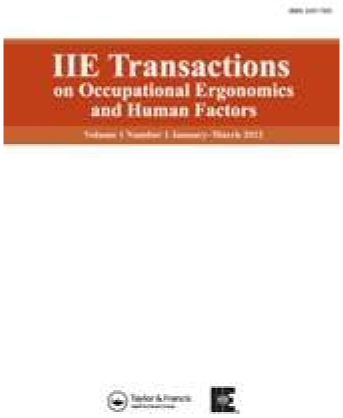

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Effects of manual material handling workload on measures of fall risk

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Effects of manual material handling workload on measures of fall risk

Occupational Applications. We found, contrary to expectations, that performing a fatiguing simulated heavy manual material handling (MMH) task did not adversely affect the risk of trip-induced falls when compared to a less-fatiguing light MMH task. However, when considering these MMH tasks together rather than in comparison, our results provide evidence for adverse effects of fatigue on both gait and the ability to recover balance after tripping. The current results provide additional evidence that physical fatigue increases fall risk, start to clarify the mechanisms by which this increase occurs, and can help in developing and evaluating fall prevention strategies targeting these mechanisms.

Technical Abstract.

Background: Falls are a leading cause of occupational injuries, and the incidence of occupational falls may be exacerbated by physical fatigue resulting from physically-demanding work. Purpose: The goal of this study was to evaluate the effects of occupationally-relevant physical fatigue on the risk of trip-induced falls. Methods: Thirty-six healthy young adults performed two-hours of a simulated heavy manual material handling (MMH) task (experimental group) or a light MMH task (control group). Risks of tripping and slipping were evaluated before and after completing the task, and one laboratory-induced trip while walking was induced after completing the MMH task. Results: Compared to the light MMH task, the heavy MMH task did not adversely affect the risk of tripping or slipping during gait, reactive balance after tripping, or fall rate after tripping. These results may have been due to an insufficient difference in fatigue level between groups. When both groups were considered together, however, the MMH tasks resulted in an unsteady gait, an increased risk of slipping while walking and carrying a load, and a fall rate that was substantially higher than reported in other studies. Conclusions: Although the effects of the heavy and light MMH tasks did not differ, changes in fall risk measures when considering both MMH tasks as one provide evidence for the biomechanical mechanisms by which physical fatigue may increase the risk of occupational falls.

Keywords: slips, trips, and falls; manual material handling; fatigue

1. Introduction

Slip, trips, and falls are the second leading cause of nonfatal occupational injuries or illnesses requiring days away from work (U.S. Bureau of Labor Statistics, 2016), and the risk of slips, trips, and falls may be exacerbated by physically-demanding work. Acute responses to such work can include neuromuscular fatigue (Gandevia, 2001), increased cardiovascular load (Lunde et al., 2016), and mental fatigue from prolonged high or low levels of mental simulation (Marek et al., 1988). For the purpose of the current investigation, the former two will be collectively referred to as *physical fatigue*. Numerous studies have shown that physical or mental fatigue can have adverse effects on fall risk. For example, neuromuscular fatigue resulting from localized muscle exertions can cause muscle pain, discomfort, and alter the perception of effort, increase reaction time and reduce muscle force generating capacity (Viitasalo & Komi, 1980), increase postural sway during quiet standing (Davidson et al., 2004; Yaggie & McGregor, 2002), and impair the ability to maintain balance without stepping following an external perturbation (Davidson et al., 2009). An increased cardiovascular load resulting from walking and running can impair joint position sense (Skinner et al., 1986) and increase postural sway during quiet standing (Morrison et al., 2016; Nardone et al., 1997). Mental fatigue resulting from a computer-based cognitive task can increase gait variability (Behrens et al., 2018), increase the risk of slipping (Lew & Qu, 2014), and impair balance recovery after slipping (Lew & Qu, 2014).

Tripping is estimated to cause 23-32% of all occupational falls (Amandus et al., 2012; Lipscomb et al., 2006). Three studies we are aware of have investigated the effects of physical or mental fatigue on the risk of trip-induced falls. (Papa et al., 2015) investigated the effects of quadriceps and hip extensor neuromuscular fatigue on single-step balance recovery following release from a static forward lean (similar to forward falls due to tripping). They reported a reduction in recovery step velocity, which could increase trip-and-fall risk given the time-critical nature of the response. Mademli et al. (2008) investigated the effects of knee flexor and extensor neuromuscular fatigue on single-step balance recovery following release from a static forward lean. They reported that fatigue altered dynamic balance reactions, including increased knee flexion following touchdown of the recovery step, which could increase fall risk given the importance of sufficient limb support during balance recovery. Qu et al. (2019) investigated the effects of physical fatigue resulting from repeated sit-to-stand exercises, or mental fatigue resulting from a computer task, on trip-induced fall risk. They reported that mental fatigue adversely affected balance recovery kinematics following a laboratory-induced trip, but that physical fatigue had no effect. While these studies support the likelihood of adverse effects of fatigue on the risk of trip-induced falls, fatigue was induced using experimentally-contrived and controlled methods; thus, outcomes from these studies might differ from fatigue resulting from occupationally-relevant, physically-demanding work.

To address this knowledge gap, the goal of this study was to evaluate the effects of occupationally-relevant physical fatigue on the risk of trip-induced falls. A simulated manual material handling (MMH) task was employed as a fatiguing activity. One group of participants completed this task using weighted cartons to induce fatigue, while another group served as a control and completed the task using empty cartons. Our primary interest was on gait measures associated with the risk of tripping and fall risk, and reactive balance kinematics and fall rate after a laboratory-induced trip. As a secondary interest, we also explored gait measures associated with the risk of slipping, given that slipping contributes to 40-50% of all occupational fall-related injuries (Courtney et al., 2001) and that such measures were easily accessible from our data. Our first hypothesis was that a heavy MMH task would increase the risk of tripping more than a light MMH task. Our second hypothesis was that a heavy MMH task would adversely affect reactive balance and fall rate following a laboratory-induced trip more than a light MMH task. Our third hypothesis was that a heavy MMH task would increase the risk of slipping more than a light MMH task. We also investigated walking with and without load carriage in the event that load carriage exacerbated any effects of fatigue. This study aimed to improve our understanding of how fatigue-inducing physical work affects fall risk due to tripping or slipping and to identify biomechanical mechanisms underlying these effects. Such information could inform the development of targeted interventions to reduce the number of occupational falls.

2. Methods

2.1. Participants

A total of 36 young adults (19 females) participated in the study, with an age range of 19-35 years and body mass index (BMI) of 19.1-32.1 kg/m^2. Participants were recruited from the university and local community using email announcements, flyers, and newspaper advertisements. Inclusion criteria required that participants not have any self-reported musculoskeletal or neurological conditions that affect balance or gait, were able to walk unassisted for 60 minutes, and had not previously experienced a laboratory-induced slip or trip. The study was approved by the Virginia Tech Institutional Review Board, and all participants provided written informed consent prior to participation. As a part of the informed consent process, participants were informed that they "may or may not experience a slip or trip while walking" during the study.

2.2. Protocol

A two-group experimental design was used wherein gait measures related to risk of tripping and slipping were obtained before and after the MMH task, and reactive balance and fall rate in response to a laboratory-induced trip were obtained after the MMH task. Participants were pseudo-randomly assigned to either a heavy or light MMH group using minimization (Taves, 1974). After randomly assigning 10 participants to each group, subsequent group assignment for each participant was based upon not only balancing group sizes but also minimizing group differences in age (discretized into categories of 18-23, 24-29, and 30-35 years), sex, and BMI (discretized into categories of 18-24.9, 25-29.9, and 30-36 kg/m^2), given evidence that these factors can influence trips and falls (Garman et al., 2015; Pavol et al., 1999). Participants completed two sessions. The first session was for familiarization and involved participants practicing the MMH task and walking along a laboratory walkway while wearing a safety harness. The second session was for data collection. During this second session, participants first performed walking trials, both with and without anterior load carriage, to evaluate the risk of tripping and slipping prior to performing the MMH task. Next, participants performed their assigned MMH task for two hours. Following this task, walking trials were repeated to re-evaluate the risk of tripping and slipping during gait. Finally, one laboratory-induced trip was induced to evaluate reactive balance and fall rate. Only one trip was induced for each participant after their assigned MMH task to avoid unintended learning effects resulting from repeated exposure to laboratory-induced trips (Rhea & Rietdyk, 2011; Wang et al., 2012).

Gait was evaluated before the MMH task. Participants were asked to walk along a 12-meter-long level walkway at a pace "as if you have somewhere to go" while looking straight ahead. After several practice trials, participants completed five trials each with and without anterior load carriage. The load during these trials was a carton set to 15% body weight, and participants were instructed to hold the load in front of their body with their elbows at approximately 90 degrees. The order of load carriage conditions was counterbalanced across participants. All participants wore the same model of rubber-soled sneakers and a safety harness that was connected by a chain to a track on the ceiling. The length of the chain was adjusted such that the distance between each participant's knee and the floor, when kneeling and fully supported by the harness, was approximately 20 cm.

Immediately adjacent to the walkway, participants then performed a simulated MMH task (Figure 1) that was adapted from Sedighi Maman et al. (2017). One cycle of the MMH task involved transporting 12 cartons using a two-wheeled dolly, one at a time, to a destination 12 meters away, and stacking the cartons in an arrangement described on an instruction sheet (Figure 1). When all 12 cartons had been moved to the destination, the next cycle was completed by moving the cartons back to their original location. Participants performed six 20-minute cycles of this task, for a total task time of 120 minutes. During each cycle, a metronome was used to pace participants so that they moved and stacked one box every 45 seconds. For the heavy MMH task, the cartons consisted of four each having masses of 9, 16, and 23 kg; for the light MMH task, all cartons had a mass of 2 kg. The maximum mass of 23 kg was selected to comply with the National Institute for Occupational Safety and Health's maximum recommended load to be lifted under ideal conditions (Waters et al., 1993).

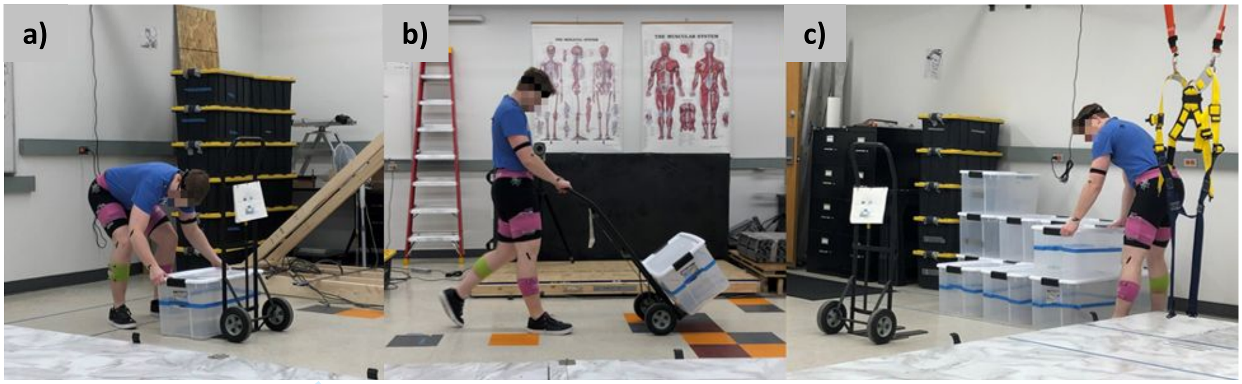

Figure 1. Each cycle of the manual material handling task involved: a) loading cartons, one at a time, onto a two-wheeled dolly; b) transporting the cartons, one at a time, to a destination; and c) stacking them, one at a time, in an arrangement described on an instruction sheet.

After each 20-minute cycle of the MMH task, participants completed 5-10 walking trials (exact number varied pseudo-randomly) along the adjacent walkway as described above, which was done to avoid participants anticipating the laboratory-induced trip after the sixth cycle (participants were not aware of how many cycles of the task would be completed). To minimize the time (and therefore fatigue recovery) between the sixth cycle of the MMH task and the laboratory-induced trip, trials to re-evaluate the risk of tripping and slipping during walking with load carriage were completed after the fifth cycle of the MMH task. Following the sixth cycle of the MMH task, five walking trials were completed to re-evaluate the risk of tripping and slipping without load carriage, followed by a laboratory-induced trip. The trip was induced using a pneumatically-actuated tripping obstacle (122 x 8 cm plate) that was initially concealed in the walkway. Upon activation, the obstacle quickly raised so that it protruded 8.6 cm above the walkway. The obstacle was triggered, without warning, while participants walked along the walkway (Figure 2), such that the dominant foot contacted the obstacle near mid-swing.

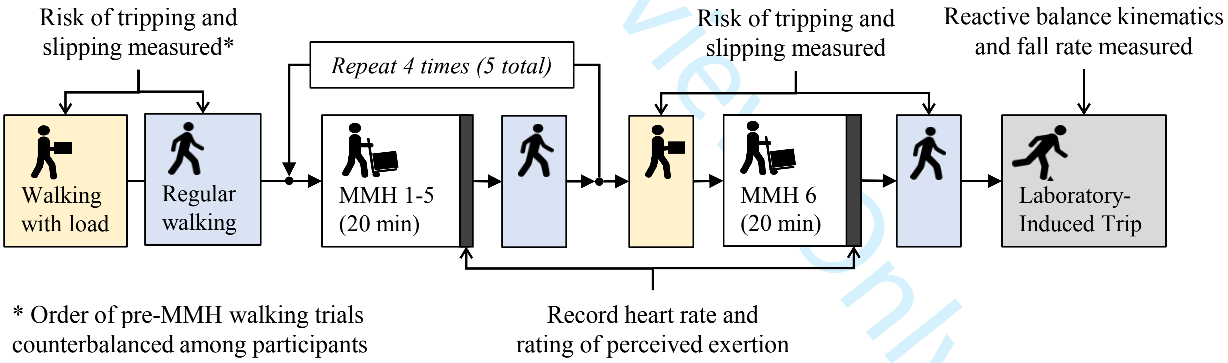

Figure 2. Schematic showing the protocol for the second session, including walking trials prior to the MMH task, six 20-minute cycles of the MMH task, walking trials following the MMH task, and the laboratory-induced trip.

2.3. Physiological Workload

Exertion level was evaluated using two methods. First, participants provided a subjective rating of perceived exertion (RPE) using the 6-20 Borg scale (Borg, 1982) before and after the MMH task. Second, cardiovascular load was measured as relative heart rate after completing the MMH task (Equation 1; Lunde et al., 2016; Jakobsen et al., 2014). Heart rate was recorded using an optical heart rate monitor (Polar OH1, Polar Electro Inc., Bethpage, NY) on the right upper arm (Scherr et al., 2013). Resting heart rate was measured after five minutes of sitting prior to the start of the MMH task, while maximum heart rate was estimated using 208 – 0.7 × age (Tanaka et al., 2001).

$$\text{Cardiovascular load (\%)} = \frac{\text{heart rate after MMH task} - \text{resting heart rate}}{\text{maximum heart rate} - \text{resting heart rate}} \times 100 \qquad (1)$$

2.4. Data Collection

During the walking trials and laboratory-induced trip, lower extremity kinematics were measured using reflective skin markers sampled at 120 Hz using a motion capture system (Qualisys North America, Lincolnshire, IL). Raw data were low-pass filtered at 12 Hz using a fourth-order, zero-phase lag Butterworth filter. Thirty-three reflective markers were placed on anatomical landmarks, and rigid marker clusters were placed on the sacrum and each thigh and shank. Forces applied to a harness chain were sampled at 1200 Hz using a uniaxial load cell (Cooper Instruments, Warrenton, VA). Ground reaction forces were sampled at 1200 Hz using a 0.9 × 0.9-meter force platform embedded in the walkway. Both force platform and load cell signals were low-pass filtered at 40 Hz using a fourth-order, zero-phase-lag Butterworth filter.

2.5. Risk of Tripping and Slipping during Gait

Before and after the MMH task, several gait measures were obtained over the five walking trials, with a mean (SD) of 14 (4) steps for each participant and load carriage condition. Gait speed was obtained from the mean anteroposterior (AP) speed of a marker on the sacrum. Step length was the AP distance between markers on the calcanei during consecutive steps. Step width variability was used as a measure of overall gait stability, and was derived as the standard deviation of step width (mediolateral distance between markers on the calcanei during consecutive steps) across all steps for each participant and load carriage condition. Risk of tripping was evaluated using minimum toe clearance (MTC) and MTC variability, where a decrease in MTC or an increase in MTC variability are associated with an increased risk of tripping (Byju et al., 2016). MTC was calculated as the minimum vertical position of the anterior edge of the shoe during the swing phase of gait, and MTC variability was the standard deviation of MTC. Due to an inadvertent 7.3 mm difference in height of the 12-meter-long walkway from the highest to lowest points measured by the motion capture system, a ‘zero’ level was identified as the minimum position among virtual markers on the sole of the stance limb shoe at the time at which MTC was identified. Risk of slipping was evaluated using the required coefficient of friction (RCOF) due to its association with risk of slipping (Beschorner et al., 2016). RCOF was calculated as the peak ratio of the resultant shear and normal ground reaction forces during the stance phase of gait (Chang et al., 2011).

2.6. Fall rate and Reactive Balance Kinematics

Each trip was classified as either a recovery, fall, harness-assist, or miss, using the force applied to the harness rope and a method described by Yang and Pai (2011). A recovery occurred if a 1-second moving average of the load cell signal was less than 4.5% body weight × second during the trial. A fall occurred if the harness support exceeded 30% of the participant’s body weight. Trips not satisfying either criteria were deemed harness-assisted, indicating an ambiguous characterization had participants not been wearing the harness. Missed trips occurred if the leading edge of the swing foot did not contact the tripping obstacle during mid-to-late swing phase, and typically occurred when the obstacle was not triggered at an appropriate time by the investigator. These trips resulted from improper triggering of the obstacle and were excluded from further analysis. Three measures of reactive balance were determined, based on the importance of controlling trunk flexion and executing a recovery step of sufficient length in order to avoid falling after tripping (Grabiner et al., 1993). Maximum trunk flexion angle was the most forward angle from vertical of a line connecting the midpoint between the hip joint centres (Piazza et al., 2004) to the midpoint between markers on each acromion process, measured after trip onset. Recovery step time was the time from trip onset to touch-down of the first recovery step over the obstacle. Recovery step length was the AP distance between lateral malleoli markers at touch-down of the first recovery step over the obstacle. Recovery stepping strategy was classified as either elevating or lowering (Eng et al., 1994).

2.7. Statistical Analysis

Several statistical analyses were performed. Participant characteristics were compared between groups using a one-way ANOVA. Gait measures were used in a three-way, mixed-model ANCOVA, to investigate the effects of group (heavy or light MMH), time (before or after MMH task), load carriage (without or with), and all interactions, with gait speed as a covariate. Non-significant interactions with the highest *p*-values were removed one at a time to obtain a final model with only statistically significant interactions. No three-way interactions were significant. To address our first and third hypotheses, our primary interest was the group × time interaction followed by pairwise comparisons using Tukey's HSD test. For continuous measures obtained from laboratory-induced trips, a one-way ANCOVA was used to investigate the effects of group (heavy or light MMH), with gait speed and BMI included as covariates. For trip outcome, a Fisher's Exact Test was used to investigate the effects of group on fall rate. To address our second hypothesis, our primary interest was a main effect of group on trip outcome and reactive balance measures. All statistical analyses were performed using JMP Pro 8 with a significance level of .05. All summary statistics are reported as means (SD).

3. Results

There were no differences in sex, age, height, or BMI between participants in the heavy and light MMH groups (Table 1). At the end of the MMH task, participants in the heavy MMH group exhibited 10% higher cardiovascular loads and RPEs 3.6 higher RPE than that those in the light MMH group. All but one participant completed all six cycles of the MMH task. One female participant from the heavy MMH group elected to not perform the final cycle of the MMH task due to excessive lumbar fatigue (final RPE = 17). Data for this participant were included in the analysis, given that her RPE was higher than the mean of that group and thus not low for prematurely stopping the task.

Table 1. Participant characteristics and physiological workload after the MMH task. Note that RPE = rating of perceived exertion, and cardiovascular load and RPE were measured at end of the MMH task.

	Heavy MMH Group (*n*=19)	Light MMH Group (*n*=17)	*p*-value
Female/Male	11/8	8/9	.739
Age (years)	24.2 (2.5)	26.4 (3.8)	.099
Height (m)	1.67 (0.06)	1.70 (0.05)	.352
BMI (kg/m^2)	25.1 (3.2)	24.6 (2.2)	.233
RPE (Borg 6-20)	13.8 (2.9)	10.2 (2.4)	**<.001**
Cardiovascular load (%)	31.8 (12.8)	21.8 (10.0)	**.013**

Gait speed was 1.70 (0.10) m/s across all participants and conditions, and there were no significant interactive effects or main effects of group (*p*=.549), time (*p*=.491), or load carriage (*p*=.105). There were no group × time interaction effects for any other gait measure (Figure 3). There was a load carriage × time interaction effect on RCOF: after the MMH task, RCOF was 0.003 (1.3%) higher with load carriage and 0.023 (9.7%) higher without load carriage (*p*=.006). There were main effects of time in that, after the MMH task, step width variability was 3.2 mm (12.7%) higher (*p*=.001) and RCOF was 0.013 (5.5%) higher (*p*=.001). There were also main effects of load carriage. During load carriage compared to walking without load carriage, step length was 0.02 meters (2.2%) shorter (*p*<.001), MTC was 2.1 mm (19.7%) higher (*p*=.005), MTC variability was 0.72 mm (18.6%) higher (*p*=.020), and RCOF was 0.013 (5.1%) lower (*p*<.001)

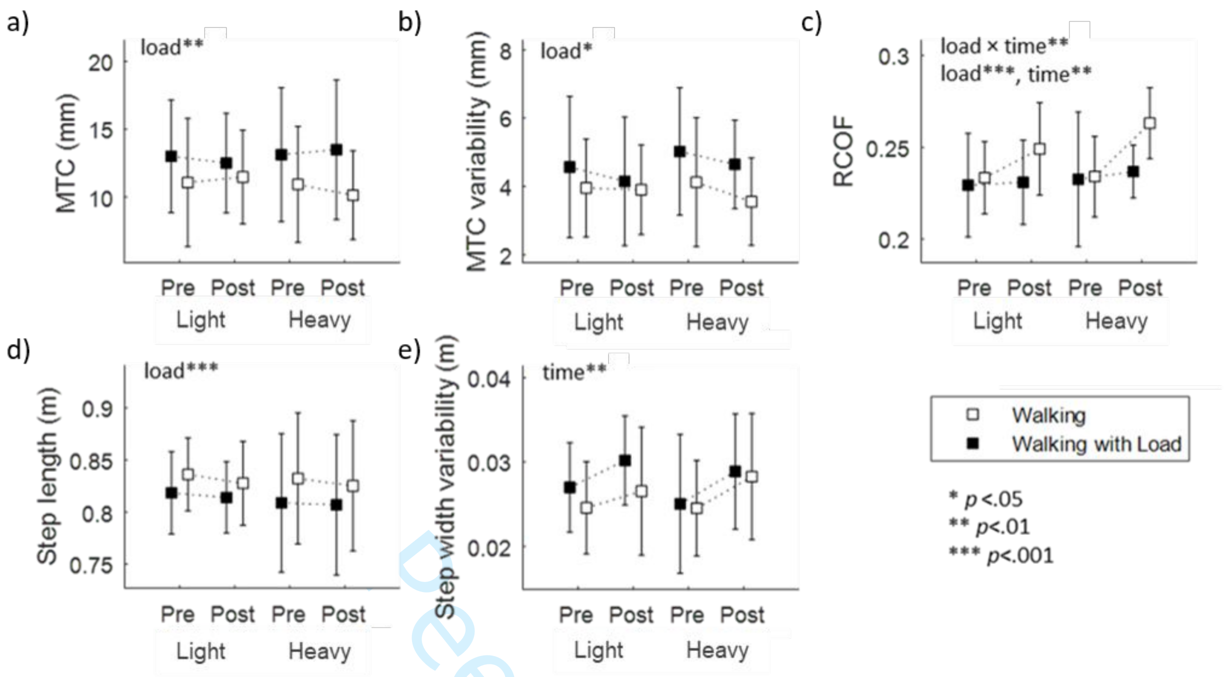

Figure 3. Gait measures for each group (light and heavy MMH) before (Pre) and after (Post) the MMH task, while walking with and without a load. Risk of tripping was quantified using a) minimum toe clearance (MTC) and b) MTC variability. Risk of slipping was quantified using c) required coefficient of friction (RCOF). Other gait measures included d) step length and e) step width variability. Symbols and bars respectively indicate means and standard deviations for each group. Significant main effects of load, time, and interaction effects of load × time are indicated by asterisks.

Sixteen participants were successfully tripped in each group. Four trips (three heavy and one light MMH) were classified as misses. Fall rate did not differ between groups (*p* = .732; Table 2). Maximum trunk angle was 5.3 degrees (10.7%) smaller in the heavy MMH group compared to the light MMH group (*p* = .024). No other reactive balance measures differed significantly between groups.

Table 2. Fall rate and reactive balance measures.

	Heavy MMH Group (*n*=16)	Light MMH Group (*n*=16)	*p*-value
Fall rate(fall/HA/recovery)	5/2/9	5/4/7	.732
Maximum trunk angle (deg)	44.1 (8.8)	49.4 (9.0)	**.024**
Recovery step length (m) *	0.90 (0.22)	1.01 (0.16)	.261
Recovery step time (ms)	459 (83)	495 (66)	.203
Strategy (Elevating/Lowering)	10/6	8/8	.722

* Normalized to body height for statistical analysis. HA = harness assist

4. Discussion

To our knowledge, this was the first study to investigate the effects of occupationally-relevant fatigue on the risk of tripping and slipping, or reactive balance after tripping. We hypothesized that a heavy MMH task would increase the risk of tripping (and slipping) more than a light MMH task. We also hypothesized that a heavy MMH task would adversely affect fall rate and reactive balance after a laboratory-induced trip more than a light MMH task. Although both subjective and objective measures of exertion level were higher after the heavy MMH task, none of our hypotheses were supported because no dependent variables were differentially affected by these two tasks (other than maximum trunk angle, which was smaller after the heavy MMH task and thus suggesting a smaller risk). Although we did not employ any objective measures of neuromuscular fatigue or any measures of mental fatigue to characterize the effects of our interventions, two measures support that the resulting fatigue level was similar to actual physically-demanding work. First, mean RPEs (heavy MMH = 13.8 and light MMH = 10.2) were comparable to values of 8-14 reported by construction workers and bricklayers (Arias et al., 2015; Roja et al., 2016). Second, mean cardiovascular loads immediately after the MMH tasks (heavy MMH = 31.8% and light MMH = 21.8%) were comparable to reports of 18-24% among blue-collar workers who perform heavy lifting tasks (Jakobsen et al., 2014) and 16.4% among construction workers during their work day (Jakobsen et al., 2014; Lunde et al., 2016).

Multiple potential reasons could explain the lack of differential effects between the heavy and light MMH tasks. First, our protocol may have resulted in a fatigue difference between the two groups that was insufficient to reveal differences in our measures of balance and fall risk. We attempted to set exertion levels such that the heavy MMH task would result in a realistic and meaningful fatigue state, but not so overly demanding that some participants would not be able to complete the entire task duration. This approach, though, may have limited the differences in fatigue between groups. Second, a non-trivial amount of fatigue recovery may have occurred before the laboratory-induced trips. Trips were induced 2-4 minutes after the end of the MMH tasks, and recovery from fatigue during this time may have lessens both the effects of fatigue and any differential effect between the heavy and light tasks. In previous studies, increases in postural sway during quiet standing after neuromuscular fatigue, as well as an increased cardiovascular load after walking, were found to recover to pre-fatigue levels in 5-20 minutes (Nardone et al., 1997; Papa et al., 2015; Pline et al., 2006; Schieppati et al., 2003; Yaggie & McGregor, 2002). While the temporal resolution of these results was limited, and the time course of fatigue recovery is likely dependent upon the specific muscle groups and fatigue-inducing protocol involved, this evidence suggests that meaningful recovery may have occurred during the 2-4 minutes prior to trips. Third, Qu et al. (2019) also reported no effects of physical fatigue from repeated sit-to-stands on fall rate and reactive balance kinematics after a laboratory-induced trip. They speculated that participants may have been able to compensate for fatigue through a neuromuscular adaptation during balance recovery. Fourth, it is possible that physical fatigue does not adversely affect the measures of fall risk and reactive balance we obtained. However, we are skeptical of this possibility, given broad evidence of adverse effects of physical fatigue on neural and muscular mechanisms (Gandevia et al., 1995).

Although none of the gait measures related to risk of tripping or slipping investigated here exhibited a group x time interactive effect, some exhibited main effects of time that were consistent with earlier reports of gait changes after fatigue-inducing activities. Here, both participants in both the heavy and light MMH groups combined exhibited a mean increase in step width variability of 3.2 mm after the task, and such an increase is considered an indicator of reduced stability and increased fall risk (Hausdorff et al., 2001; Maki, 1997). Qu & Yeo (2011) and Nagano et al. (2014) both reported a 3-4 mm increase in step width variability among young adults after running or fast walking on a treadmill. Also, participants in both MMH groups here had an overall mean 0.013 increase in RCOF after the MMH task, with an increase considered an indicator of increased slip risk (Beschorner, Albert & Redfern, 2016). The increase in RCOF here is consistent with Parijat and Lockhart (2008), who reported an estimated 0.03 increase in RCOF without load carriage after repeated bilateral contractions of the quadriceps until maximum voluntary contractions were 60% of baseline. Collectively, these studies suggest that physical fatigue results in less stable gait and an increased slip risk, and that the effects of fatigue may be dependent upon task-related factors, such as the specific fatigue pattern induced and/or load carriage.

We reviewed eight studies that exposed a total of 109 young healthy-weight adults to laboratory-induced trips when unfatigued, and from this found that only *one* fall occurred upon first exposure to a trip, for a fall rate of 0.9% (Qu et al., 2019; Grabiner et al., 1993; Grabiner et al., 1996; Pijnappels, Bobbert, & van Dieen, 2005; Pijnappels, Bobbert, & van Dieën, 2005; van der Burg et al., 2007; Garman et al., 2016; Wang et al., 2012). This rate is substantially lower than what was found in the present study, in which five participants fell in each of the MMH groups, for an overall fall rate of 31%. While methodological differences may explain some of this disparity in fall rate, the magnitude of the disparity could also suggest both an adverse effect of the MMH tasks used here and an insufficient difference in fatigue level between MMH groups to reveal any resulting differences in fall rate or reactive balance.

Although the present study focused on physical fatigue, participants in both MMH groups may have also experienced general or cognitive fatigue that contributed to the high rate of trip-induced falls. Results from prior studies support an adverse effect of mental workload on physical capacity in terms of fatigability and recovery (Mehta & Agnew, 2012), as well as an adverse effect of mental fatigue on reactive balance after tripping (Qu et al., 2019). Although the current MMH task was not cognitively demanding, some participants reported feelings of fatigue due to the monotony and repetition of the task. Future work that explores the combined effects of mental and physical fatigue, which are common in occupational tasks, may elucidate how certain occupational tasks increase the risk of falling.

Physical fatigue can adversely affect several aspects of the neuromuscular system that are important during gait and the time-critical kinematic response to a trip (Lew & Qu, 2014). While the lack of fatigue effects on our reactive balance measures precludes any conclusions regarding the biomechanical mechanisms of the higher fall rate here compared to prior studies, several neuromuscular mechanisms are possible. Neuromuscular fatigue can decrease muscle force generating capacity (Viitasalo & Komi, 1980), decrease maximal contraction velocity and rate of force development (Beelen & Sargeant, 1991; Thorlund et al., 2008), increase reaction time (Viitasalo & Komi, 1980), and alter the peripheral proprioceptive system and central processing of sensory information (Taylor et al., 2000). These effects can diminish the precision of motor control (Sharpe & Miles, 1993) and result in a clumsiness (Mademli et al., 2008) that could explain the increase in step width variability found here. There is also evidence to support that compensatory strategies are used to offset the adverse effects of fatigue during balance tasks involving standing (Simoneau et al., 2006). However, the identification of a multi-joint kinetic compensatory strategy during balance tasks involving stepping has been limited (Mademli et al., 2008). Moreover, the effects of fatigue and the use of a compensatory strategy to offset these effects may be dependent upon how fatigue is induced and the musculature involved.

Our results, when considering both groups together and in comparing with other studies, provide some evidence for an increased risk of falls due to fatigue induced by occupationally-relevant physically-demanding work. A better understanding of the biomechanical mechanisms by which fatigue increases the risk of falls can inform the development of controls to mitigate this risk. For example, if one concludes that physically-demanding work increases trip-induced fall risk, determining the duration of exposure to the work that increases risk could be used to schedule rest breaks. Alternatively, neuromuscular training (Bieryla et al., 2007) may be able to modify worker walking or balance recovery responses to reduce trip-induced fall risk.

In conclusion, results of the present study did not support our hypotheses of differential effects of fatigue from heavy and light MMH tasks on the risk of falls. However, our results did support that a more unstable gait and a higher risk of slip initiation occurred after both MMH tasks. In addition, the higher rate of falls after a laboratory-induced trip found here compared to prior studies suggests a potential adverse effect of the fatiguing MMH task on trip-induced fall risk.

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