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Knee Strength Capabilities and Slip Severity

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Slips and falls are a serious public health concern in older populations. Reduced muscle strength is associated with increased age and fall incidence. Understanding the relationships between specific joint muscle strength characteristics and propensity to slip is important to identify biomechanical factors responsible for slip-initiated falls and to improve slip/fall prevention programs. Knee corrective moments generated during slipping assist in balance recovery. Therefore, the study goal was to investigate the relationship between knee flexion/extension strength and slip severity. Isometric knee flexion/extension peak torque and rate of torque development (RTD) of the slipping leg were measured in 29 young and 28 older healthy subjects. Motion data were collected for an unexpected slip during self-paced walking. Peak slip velocity (PSV) of the slipping heel served as a slip severity measure. Within-sex and age group regressions relating gait speed-controlled PSV to strength of the slipping leg revealed significant inverse PSV-knee extension peak torque and PSV-knee flexion/extension RTD relationships in young males only. Differences in PSV-strength relationships between sex and age groups may be caused by greater ranges of strength capabilities in young males. In conclusion, the ability to generate higher, more rapid knee flexion/extension muscle moments (greater peak torque/RTD) may assist in recovery from severe slips.

Keywords: muscle force, muscle torque, lower extremity

Falls, a well-acknowledged public health concern, are more prominent with increasing age. Epidemiological estimates indicate that approximately one in every three older adults (>65 years) falls each year (Tinetti et al., 1988), a 10-fold increase compared with younger individuals (Thomas and Brennan, 2000). In the United States, falls are the leading cause of unintentional nonfatal and fatal injuries in individuals over 65 years old (NCIPC, 2006). Base-of-support perturbations such as slips, trips, and stumbles initiate nearly 67% of falls in older adults and are reportedly the most common causes of falls in individuals over 60 years old (Berg et al., 1997; Bloem et al., 2001; Lloyd & Stevenson, 1992, Scuffham et al., 2003). Slips and trips account for up to 49% of falls with fractures (Keegan et al., 2004). Slips specifically are a significant cause of falls in older adults (Sjögren & Björnstig, 1991; Björnstig et al., 1997) and account for nearly 44% of fatal and nonfatal occupational same-level falls (ISA, 2000; USDOL-BLS, 1992–1998). Slip-initiated falls are also a risk factor for fractures, accounting for 10–26% of fall-related hip fractures in older adults (Luukinen et al., 2000; Norton et al., 1997; Nyberg et al., 1996).

To regain balance and avoid a slip-initiated fall, the body must generate a fast, effective corrective response. Two major reactions are generated by the knee of the leading/slipping leg in response to an unexpected slip to prevent a fall and continue normal gait (Cham & Redfern, 2001; Chambers & Cham, 2007; Moyer et al., 2009). The primary reaction involves initiation of a corrective knee flexion moment at approximately 100–150 ms after heel contact onto the contaminated floor (Figure 1). This response decelerates forward progression of the slipping foot, bringing the foot closer to the body center of mass. The secondary reaction, a knee extension moment generated by the slipping leg at approximately 150–200 ms, prevents knee buckling and contributes to forward movement of the body over the supporting foot to continue gait (Cham & Redfern, 2001; Chambers & Cham, 2007; Moyer et al., 2009). These corrective moments generated in response to a slip are active muscle reactions observed in young and older adults (Chambers & Cham, 2007). Thus, it is likely that knee flexor/extensor strength influences the effectiveness of corrective reactions and, in turn, slip severity.

Aging has been associated with decreased peak muscle strength and explosive strength measures such

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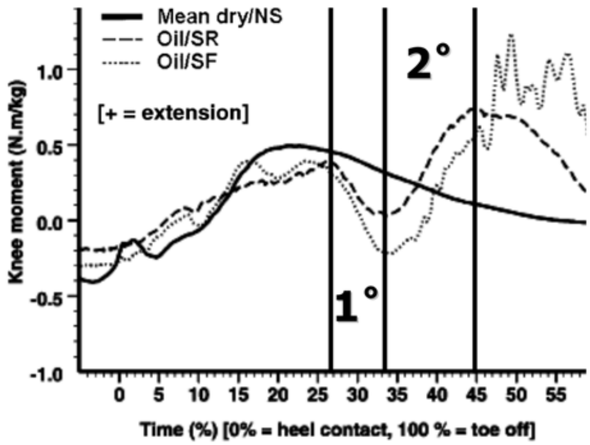

Figure 1 — Profile of knee moment generated by the leading/slipping leg during stance phase on dry floors (mean) and typical slip-recovery (SR) and slip-fall (SF) events on oily floors. Vertical lines denote time periods (% stance) in which the primary knee flexion (1°) and secondary knee extension (2°) corrective moments occur. The primary corrective moment acts to decelerate the forward progression of the slipping foot, thus minimizing the distance between the center of mass of the body and the stance foot. The secondary corrective moment is believed to play a role in preventing knee buckling and contributes to the progression of the body's center of mass over the stance foot. (Adapted from Cham and Redfern, 2001).

as rate of force/torque development (RFD/RTD) and angular impulse (Izquierdo et al., 1999; Johnson et al., 2004; Perry et al., 2007, Thelen et al., 1996). Both peak and explosive strength measures show decreases in fallers compared with nonfallers (Gehlsen & Whaley, 1990; Perry, et al. 2007; Whipple et al., 1987). Ability to exert a rapid rise in muscle force in response to external perturbations is suggested to contribute to balance recovery and fall prevention (Aagaard et al., 2002; Chang et al., 2005; Izquierdo et al., 1999; Thelen et al., 1996). Thus, higher explosive strength generation capabilities specifically may help restore dynamic equilibrium and aid in fall prevention in the elderly (Aagaard et al., 2002; Chang et al., 2005). Several studies have noted the importance of evaluating strength characteristics, e.g., RTD, during time intervals relevant to a particular functional movement (Aagaard et al., 2002; Andersen & Aagaard, 2006). For instance, it is expected that physiological time intervals corresponding to slip-initiated recovery efforts would be greater than 0–100 ms based on the onset of flexion/extension corrective knee moments.

To our knowledge, only one study has investigated the importance of leg muscle strength in specifically preventing a slip-initiated fall (Lockhart et al., 2005). Results showed that subjects with stronger lower extremities experienced less severe slips, reinforcing that slip recovery ability may be related to lower extremity peak strength. In that study, only overall peak leg strength was examined (Chaffin et al., 1978), and peak and explosive strength measures at individual joints instrumental in slip-recovery efforts, such as the knee, were not assessed (Lockhart et al., 2005).

In summary, knowledge of individual joint muscle strength contributions to slip recovery is limited and may be critical to the development of effective fall prevention programs. Corrective moments generated by the knee are critical in slip-related balance recovery. Thus, the goal of this study was to investigate the relationship between knee flexion/extension strength and slip severity in young and older adults. Specific strength variables considered in this analysis included knee flexion and extension peak torque, RTD, and angular impulse. We hypothesized that reduced strength would be associated with increased age and slip severity.

Methods

Subjects

Twenty-nine young and 28 older subjects between the ages of 20 and 31, and 50 and 65 years old, respectively, were recruited for participation (Table 1). Participants were screened by a physician for clinically significant neurological, cardiovascular, pulmonary, and orthopedic abnormalities that affect normal balance and gait. Study protocol was approved by the University of Pittsburgh Institutional Review Board and written informed consent was acquired for each subject before participation. Testing occurred over two visits: strength testing in Visit 1 and gait testing in Visit 2.

Strength Measurements

Subjects were seated and left leg isometric knee flexion and extension strength at 45° of knee flexion was collected at 1000 Hz using a Biodex AP System 2 (Biodex Medical Systems, Inc., Shirley, NY). Collection at 45° of knee flexion was chosen because this value is the approximate midpoint of the wide range of motion corresponding to the dynamic slip response, which may span from 0° of knee flexion at heel contact to 90° during knee buckling and collapse. Submaximal trials to approximately 50% of maximum were collected before each maximum voluntary contraction (MVC) trial to familiarize subjects with strength testing protocol. For MVC trials, subjects were instructed to contract as hard and fast as possible for 5 s and then relax for 10 s for three repetitions, and received standardized verbal coaching by a physical therapist throughout (Chaffin et al., 1999). Knee extension strength was collected first, followed by knee flexion. Only MVC trials were analyzed.

Strength Data Processing

Isometric strength data were first low-pass filtered at 20 Hz using a fourth-order zero phase-lag Butterworth filter (Winter, 1990). The mean torque value during the resting period was subtracted from the time series to set

Table 1 Mean (*SD*) and [Minimum–Maximum] of Subject Population Characteristics Stratified by Age Group and Sex

	Sex/Age Group				
Characteristics	**Young female (*n* = 14)**	**Young male (*n* = 15)**	**Older female (*n* = 15)**	**Older male (*n* = 13)**	**Age / Sex effects**
Age (years)	25 (4) [20–31]	23 (2) [21–26]	55 (3) [50–60]	58 (6) [50–65]	$p_{age} < 0.01$ $p_{age \times sex} < 0.05$
Stature (cm)	166 (5) [158–174]	178 (7) [164–190]	164 (5) [157–175]	177 (6) [168–191]	$p_{sex} < 0.01$
Body mass (kg)	63 (12) [52–88]	75 (11) [56–98]	82 (18) [56–112]	88 (13) [61–112]	$p_{age} < 0.01$ $p_{sex} < 0.05$

Note. Age group and sex differences in stature, body mass, and age were tested using an ANOVA model. Specifically, age, stature, and body mass were each entered individually as the dependent variable in an ANOVA model, with age group (young/older), sex (male/female), and their interaction as fixed effects. Statistically significant effects are reported in the last column.

resting period torque to zero (Pohl et al., 2002). The derivative of the torque data, as well as its mean and standard deviation during the resting period, were computed for determining the onset of contraction. Specifically, onset of contraction was defined as the first time point, working backward from peak torque of each repetition, at which the torque derivative was less than or equal to the mean baseline resting torque derivative value plus two standard deviations and the torque value was less than or equal to 2.5% of peak torque value (Pohl et al., 2002; Aagaard et al., 2002). Onsets were visually verified.

Peak torque was determined as the maximum torque value for each repetition. Rate of torque development was calculated for each repetition as the slope of the torque-time curve during the following time intervals, with 0 ms as onset of contraction (Andersen & Aagaard, 2006): (1) 0–100, (2) 0–110, . . . , (6) 0–150 ms for knee flexion and (1) 0–150, (2) 0–160, . . . and (6) 0–200 ms for knee extension. As mentioned previously, RTD was evaluated in these time intervals relevant to slip-related balance recovery efforts (Andersen & Aagaard, 2006; Cham & Redfern, 2001; Chambers & Cham, 2007; Moyer et al., 2009). Angular impulse was calculated as the area under the torque-time curve for each time interval (Aagaard et al., 2002). Within-subject ANOVA models revealed similar strength measures across all three repetitions ($p > .05$). Thus, mean values across the three repetitions were used in subsequent analyses.

Gait Testing Protocol

Subjects were instructed to walk self-paced along an 8-m vinyl tile walkway, focusing their vision toward an X taped onto the opposite wall. Hindfoot kinematics were tracked using four reflective markers (Figure 2). Subjects were fitted with a safety harness and practiced walking across the walkway. All subjects wore the same brand and model polyvinyl chloride sole shoes. Ground reaction forces were collected at 1080 Hz using two Bertec FP4060 (Bertec Co., Columbus, OH) force platforms embedded in the floor at the walkway midpoint. Shoe kinematic data were recorded at 120 Hz using a Vicon 612 motion capture system (Vicon, Lake Forest, CA).

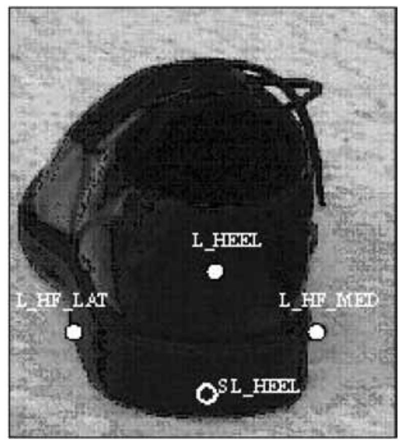

Figure 2 — Placement of the markers tracking the kinematics of the hindfoot in the left leading/slipping leg. Filled circles (L_HEEL, L_HF_LAT, and L_HF_MED) represent markers that remain on the shoes during the static/calibration and dynamic walking trials, and the hollow circle (SL_HEEL) denotes the "true" heel marker that was present only during the static calibration trial. The kinematics of the SL_HEEL marker were used to determine peak slip velocity. (Adapted from Moyer et al., 2006).

Subjects were exposed to two environmental conditions: a baseline condition, in which subjects walked on a known dry floor, and an unexpected slippery condition, in which the floor was contaminated with a glycerol-water solution (75–25%) without participant's knowledge. Coefficients of friction for the dry and slippery conditions, measured by the English XL VIT Slipmeter (ASTM F1679) at the shoe-floor interface, were 0.53 and 0.03, respectively. To prevent the subject from discerning the contaminated floor, the laboratory lights were dimmed during testing. Between all trials, subjects listened to music and faced away from the walkway to distract them from noticing possible application of the contaminant. Subjects were informed that the first few trials would be dry and two to three baseline trials were first collected to capture normal gait. The left leading leg force plate was then covered with glycerol solution, creating an unexpected slippery condition (Moyer et al., 2006). In this study, only the first unexpected slip trial was analyzed, eliminating effects of anticipation and adaptation.

Gait Data Processing

Inferior slipping heel kinematics (SL_HEEL marker in Figure 2) were used to quantify slip severity. Because the SL_HEEL marker is easily knocked off during gait, it was physically present only during static calibration trials. To derive the position of the SL_HEEL marker during gait, a rigid body assumption was used and the SL_HEEL marker trajectory was reconstructed from its three-dimensional relationship with other hindfoot markers collected during the static calibration trial (Moyer et al., 2006). Only subjects whose left heel completely contacted the contaminated force plate at heel contact during the unexpected slip trials were considered in this study. The medial/lateral and anterior/posterior positions of the virtual slipping foot SL_HEEL marker were numerically differentiated to compute heel velocity components. Resultant horizontal heel velocity was calculated at each time point as the magnitude of the vector containing anterior/posterior and medial/lateral components. Peak slip velocity (PSV), determined as the first local maximum horizontal heel velocity 50 ms after heel contact on the slippery surface, was calculated as a slip severity measure (Figure 3, Moyer et al., 2006). All PSV values were visually verified by inspecting the horizontal heel velocity curves. PSV as a continuous measure was used rather than a falls/no falls classification to quantify slip severity owing to the lack of consistency and variety of ways with which falls are categorized across literature (Moyer et al., 2006).

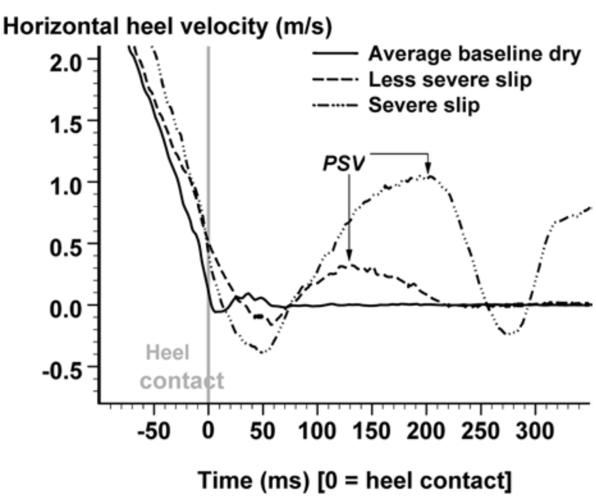

Figure 3 — Typical horizontal velocity measured at the heel of the slipping foot in a severe and less-severe slip. Downward facing arrows reflect how peak slip velocity was derived, i.e., first local maximum after heel contact (time = 0). (Adapted from Cham and Redfern, 2002).

Statistical Analysis

Knee flexion/extension strength variables (peak torque, RTD, and angular impulse) were divided by body weight and height to control for body size differences across subjects. All strength variables and PSV underwent log transformations to ensure that the normality assumption held true. First, correlation analyses comparing individually RTD and angular impulse values across the six time intervals (0–100 to 0-150 ms for knee flexion, 0–150 to 0-200 ms for knee extension) were performed and revealed that flexion and extension RTD and angular impulse values were strongly correlated across time intervals ($p_{\text{time interval}} < 0.05$, $r > .98$). Thus, two time intervals, 0–130 ms for knee flexion and 0–180 ms for knee extension, were chosen for remaining analyses because these time intervals were representative of those during which a knee corrective response to an unexpected slip is necessary (Andersen & Aagaard, 2006; Cham & Redfern, 2001; Moyer et al., 2009).

The main statistical analysis consisted of two parts. First, sex and age group differences in PSV (log transformed) and strength variables (divided by body weight and by stature, log transformed) were investigated. Specifically, strength variables and PSV were individually entered into a linear regression model with sex (male and female), age group (young and older), and their interaction as fixed effects. Statistical significance was set at 0.05.

The second part of the analysis, performed within-sex and within-age group, was conducted to examine whether strength characteristics explained variability in slip severity (PSV) after controlling for gait speed. Specifically, a linear regression model was fitted with PSV as the response variable and gait speed as the predictor (Figure 4). A second linear regression model was fitted with the gait speed-adjusted residuals for PSV from the first model as the response variable and strength variables (knee flexion/extension peak torque, RTD, and

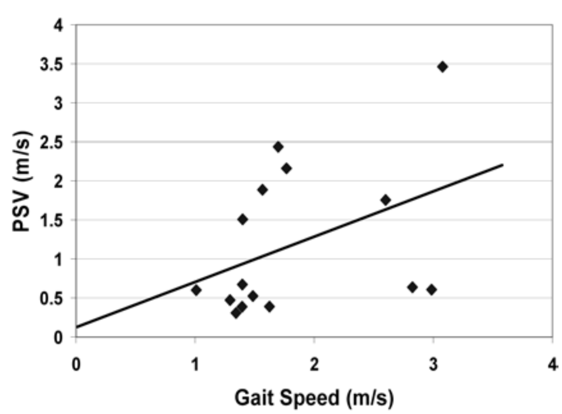

Figure 4 — Results of regressing PSV on gait speed.

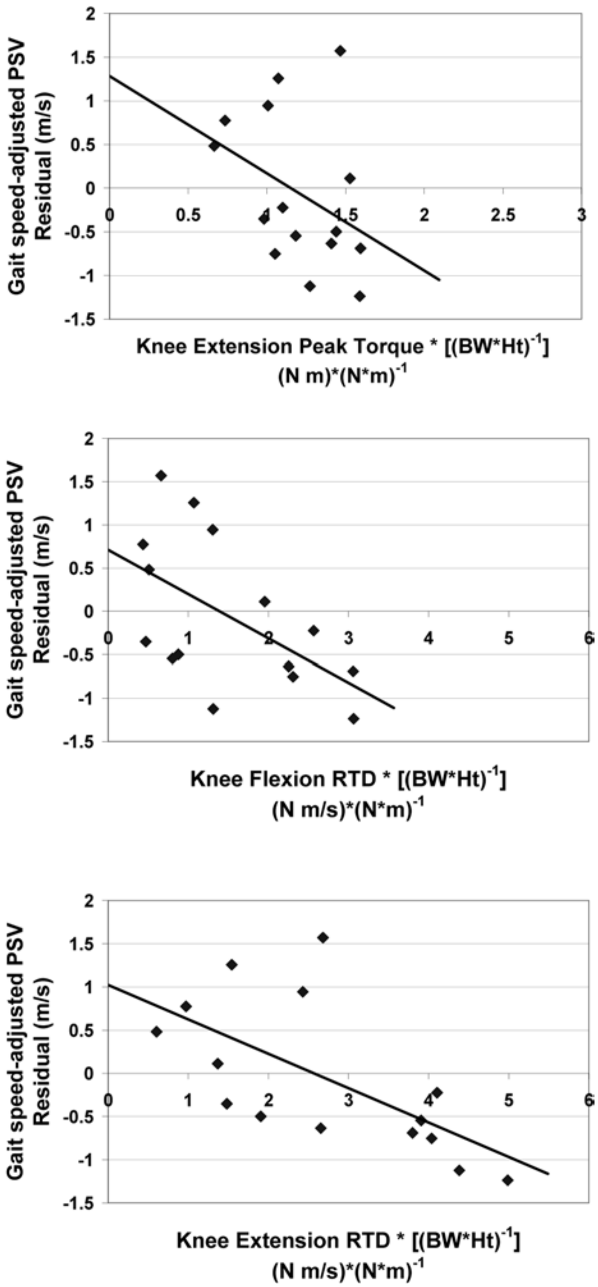

Figure 5 — Results of regressing gait speed-adjusted PSV residuals on knee extension peak torque ($p < .05$), knee flexion RTD ($p < .05$) and knee extension RTD ($p < .01$) in the young male group of participants. Peak torque and RTD were divided by body weight and by stature to control for body size across subjects. Gait speed-based predictions of slip severity as measured by PSV are increased by up to 1 m/s in subjects with limited ability to generate high knee extension peak torque and fast knee flexion and extension RTDs. Conversely, subjects with greater knee extension peak torque and knee flexion/extension RTD abilities experienced less severe slips, independent of gait speed.

angular impulse) entered individually as predictor variables (Figure 5). This allowed associations between PSV and strength to be examined independent of gait speed. Results were similar for RTD and angular impulse owing to interrelatedness (slope of / area under the same curve). Therefore, only the results for RTD are reported. Statistical significance was set at 0.05.

Results

Slip severity, quantified using PSV, was similar across sex and age groups (p_{sex}, p_{age}, $p_{sex \times age} > 0.05$, Table 2; mean ± SD = 1.13 ± 0.73 m/s). Strength characteristics normalized to body size were significantly different between sex and age groups (p_{sex}, $p_{age} < 0.05$, Table 2). Specifically, greater strength characteristics were found in young vs. older and male vs. female subjects. Young male subjects exhibited the highest values and greatest range of strength characteristics in comparison with other participant groups (Table 2). Finally, strength characteristics of older female, older male, and younger female subjects were similar (Table 2).

The main analyses were used to investigate associations between slip severity as measured by gait speed-independent PSV and individual strength measures (knee flexion/extension peak torque and RTD) within each sex/age group. These analyses revealed statistically significant relationships between PSV and knee extension peak torque ($p_{KE\ torque} < 0.05$), as well as with knee flexion and extension RTD ($p_{KF\ RTD} < 0.05$, $p_{KE\ RTD} < 0.01$) in only young male participants. Specifically, about 27% of the variance in the gait speed-adjusted PSV residuals was explained by knee extension peak torque, while 33% and 45% was explained by knee flexion and extension RTD, respectively. Paired plots, that is, Figure 4 with the individual panels of Figure 5, graphically represent details of PSV–strength associations in young males. Specifically, subjects with the lowest RTD and peak torque values in Figure 5 experienced PSV values approximately 1 m/s greater than their gait speed-based predictions of PSV. This indicates a higher propensity for increased slip severity. Conversely, gait speed-based predictions of PSV were reduced by about 1 m/s for participants generating the greatest knee extension peak torque and flexion/extension RTDs, leading to less severe slips. The female participant and older male groups showed no statistically significant relationships between gait speed-adjusted PSV and strength characteristics ($p_{KF\ torque}$, $p_{KE\ torque}$, $p_{KF\ RTD}$, and $p_{KE\ RTD} > 0.05$).

Discussion

The relationship between knee strength and gait speed-adjusted slip severity (PSV) was investigated in healthy young and older adults. The study focused on the knee because of its role in slip recovery efforts. Specific strength characteristics included knee flexion and exten-

Table 2 Mean (*SD*) and [Minimum–Maximum] of PSV and Muscle Strength (Adjusted for Body Weight and Height) Characteristics Stratified by Age Group and Sex

	Age / Sex Group				
Characteristics	Young female (n = 14)	Young male (n = 16)	Older female (n = 15)	Older male (n = 13)	Age / Sex effects
Knee Flexion Peak Torque (Nm·[kg·m]$^{-1}$)	5.4 (1.1) [4.0–7.7]	7.4 (1.4) [5.2–10.2]	3.8 (1.1) [2.2–5.4]	4.5 (0.9) [3.2–6.5]	$p_{age} < 0.0001$ $p_{sex} < 0.0001$
Knee Extension Peak Torque (Nm·[kg·m]$^{-1}$)	10.3 (2.4) [7.1–13.4]	11.8 (2.9) [6.5–15.6]	6.8 (1.9) [3.6–9.4]	7.0 (1.2) [4.7–8.6]	$p_{age} < 0.0001$ $p_{sex} < 0.0001$
Knee Flexion RTD (Nm/s·[kg·m]$^{-1}$)	8.1 (4.8) [2.9–20.8]	14.8 (9.3) [4.3–30.1]	5.4 (3.3) [1.7–13.9]	6.5 (2.1) [3.9–11.9]	$p_{age} < 0.001$ $p_{sex} < 0.01$
Knee Extension RTD (Nm/s·[kg·m]$^{-1}$)	14.1 (7.6) [2.9–31.0]	26.7 (13.7) [5.9–48.9]	13.1 (8.6) [2.6–31.7]	12.0 (5.2) [3.2–23.8]	$p_{age} < 0.05$ $p_{sex} < 0.05$
PSV (m/s)	1.1 (0.5) [0.3–1.8]	1.2 (0.9) [0.3–3.5]	1.0 (0.6) [0.2–2.7]	1.7 (0.8) [0.3–3.2]	

Note. Age group and sex differences in PSV and muscle strength characteristics, corrected for body weight and height, were tested using an ANOVA model. Specifically, PSV and muscle strength variables were each entered individually as the dependent variable in an ANOVA model, with age group (young/older), sex (male/female), and their interaction as fixed effects. Statistically significant effects ($p < 0.05$) are reported in the last column.

sion peak torque and explosive measures (RTD and angular impulse). Rate of torque development and angular impulse were significantly correlated and thus only RTD-related findings were presented. In the main analysis, flexion and extension RTDs were computed from 0 (onset of contraction) to 130 ms and 180 ms, respectively. These time intervals were physiologically relevant, corresponding to the timing of primary flexion and secondary extension corrective knee reactions in an unexpected slip. Owing to significant age/sex strength differences even after controlling for body weight and stature, the main analyses—focused on the PSV-strength associations—were conducted within sex and age groups. In young males, statistically significant gait-speed independent relationships were found between slip severity and knee extension peak torque and with knee flexion/extension RTD. Specifically, slip severity in subjects with reduced knee extension peak torque and flexion/extension RTDs was greater than expected based on gait speed-based predictions of PSV. No statistically significant associations were found between strength characteristics and gait speed-adjusted PSV in the other three age/sex groups.

The statistically significant relationships between strength and slip severity in only young males was somewhat surprising and may be due to greater variability and range in strength capabilities of young male participants compared with other groups, as evidenced by the standard deviation and range listed in Table 2. Thus, statistical significance level and strength differences in peak torque- and RTD-PSV relationships between subject groups may have resulted from variations in strength data distribution characteristics between these groups. Overall, average RTD values in young males were about two times greater than in other sex and age groups. Thus, another explanation for the sex/age group differences in the RTD-PSV relationship may be that minimum strength threshold capabilities are needed for impact of strength on slip severity to be evident and that, in this study, these thresholds are met in young males only.

Results here agree with those from previous research, which has reported that individuals with reduced lower extremity peak strength are at greater risk of experiencing severe slips (Lockhart et al., 2005). Although knee strength was not specifically examined, it is suspected that knee extension peak torque, associated with slip severity in our study, is a significant contributor to overall lower extremity peak strength considered in Lockhart et al. (2005). While information relating slipping and strength is somewhat scarce, previous research examining other external disturbances such as tripping and forward lean perturbations have also cited, in varying degrees, the importance of lower extremity peak torque and RTD in falls avoidance (Grabiner et al., 2005; Pavol et al., 2002; Pijnappels et al., 2007). Although reported influences of specific joint and overall lower extremity strength on fall recovery varies, sources agree that increased ability to generate sufficient lower extremity muscle response within an appropriate time frame, i.e., high torque with fast RTDs, is related to fall prevention ability (Grabiner et al., 2005; Pavol et al., 2002; Pijnappels et al., 2007). Similar to our study, Pijnappels et al. (2007) reported reduced knee extension peak torque, knee extension RTD, and overall leg extension peak torque (including knee torque contributions) in fallers versus nonfallers during tripping. It is challenging to extract which variable, peak torque or RTD, plays a more critical role in slip/trip recovery efforts as these variables are correlated; that is, typically subjects with greater RTD will generate increased peak torque. However, given that limited time is available for reaction to a slip before falling and that corrective torques do not reach maximum capabilities, it is suspected that RTD, which reflects rapid force generation abilities, may be most crucial in successful balance recovery efforts (Aagaard et al., 2002; Chang et al., 2005).

This study suggests that knee flexion strength plays a less critical role than extension strength in slip recovery efforts. Biomechanical gait factors may explain this finding. At heel contact during gait, the knee of the leading leg is producing a flexion torque (Beschorner & Cham, 2008; Winter, 1991). An increase in knee flexion torque at heel contact is associated with reduced heel contact heel acceleration, which is further correlated with decreased slip-fall risk (Beschorner & Cham, 2008). Knee extensors are activated soon after heel contact to produce the torque needed for the loading phase, preventing knee buckling and contributing to vertical trunk support (Kepple et al., 1997). During a slip, the primary corrective torque, consisting of increased knee flexor activity, also occurs during this loading phase when net knee extension torque is generated (Figure 1). This increased flexor activity decelerates the slipping foot. However, a maximal flexion reaction is not necessary for two reasons: (1) reduced coefficient of friction of the shoe-floor interface during a slip causes minimal shear forces to oppose the knee flexion response; (2) maximal knee flexion torque would increase the risk of knee buckling and body collapse. Thus, requiring a submaximal knee flexor reaction may explain the lack of or weaker associations between knee flexion strength and slip severity. Conversely, a stronger secondary knee extension reaction is still necessary, especially during severe slips, to prevent knee buckling and bring the body over the supporting foot in an attempt to continue gait (Figure 1). In summary, whereas knee flexors may be important in slip initiation at heel contact, the secondary corrective knee extension torque occurring later in stance appears to require more strength than the primary corrective knee flexion response. This may explain the reason for the apparent greater implication of knee extension strength in slip recovery efforts compared with knee flexion strength.

The appropriateness of PSV as a slip severity measure may be questioned because it occurs relatively early in the slip, sometimes before initiation of the primary corrective reaction (see "less severe slip" in Figure 3). Overall slip distance, measured at the heel during the duration of the slip, is reportedly a reliable slip severity measure (Moyer et al., 2006; Perkins, 1978; Strandberg & Lanshammar, 1981). Unfortunately, measuring slip distance accurately in the laboratory is difficult because subjects often slip beyond the motion capture volume. The strong association between slip distance and PSV ($r \sim 0.9$), however, allows for use of PSV as a comparable slip severity measure (Moyer et al., 2006). Because PSV occurs earlier during the slip, typically within the capture volume, it can be measured and applied more accurately as a slip severity predictor (Moyer et al., 2006). Figure 3, which depicts horizontal heel velocity profiles of severe and less severe slips, illustrates the association between PSV and slip severity.

A number of limitations exist in this study. First, because study participation involved exposure to a slippery environment and subject safety was a concern, participants in the older age group were required to be healthy and younger than the age at which the greatest increases in likelihood and falls incidence occur (NCIPC, 2006). Despite this potential limitation, we feel the findings unraveled in this study are still valuable for the following reasons: (1) if strength-slip severity associations are found in younger healthy adults, these effects are expected to be even more significant and applicable in the older, less fit general population, confirming the need for in-depth studies focused on older, more frail adults; (2) findings of this study are relevant in ergonomic efforts targeted on occupational fall prevention in adults still in the labor force who are typically younger and healthier than sedentary older adults in the general public. Second, strength of joints other than the knee of the leading/slipping leg may be important in slip-recovery efforts. Indeed, Pijnappels et al. (2007) suggested that the best indicator for classification of subjects as fallers and nonfallers was overall leg extension peak torque, which would incorporate all lower extremity joint strength contributions, including knee extensors. In slipping research, Lockhart et al. (2005) also employed an overall lower extremity strength testing protocol evaluating combined leg lifting strength (Chaffin et al., 1978). The goal of this study was focused on specific joint strength capabilities (e.g., knee) to understand underlying biomechanical mechanisms involved in slips. While ankle strength of the leading/slipping foot may not contribute to a reduced risk of severe slips, the hip joint of the same leg has shown importance in slip recovery efforts (Cham & Redfern, 2001). Hip strength was not measured in this study to minimize fatigue effects. However, knee and hip strength are well correlated (Lamoureux et al., 2002). A final limitation may be the narrow range of strength capabilities found in our study participants. Specifically, the strength capabilities of both female and older male groups were comparable. Thus, a subject base with a greater range of strength capabilities may allow for further analysis of the impact of strength on slipping.

In summary, this study suggests that knee strength—particularly extension strength (peak and explosive measures)—is important in slip recovery efforts. This may imply that fall prevention programs should include strength training focused not only on improving maximum strength, but also on muscle force generation abilities in short time intervals. Finally, explosive strength measures, such as RTD, collected from an isometric strength task can be successfully related to dynamic balance recovery tasks provided the time intervals used for the computation of strength measures are physiologically relevant to the postural task.

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