.29)	$p_{\text{hazard}} = 0.0124$
TA					
Latency	23.77 (0.36)%; 156(4) ms	22.40(0.59)%; 151 (5) ms	26.35 (2.24)%; 209 (28) ms	24.58 (1.02)%; 228(12) ms	
Duration	14.62(1.45)%; 96(10) ms	49.71 (5.31)%; 329 (34) ms	23.03 (4.82)%; 181 (38) ms	34.13(1.57)%; 327 (24) ms	$p_{\text{hazard}} = 0.0041$
Power	25.27 (5.28)	21.90(4.68)	30.65 (5.67)	26.73 (2.58)	$p_{\text{hazard}} = 0.0026$
MG					
Latency	25.27 (2.64)%; 165(17) ms	21.90(2.02)%; 151 (12) ms	30.65 (3.28)%; 235(21) ms	26.73 (1.05)%; 280(31) ms	
Duration	13.35(1.65)%; 89 (11) ms	22.42 (3.34)%; 160(26) ms	31.80(6.78)%; 260 (67) ms	20.80 (1.93)%; 190(20) ms	
Power	0.08 (0.07)	0.35(0.14)	0.44 (0.06)	0.29 (0.08)	

* Only $p < 0.05$ are presented for variables with respect to normalized time.

their interaction as independent variables. Only the ankle muscle CCI was significantly different between hazardous and non-hazardous slips ($p = 0.0045$). More specifically, adults who normally walked with greater ankle muscle co-contraction around HC experienced non-hazardous slips (Fig. 3).

3.3. Objective 3: proactive strategies

Following an US, the number of subjects who walked using increased muscle activity of the MG around HC was greater in the AD condition than in BD trials. In addition to the four young adults and one older adult who walked as previously described in known dry environments (BD), two more young adults and five additional older adults (4 H and 3 NH slips) activated their MG around HC, resulting in a total of six young adults (54%) and six older adults (67%) that utilized this strategy.

Anticipation effects were investigated using mixed linear ANOVAs conducted on the onset, duration and power of the muscular activity as well as on the ankle/knee muscle CCI using age group (young/older) and anticipation condition (BD/AD) as fixed effects, and subject as a random effect. In addition to the overall age group effect noted in the MH onset (earlier in young adults, Table 3), two main anticipation condition effects were found:

(1). Alerting subjects of the possibility of a slippery surface resulted in increased power of the MH, MG and VL activation (Table 3). The greatest increase in power was noted in MH.
(2). MG onset was sooner in stance in AD conditions compared to BD trials. This finding was confirmed both in young and older adults (Table 3).

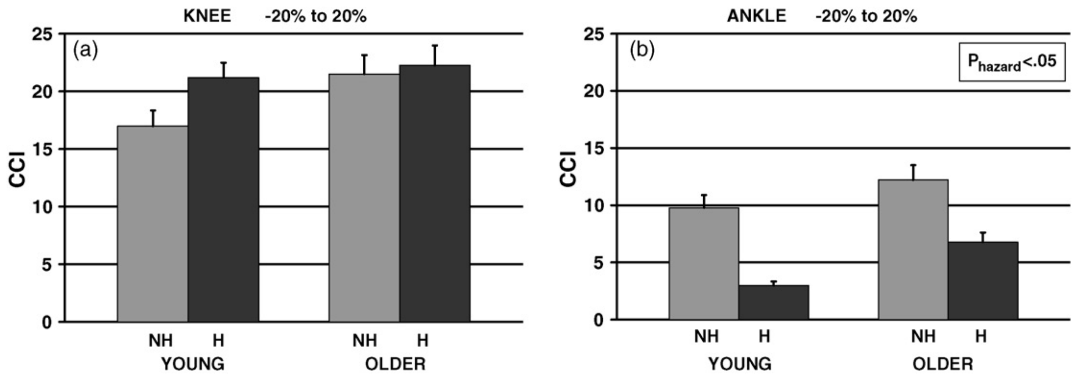

Fig. 3. Effect of co-contraction during gait on slip severity as measured by hazardous condition. (a) co-contraction at the knee around HC (−20% to 20%), (b) co-contraction at the ankle around HC (−20% to 20%). Young adults are shown on the left while older adults are on the right. Black bars correspond to hazardous slips and gray bars are non-hazardous slips during the unexpected slip. Overall significance is given in top right corner of each graph. SE bars given. Adults who normally walked with greater ankle muscle co-contraction around HC experienced non-hazardous slips.

Table 3
Mean (S.E.) muscular activation generated in BD and AD conditions with respect to normalized time [%]; raw time [ms]

Muscle EMG variable	Young		Old		Statistics
	BD	AD	BD	AD	p-Value*
VL					
Onset	−14.48(0.64)%; −97(1) ms	−15.84(1.47)%; −98 (2) ms	−13.49(0.94)%; −105(2) ms	−12.78(1.45)%; −92 (3) ms	
Duration	43.58(1.19)%; 300 (2) ms	44.08(1.84)%; 316(2) ms	46.85(3.11)%; 401 (7) ms	44.68(5.15)%; 371 (12) ms	
Power	0.20(0.01)	0.25 (0.02)	0.18(0.01)	0.18(0.01)	$p_{\text{condition}} = 0.0012$
MH					
Onset	−23.49 (0.64)%; −157(1) ms	−25.38 (0.93)%; −168(1) ms	−20.96 (0.88)%; −167(3) ms	−20.79 (0.96)%; −161 (2) ms	$p_{\text{age}} = 0.0334$
Duration	38.67(1.63)%; 272 (3) ms	46.06 (2.26)%; 327 (3) ms	44.21 (2.52)%; 394 (8) ms	41.69(2.68)%; 330 (5) ms	$p_{\text{age} \times \text{condition}} = 0.0060$
Power	0.16(0.01)	0.25 (0.02)	0.17(0.02)	0.24 (0.04)	$p_{\text{condition}} = 0.0002$
TA					
Onset	−5.35 (0.96)%; −31 (1) ms	−3.70(3.14)%; −22 (4) ms	−9.50(1.29)%; −76 (2) ms	−7.53 (1.50) −53 (3) ms	
Duration	32.24 (3.98)%; 238 (6) ms	41.10(6.54)%; 287 (8) ms	33.73 (2.65)%; 268 (5) ms	28.53(4.31) 199 (7) ms	
Power	0.22 (0.02)	0.20 (0.02)	0.21 (0.01)	0.24 (0.02)	
MG					
Onset	29.01 (1.84)%; 196(3) ms	23.30(1.82)%; 147(2) ms	37.87(2.41)%; 319 (10) ms	32.82 (3.52)%; 242 (6) ms	$p_{\text{condition}} = 0.0013$
Duration	51.91 (1.77)%; 356 (3) ms	57.86(2.18)%; 362 (3) ms	37.77 (2.52)%; 327 (7) ms	39.80 (3.07)%; 292 (6) ms	$p_{\text{age}} = 0.0003$ $p_{\text{condition}} = 0.0401$
Power	0.17(0.01)	0.16(0.01)	0.18(0.02)	0.21 (0.02)	$p_{\text{condition}} = 0.0382$

* Only $p < 0.05$ are presented for variables with respect to normalized time.

The interaction of anticipation condition and age group had a significant impact on the duration of posterior muscles (Table 3). Specifically, young adults activated their MH and MG longer when anticipating a slippery surface (relative to BD patterns) compared to older adults (Table 3).

Additionally, anticipation resulted in a significant increase of co-contraction at the ankle ($p = 0.0043$) and knee ($p < .0001$) in both age groups (Fig. 4). Co-contraction increased by an average of 29% at the ankle and 32% at the knee during AD conditions across both age groups. There was no significant difference in gait velocity during anticipation.

4. Discussion

This research focused on muscle activation patterns generated in response to slipping and anticipation of slippery surfaces in the stance leg. This study differentiated lower extremity muscle responses of the VL, MH, TA and MG between hazardous and non-hazardous slips. Additionally, muscle activity when anticipating slippery floors during gait on dry surfaces was examined to provide information about how people change their gait to reduce the likelihood of a slip (proactive strategies). Age-related differences in both reactive and proactive strategies were also investigated. The number of BD trials had to be limited in order to generate an US. However, the muscle activation patterns reported here during BD were similar to those previously reported during gait [23].

The initial reaction to a slip consisted of the activation of the MH, TA, MG, and finally, VL (in this order). This latency pattern is consistent with reported moment data in our previous study investigating naturally occurring slip, i.e. primary knee flexion response followed by secondary knee extension response [6]. Latencies reported are calculated from HC; on average a slip begins between 50 and 80 ms after HC [24]. The response to an US was scaled to its severity with muscular reactions generated during hazardous slips characterized by longer durations and more powerful reactions. It is worth noting that the duration and reactive power in four hazardous slips may have been underestimated because of the premature end of slip set as the point where a subject slipped off the force plate or was assisted by the harness.

An increased power of the TA, as well as duration, was noted during hazardous slips. Some studies using a base of support translation perturbation to simulate a slip have indeed reported increased power in the lower leg muscles in balance recovery attempts (e.g. [20]). This activation of the TA during hazardous slips may result in the delayed achievement of foot-flat, an important aspect in slip recovery and continuation of gait [5,6,15]. On the other hand, in our previous research investigating moment data, we reported a null ankle moment during severe slips [6]. This finding combined with the results of this study, i.e. scaling of the response to slip severity, suggest increased activity observed in the lower leg muscles resulted in increased in ankle muscle co-contraction, a potentially important response previously unreported.

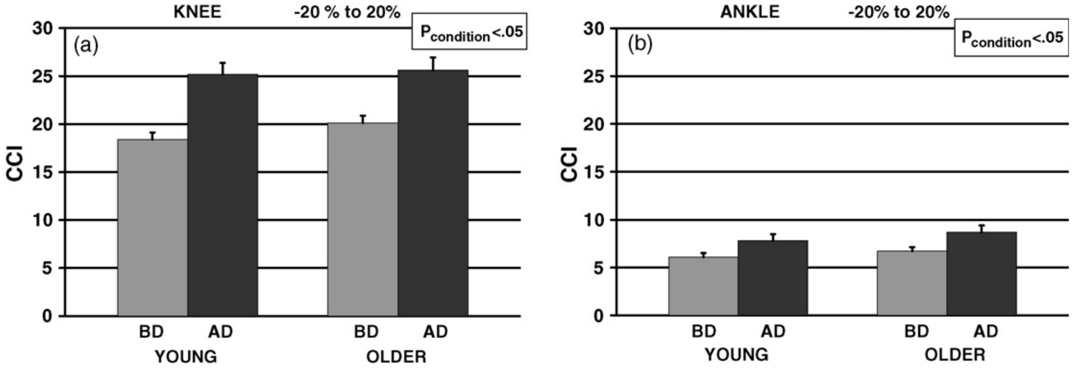

Fig. 4. Effect of anticipation on co-contraction during gait. (a) co-contraction at the knee around HC (−20% to 20%), (b) co-contraction at the ankle around HC (−20% to 20%). Young adults are shown on the left while older adults are on the right. Black bars correspond to alert dry and gray bars are baseline dry. Overall significance is given in top right corner of each graph. SE bars given. Anticipation of a slippery surface resulted in a significant increase of co-contraction at the ankle and knee in both age groups.

This study supports the previously reported findings regarding the critical response of knee and hip joint in recovery reactions initiated by unanticipated severe slips [6]. Interestingly, the latency of the primary knee flexion response (MH latency) was not statistically different between hazardous and non-hazardous events; however VL latency (onset of secondary response) was significantly later in hazardous slips. Activating the VL later may be associated with at least two detrimental effects on balance recovery and gait cycle progression: (1) delayed anterior movement of the body COM over the base of support [25], and (2) knee buckling (our previous research has indeed reported decreased knee extension later in stance in fall cases [6]). Delayed VL latency in hazardous slips may also be contributed to a slower limb-loading rate [15].

Age-related differences were noted as young adults showed significantly longer reactive durations compared to older adults. Overall, hazardous slips tended to be associated with higher reactive power compared to non-hazardous slips in young adults compared to older adults. When experiencing a hazardous slip, young adults demonstrated a longer, more powerful response. Similar age-related limitations in temporal and reactive power of response to a perturbation have been reported previously [8,19]. This difference might be directly related to the reduced lower extremity strength or ability to generate powerful, fast responses reported in older adults [26].

Anticipating slippery surfaces affected temporal aspects and power of the muscular response as well as co-contraction of the stance leg muscles. In general, anticipation of a slippery surface resulted in an increase in the number of subjects who activated their MG near HC as well as earlier onsets and longer durations of the posterior muscles in the stance leg. Additionally, alerting older and young adults of the possibility of a slippery surface resulted in increased power of activation of MG, VL and MH and co-contraction at the ankle and knee.

The EMG results reported here can help explain how previously reported kinematic and kinetic adaptations related to slippery floor anticipation effects are generated. These adaptations, including taking shorter steps, reducing foot-floor angle and vertical heel velocity at HC and an increase in knee flexion and hip moment, resulted in an overall decrease in slip-fall potential [7,15,17]. For example, increased activity of MG around HC when anticipating a slippery floor would result in a decreased foot-floor angle at HC [15,16]. Another example relates to the increased knee flexion moment and hip extension moment when anticipating slippery surfaces, which can be at least partially attributed to increases in MH and MG activity.

Ankle and knee muscle co-contraction increased with slippery floor anticipation in both age groups. Increased muscle co-contraction at the ankle may play a role in the control of foot positioning [27]. Increased co-contraction might also make it more difficult to initiate a slip if the ankle joint is ‘‘stiffer’’ (Fig. 3b). While increasing ankle muscle co-contraction is clearly beneficial to decrease the risk of a hazardous slip, it is unclear if an increase in knee muscle co-contraction is helpful when slipping. On one hand, some increase in muscular activity may be beneficial to prepare for a fast response should a slip occur. Conversely, it is also possible that too much co-contraction would result in ‘‘stiffening’’ the knee joint, hindering a quick reaction. As mentioned previously, the knee joint corrective response is critical in recovering from severe slips. Unfortunately there is no commonly accepted method to calculated co-contraction or define ‘‘stiff’’; thus, results reported here are dependent upon the index chosen.

Both young and older adults adapted their muscle activation patterns during their gait when anticipating a slippery surface, consistent with the findings that healthy older adults were fully capable of learning to better recover from or adjust to a perturbation [9,12]. However, certain age-related differences were noted in the temporal and power aspects of the stance leg flexors. Young adults activated their MH and MG significantly sooner and longer than older adults during AD. Increased muscle activation duration of young adults compared to older adults has been previously reported under similar conditions [13]. Additionally, young adults increased the power of their MH significantly more when anticipating a slippery surface compared to older adults. These age-related differences in the stance leg flexor muscles would result in a slower leg and foot at HC compared to older adults when being alerted of the possibility of slipping compared to baseline conditions.

5. Conclusion

In conclusion, greater muscle co-contraction at the ankle around HC during normal gait resulted in less severe unexpected slips. Once a slip is initiated, the muscle activation patterns found in this study suggest once again that corrective reactions generated at the knee and hip joints of the stance leg are critical to recover from severe unexpected slips during gait on contaminated floors. When experiencing a hazardous slip, young adults demonstrated a longer, more powerful response compared to older adults implying that older adults may have a higher incidence of falls because they cannot react with the power required to recover balance in response to a hazardous slip. This finding may explain the higher incidence of falls found in the elderly.

Finally, when adapting to a potentially slippery surface, both young and older adults significantly change their muscle activation patterns during gait in a similar manner. In general, anticipation of a slippery surface resulted in earlier onsets, longer durations and more powerful activity of flexors muscles in the stance leg compared to gait in known dry environments. These effects were more evident in young adults than older adults. Alerting of the possibility of a slippery surface resulted in increased muscle co-contraction at the ankle and knee in both age groups.

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