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Effects of lower extremity muscle fatigue on the outcomes of slip-induced falls

Prakriti Pariat^a and Thurmon E. Lockhart^{b,*}

^aLocomotion Research Laboratory, School of Biomedical Engineering and Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

^bGrado Department of Industrial and System Engineering, 0118, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

Abstract

Slip-induced fall accidents continue to be a significant cause of fatal injuries and economic losses. Identifying the risk factors causing slip-induced falls is key to developing better preventive measures to reduce fall accidents. Although epidemiological studies suggest localised muscle fatigue may be one of the risk factors for slip-induced falls, there has been no documented biomechanical study examining the relationship between fatigue and fall accidents. As such, the overall objective of the current study was to investigate the effects of localised muscle fatigue of the quadriceps on the slip initiation and slip recovery phases of slip-induced falls. Sixteen healthy, young participants were recruited to walk across a vinyl floor surface in two different sessions (fatigue and no fatigue). Kinematic and kinetic data were collected using a 3-D motion analysis system and force plates during both sessions. Results suggest that localised muscle fatigue of the quadriceps affected various kinematic and kinetic gait variables that are linked with a higher risk of slip-induced falls. Additionally, the results indicated that localised muscle fatigue of the knee extensor muscle caused a delayed response in producing an effective joint moment and base of support using the trailing limb to recover from a fall. The findings from this study indicate that localised muscle fatigue is a potential risk factor causing slip-induced falls.

Keywords

localised muscle fatigue; locomotion; fall accidents; slips and falls

1. Introduction

Slip and fall-related injuries and fatalities continue to pose a significant burden to industry, both in terms of human suffering and economic losses. According to the Bureau of Labor Statistics (2003), nearly 30% of workers who sustained injuries from slips and falls missed 31 or more work days. Furthermore, 14% of accidental deaths in the workplace were reportedly caused by falls (Bureau of Labor Statistics 2004). The annual direct cost of occupational injuries due to slips and falls in the US has been estimated to be in excess of \$6 billion (Courtney *et al.* 2001) and is a cause of serious public health problems with costs expected to exceed \$43.8 billion by the year 2020 in the US. In addition to the risk of fall-related injuries and fatalities, slip recovery efforts have been shown to contribute to high rates of overexertion

injuries (Courtney and Webster 2001). It has also been documented that injuries due to falls are a major cause of years lived with disability (Murray and Lopez 1996).

According to the Bureau of Labor Statistics (2004), floors, walkways or ground surfaces were the major sources of fall accidents, causing over 86% of all fall-related injuries. Additionally, intrinsic factors, such as localised muscle fatigue (LMF), are considered as major factors contributing to slip and fall accidents (Hsiao and Simeonov 2001). Although there has been a reduction of heavy manual work attributed to growing technological advances, some occupations such as construction and forestry still demand intense physical work. The literature indicates that one-third of the US workforce exerts significant physical strength on the job and experiences fatigue in the workplace (Swaen *et al.* 2003).

Previous studies have identified that changes in gait characteristics influence the risk of slip-induced falls (Syed and Davis 2000, Ferber *et al.* 2002, Lockhart *et al.* 2003). Increase in friction demand characteristics and heel contact velocity (HCV) together with reduction in transitional acceleration (TA) of the whole body centre of mass (COM) during a gait cycle have been noted as risk factors for slip-induced fall accidents (Lockhart *et al.* 2003). LMF adversely affects proprioception (Skinner *et al.* 1986), movement coordination and muscle reaction times (Hakkinen and Komi 1986), which are important components of balance control. A successful recovery from a fall depends largely on the magnitude of the counterbalancing moments generated by the lower extremity joints and the rate at which these moments are generated; both of which may be compromised due to LMF.

The knee joint musculature is termed important in producing large flexion and extension moment while recovering from a slip (Cham and Redfern 2001, Liu and Lockhart 2006). The quadriceps and the hamstrings musculature aid control of knee flexion and extension and fatiguing these muscle groups may alter knee joint moment production during normal walking and recovering from a slip. Literature suggests that LMF of the quadriceps adversely affect knee proprioception and is associated with decreases in the knee joint stabilisation time (Miller *et al.* 1976, Lattanzio *et al.* 1997). Additionally, fatiguing of the lower extremity musculature may alter gait variables pertinent to slip initiation and recovery phases.

Although epidemiological studies in combination with biomechanical testing suggest LMF may be one of the risk factors for slip-induced falls, there has been no documented biomechanical study examining the relationship between the two. The overall objective of the current study was to investigate the effects of the LMF of the quadriceps on the slip initiation and slip recovery phases of slip-induced falls. The improved understanding of the relationship between LMF and slip outcome will enhance the ability to: (a) identify LMF as a potential risk factor for slip and fall accidents; (b) develop an effective intervention method (work/rest cycle schedule, exercises) to minimise the cost and rate of injury and death associated with slips and falls. It was hypothesised that LMF will adversely affect gait and recovery responses and increase slip-induced fall accidents.

2. Method

2.1. Participants

In total, 16 healthy young adults (10 males and six females) participated in the study. Informed consent was approved by the Institutional Review Board of Virginia Tech and was signed by all of the participants prior to the study. The participants (mean age 24.66 ± 3.58 years, height 1.75 ± 0.07 m, mass 65.86 ± 10.93 kg, BMI 22.14 ± 2.54 kg/m 2) did not have any musculoskeletal injuries that may affect their ability to perform the fatiguing exertions.

2.2. Equipment

Walking trials were conducted on a linear walkway (1.5×15.5 m) embedded with two force plates (Bertec Corporation, Columbus, OH, USA). The slippery surface was covered with a water and jelly mixture (1:1) to reduce the coefficient of friction (COF) (dynamic COF was 0.12). A total of 23 reflective markers were placed over the various bony landmarks of the participants. The marker configuration of the whole body model is provided in Figure 1. A six-camera ProReflex system (Qualisys Medical AB, Gothenburg, Sweden) was used to collect 3-D position data of the participants while walking. A BiodeX Dynamometer (BiodeX Medical Systems, Inc., Shirley, NY, USA) was used to induce fatigue. A special bilateral knee attachment was constructed for the BiodeX, which essentially worked the same as with one knee attachment (Figure 1). The attachment allowed the participants to extend and flex both of their knees together. Maximum voluntary exertion (MVE) of both the knees was performed while applying minimal resistance when the joints returned to the original position. Uniform experimental shoes were provided to the participants to minimise shoe sole differences. A fall-arresting rig was used for safety (Figure 1) (Lockhart *et al.* 2003).

2.3. Fatigue inducement and experiment protocol

The experiment consisted of two different sessions, fatigue and no fatigue, within a period of 1 week. These sessions were completely randomised for all of the participants. The randomisation process divided the sessions equally between participants. Each session consisted of normal walking and slip-perturbation trials.

Bilateral quadriceps fatigue was induced using isokinetic exertions of the knees during the fatigue session. Participants were strapped on the BiodeX chair with knee and hip flexed at 90° . The BiodeX contraption was designed to limit hip motion during the fatiguing protocol. Fatigue inducement procedures were similar to those recently described by Yaggie and McGregor (2002), with the exception that bilateral fatigue of the quadriceps was employed. The extensions were performed at 60° per s, a value consistent with earlier fatigue protocols (Kay *et al.* 2000). Participants were allowed to perform a 5-min warm-up on the BiodeX and then their MVE baseline measure was recorded. After the baseline measure was recorded, participants performed bilateral knee extensions repeatedly against a resistance set at 70% of their determined baseline MVE. An MVE was performed at regular intervals (5 min) until the participants reached 60% of their baseline MVE; this was considered as the fatigue state (most of the participants reached this state within 30–50 min of exertions).

In the no fatigue session, participants were instructed to walk at a self-paced walking speed across the linear walkway for 10–15 min. Participants were asked to perform some simple tasks (filing papers) at both the ends of the linear walkway while they walked. These tasks helped to remove their attention from the floor. They were also provided with headphones to limit their hearing. The force plate and kinematic data were collected once the participants felt comfortable walking with the harness and produced consistent repetitive gait, i.e. the participant's feet landed on the centre of the force plate and in the desired sequence (right–left). Three gait cycles were recorded for each participant to represent the mean. Following this, a slippery surface was introduced without the participants' awareness and the kinetic data together with the kinematic data were collected. In the fatigue session, participants were first instructed to walk for 10–15 min and perform tasks as in the no fatigue session. After the participants produced consistent repetitive gait, they were brought to the BiodeX machine for performing the fatiguing exertions. Immediately after the fatiguing protocol (<5 min), the normal walking trial and slippery trial was conducted. Data were collected to represent the fatigue normal walking and slip trial. The time window of 5 min after the fatigue trial was decided from the results of a previous study (Parijat and Lockhart 2008), where it was found that participants took at least 10 min after the similar fatiguing protocol to return to their original

MVE. Therefore, the time period in which the data were collected post fatigue avoided any confounding effects due to recovery from imposed muscle fatigue while walking.

2.4. Data analysis

The fatigue status (no fatigue or fatigue) was the independent variable in this study. The dependent variables consisted of various kinematic and kinetic gait variables, together with slip parameters. These parameters are divided into two groups based on the effects on slip initiation and slip recovery. The slip initiation parameters were collected during a non-slippery trial and the slip recovery parameters were collected during a slippery trial.

2.4.1. Gait parameters related to slip initiation—The gait parameters consisted of HCV, required COF (RCOF), TA of the whole body COM, walking velocity and peak knee joint moment. Changes in these gait parameters have been associated with the risk of slip initiation (Lockhart *et al.* 2003, Liu and Lockhart 2006). HCV was calculated by numerically differentiating the marker position data of the heel before and after the heel contact phase of the gait cycle (Lockhart *et al.* 2003). The RCOF is one of the peaks obtained from the ratio of horizontal ground reaction force to vertical ground reaction force (Fh/Fv). It represents the minimum RCOF between the shoe and floor interface to prevent initiation of forward slipping (Redfern and Andres 1984). Walking velocity was obtained from the whole body COM velocity during forward progression using the kinematic data. TA of the whole body COM was defined as the change in the horizontal COM velocity between the heel contact phase and shortly after the heel contact phase of the gait cycle (Lockhart *et al.* 2003). 2-D sagittal knee joint moment was calculated using the inverse dynamics approach (Liu and Lockhart 2006). The joint moment was normalised to body weight for data analysis. The peak value of the knee joint moment between slip start and slip recovery was utilised for the analysis.

2.4.2. Gait parameters related slip severity and slip recovery—The slip parameters consisted of slip distances (SDI and SDII), peak knee joint moment while recovering from slip (JMP_{slip}), joint moment activation to peak (JMAP) and timing variables (i.e. reaction time), such as perturbed foot slip events (slip start, slip peak and slip stop) and unperturbed foot events (toe off, foot onset, foot down) were evaluated. Initial slip distance or SDI is indicative of severity of slip initiation. It is calculated from the heel marker position as the distance between the point of first minimum HCV and the point where peak heel acceleration occurs after the slip start (Lockhart *et al.* 2002). The slip distance II is indicative of the behaviour of the slip after the slip initiation (i.e. if the slip will result in a fall). The starting point for SDII is SDI slip stop and the end point is when the slip ends (i.e. first maximum of the horizontal heel velocity after the slip start) (Lockhart *et al.* 2002). It is generally accepted that a fall will occur during a slip if the slip distance exceeds 10 cm (Strandberg and Lanshammar 1981). The JMAP was defined as the time required to reach the peak joint moment while a reactive recovery attempt was made. These parameters have been used as indicators of slip severity and slip recovery in previous studies (Lockhart *et al.* 2003, Liu and Lockhart 2006).

The frequency of falls during both no fatigue and fatigue trials was considered as a dependent variable. Various parameters were utilised to detect the falls, including slip distances, sliding heel velocity and motion pictures. For a slip to be considered as a fall, the slip distance must exceed 10 cm and the peak sliding heel velocity must exceed the COM velocity while slipping (Lockhart *et al.* 2003). Additionally, videos for each of the participants were analysed to detect a fall, together with the position of the trunk marker (fall to vertical minimum).

In addition to the slip distances, timing variables were evaluated to aid in the interpretation of the slip data. For the unperturbed trailing foot, foot reaction onset (foot onset) was defined as the instant when the toe vertical position was at a maximum after toe off. Foot down was

calculated as the instant when the toe vertical position was its first minimum after foot onset. The time period between foot onset and foot down (unperturbed foot reaction time) was analysed to reveal how fast the unperturbed foot could substantiate its role in the recovery process after a slip perturbation. A one-way repeated measures ANOVA was used to test for significant differences between various dependent variables during the no fatigue and fatigue sessions. The statistics were performed in the JMP 5.1 and SAS 9.1 (SAS Institute, Cary, NC, USA) statistical packages treating subject as the random effect in the ANOVA tests. The level of significance was set at $\alpha < 0.05$. A multivariate analysis was performed to examine the correlation between the different dependent measures.

3. Results

For the normal walking trials in both no fatigue and fatigue sessions, the one-way ANOVA indicated that the participants walked with a higher HCV in the fatigue session ($F(1,31) = 33.86, p = 0.01$) as compared to the no fatigue session (Figure 2a). The TA in the forward direction was observed to be slower during the fatigue session ($F(1, 31) = 3.85, p = 0.04$) as compared to the no fatigue session (Figure 2b). Consistent patterns of RCOF were observed during both of the sessions in all of the participants (Figure 3). It was also observed that RCOF was higher during the fatigue session ($F(1,31) = 9.73, p = 0.04$) as compared to the no fatigue session (Figure 3; Table 1).

The sagittal knee joint moment represented flexor and extensor moment in both no fatigue and fatigue sessions (Figure 4). Two distinctive extensor moment peaks (P1 and P3) were analysed for significant differences between no fatigue and fatigue sessions. Although not statistically significant ($p > 0.05$), there was a decrease in the peak extensor knee joint moment P1 in the fatigue session as compared to the no fatigue session. Peak 3, which is also extensor dominant, was decreased in the fatigue session and was significantly different from the no fatigue session ($F(1, 23) = 16.89, p = 0.002$).

During the slip trials, the results indicated that participants exhibited a faster slip start in the case of a fatigue slip trial ($F(1, 23) = 0.68, p = 0.42$), but slip stop was much later as compared to the no fatigue slip trial (Figure 5). However, only the slip stop event was significantly different between the two sessions ($F(1, 23) = 5.61, p = 0.03$). In terms of the unperturbed foot, the period from foot onset to foot down was faster in the case of no fatigue slip trials than fatigue slip trials (Figure 5). The knee joint moment profile for reactive recovery in both no fatigue and fatigue sessions was predominantly extensor dominant. The ANOVA performed on the recovery trials from slips revealed that the peak joint moment was higher in the fatigue slip recovery as compared to the no fatigue slip recovery ($F(1,23) = 9.08, p = 0.006$). However, the JMAP time was slower in case of fatigue slip recovery ($F(1, 23) = 13.65, p = 0.02$) (Figure 6). The slip distances SDI and SDII were both longer for slips in the fatigue session as compared to the no fatigue session (SDI, $F(1,23) = 5.06, p = 0.04$, SDII, $F(1,23) = 15.16, p = 0.008$).

There were four falls in the fatigue session and one fall in the no fatigue session. The multivariate analysis between the various dependent parameters revealed correlations between certain dependent variables. The unperturbed foot reaction time and SDII ($r = 0.63, p = 0.012$) were positively correlated. Additionally, JMAP and slip stop were positively correlated ($r = 0.55, p = 0.02$), indicating that quicker reaction time leads to faster slip stop. HCV was positively correlated to RCOF ($r = 0.38, p = 0.02$) and SDII ($r = 0.52, p = 0.012$). SDII was positively correlated to peak joint moment during recovery ($r = 0.72, p = 0.007$).

4. Discussion

Bilateral fatigue of the knees was employed in the current study to examine the effects of LMF on slip initiation and recovery efforts during an unexpected slip perturbation. The major findings of this study indicated that LMF of the knee alters the important gait and slip parameters that are responsible for slip initiation and recovery from a fall. The results indicated that participants walked with a higher HCV after the fatigue trials. HCV is considered important in terms of kinematic gait parameters as it can drastically change the friction demands while walking. It has been suggested that HCV affects the RCOF by altering the ratio of horizontal to vertical foot forces (Lockhart *et al.* 2003). An increase in the HCV has been considered to increase the likelihood of slip-induced falls in previous studies (Karst *et al.* 1999, Mills and Barrett 2001).

During an external perturbation leading to a backward fall, the speed of the forward momentum of the body is essential and an inability to produce this speed may result in a fall. The TA is an important parameter in assessing this forward momentum of the body. It was observed in this study that after the fatigue session, TA in the sagittal plane was decreased.

In terms of kinetic gait parameters during normal walking trials, the results indicated a higher friction demand during the fatigue session. The friction demand characteristics have been implicated as an important predictor variable related to severity of slips and falls (Lockhart *et al.* 2003). It has been observed that the onset of lower extremity fatigue during walking changed the loading rate and increased the ground reaction forces (Syed and Davis 2000). As RCOF is dependent on the ground reaction forces (horizontal and vertical), this would mean that increased ground reaction forces due to fatigue as observed in the current study will alter friction demand characteristics. In addition, a positive correlation was observed between HCV and RCOF, suggesting that alteration in the heel contact dynamics due to fatigue may result in increased friction demand leading to a risk of slip-induced falls.

During slip trials in both the sessions, it was observed that the peak knee moment (JMP_{slip}) during the reactive recovery phase was extensor dominant and significantly higher in the fatigue slip recovery as compared to the no fatigue slip recovery. This is in agreement with the study by Ferber *et al.* (2002), which concluded a higher knee extensor moment while recovering from a perturbation. JMP_{slip} was expected to be lower in the fatigue session as LMF affects joint moment production. One of the reasons for the increase may be the recruitment of other muscle fibres (i.e. agonist co-contractions) to generate explosive strength to overcome the slip. This can also be explained based on the study by Liu and Lockhart (2006), which indicated a higher moment generation requirement while recovering from a slip. It was evident in the results that, after fatigue, participants had longer slip distances, which implied that they had severe slips ($>$ threshold SD = 10 cm). Although the magnitude of joint moment was higher, the time taken to reach the peak joint moment was slower when participants recovered after fatigue slips. Being able to rapidly develop peak joint moment was critical to balance recovery. The participants who fell were not able to rapidly produce the magnitude of joint moment required to recover from the slip. The slippery surface (COF = 0.12) and all the other environmental conditions were kept constant in the study for both the fatigue and no-fatigue slip trials. However, in the fatigued state, participants slipped longer. There was a strong correlation between SDII and the peak knee moment, indicating that longer slip distance required higher knee joint moment production to recover from a fall. However, significant variability was seen in the slip distance results. This could be attributed to the complex nature of the heel contact dynamics after a slip is initiated and also to the low sample size. Further examination of these parameters is required to clearly understand the relationship between LMF and the joint moment production during a reactive recovery. Additionally, muscle activity

data (electromyography) may provide some insights on how fatigued muscles respond to a perturbation.

In terms of reaction time of the unperturbed foot, foot down provided timing information on when the foot started to establish a larger base of support in order to assist an individual's reactive recovery process. It was observed that the unperturbed foot reaction time was longer in cases of fatigue slip trials and it had a positive correlation with SDII. This led to the belief that quicker reaction of the unperturbed foot may also reduce slip distances, resulting in a faster recovery. In a study by Lockhart and Liu (2006), it was concluded that longer unperturbed foot reaction time (from onset to touchdown) may be one of the determining factors of the higher fall incidence rate for the elderly relative to their younger counterparts. Further analysis of the changes in the muscle activity due to LMF of the quadriceps and alterations in the sensory input may help in clearly defining a relationship between LMF and the foot reaction time during reactive recovery.

Based on the discussion above, a descriptive model was created to indicate the changes in the dependent factors due to LMF during phases of slips and falls. Figure 7 illustrates the relationship between LMF and the different dependent variables together with their correlation found in the current study. It should, however, be noted that further biomechanical analyses and a larger sample size is required to completely understand these mechanisms. Additionally, many covariates are not considered in this illustration. The increase in friction demand characteristics and HCV have been linked with increased risk of slip initiation (Lockhart *et al.* 2003). The current study concluded that LMF adversely affects HCV and RCOF. Additionally, the current study revealed that there was an increase in peak knee joint moment and unperturbed foot reaction times in the fatigue slip trials. These factors were correlated to SDII. All of these variables have been shown to affect the slip recovery phase leading to falls (Liu and Lockhart 2006, Lockhart and Liu 2006). Thus, LMF may affect the slip recovery phase by altering these parameters. The solid lines in Figure 7 indicate the alterations in the dependent measures due to LMF found in the current study, which are related to slip initiation and recovery phases. The dotted lines represent the correlation between the variables. Although implicated, the correlations between the different gait and slip parameters are complex and this might challenge the interpretation of the results. In addition, the variability in the data may be responsible for masking certain characteristics of LMF related to slip-induced falls. Further biomechanical analysis of the parameters is required to understand the relationship between LMF and phases of slip-induced falls.

5. Conclusion

In summary, LMF of the quadriceps affects various kinematic and kinetic gait variables that are linked with a higher risk of slip-induced falls and, therefore, can be considered as a potential risk factor for slip-induced falls. Additionally, the results also indicate that LMF of the knee extensors caused a delayed response in producing joint moment and increasing the base of support using the trailing limb. One of the limitations of the study was that each participant reached their fatigue level at a different time. These limitations can affect the results due to the difference in the fatigue level of each individual. Additionally, quadriceps musculature consists of four different muscle groups (rectus femoris, Vastus lateralis, Vastus intermedius and rectus femoris). The current study did not isolate muscle fatigue to each of the muscles but as the quadriceps muscle group as a whole. There might be limitations as rectus femoris muscle does not fatigue in the same way as other muscles in this group. Although implicated, the 60% of baseline MVE as a fatigue state prior to testing ensured that all participants were fatigued at similar levels.

Future research will investigate the effects of LMF of multi-joint fatigue (i.e. hamstrings, ankle plantar flexors) on slip events in a real-world job scenario. However, results from the present study can be used as preliminary information on the specific gait and slip parameters that are sensitive to LMF. Other potential areas for further research include evaluating the effects of rest breaks and recovery and effects of age on fatigue.

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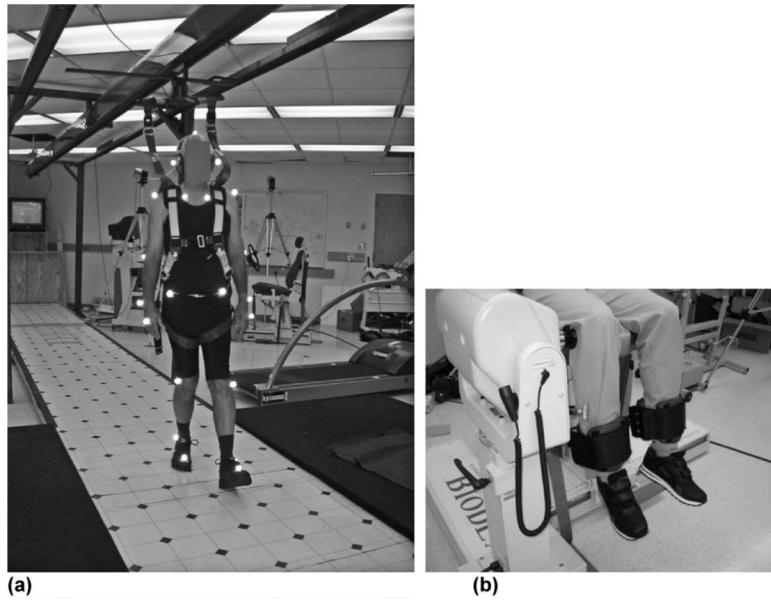
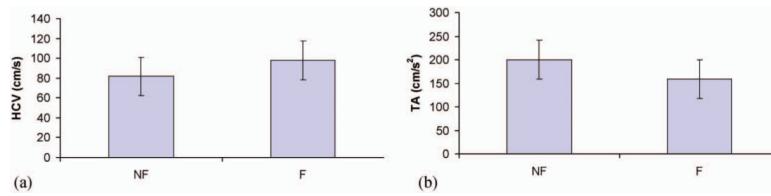


Figure 1.

(a) Reflective marker configuration of whole body along with the safety harness; (b) experiment setup for the isokinetic exertions of the knee joint using BiodeX.

**Figure 2.**

(a) Mean heel contact velocity (HCV (cm/s)); (b) mean (SD) transitional acceleration of the whole body centre of mass (TA (cm/s²)) during no fatigue (NF) and fatigue (F) sessions (walking trials).

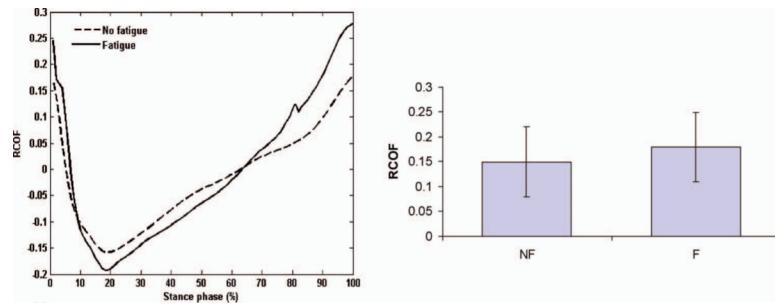


Figure 3.

Ensemble average of the required coefficient of friction (RCOF) and mean (SD) RCOF during the no fatigue (NF) and fatigue (F) sessions (walking trials).

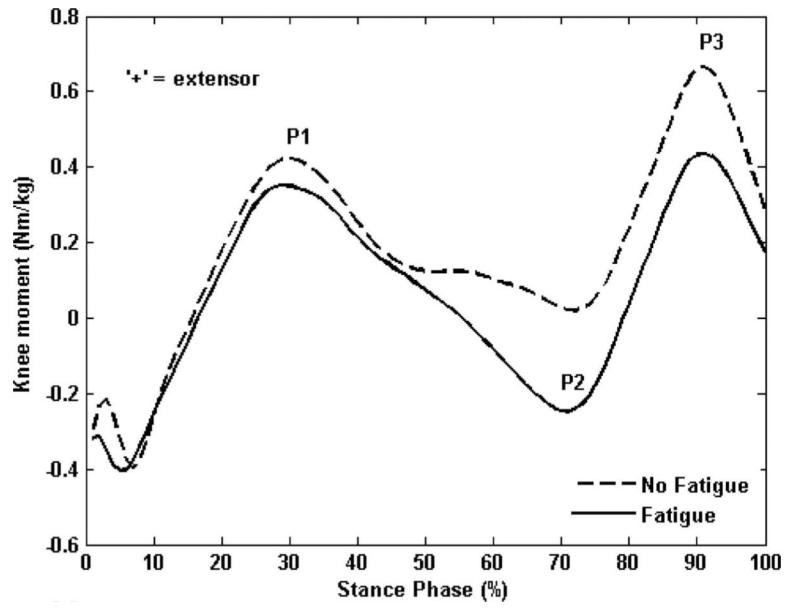


Figure 4.

Average sagittal knee joint moment profile at the stance phase of gait cycle during the no fatigue and fatigue sessions (walking trials).

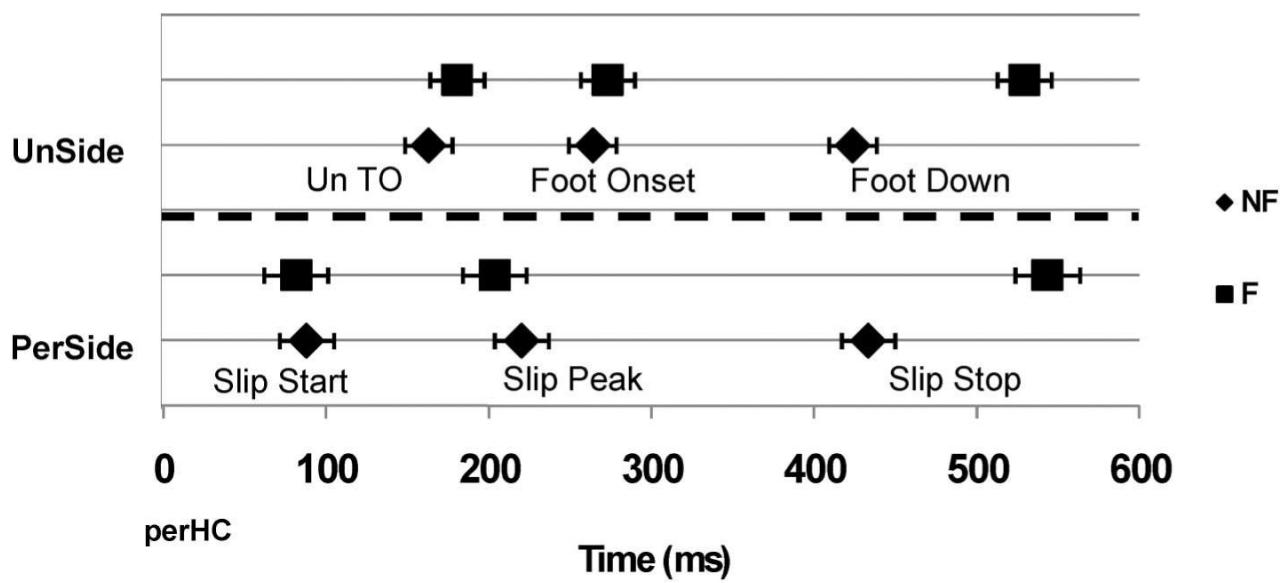


Figure 5.

Occurrence of critical events after slip start during no fatigue (NF) and fatigue (F) sessions (slip trials). UnSide = unperturbed foot; PerSide = perturbed foot/slipping foot; Un TO = unperturbed foot toe off.

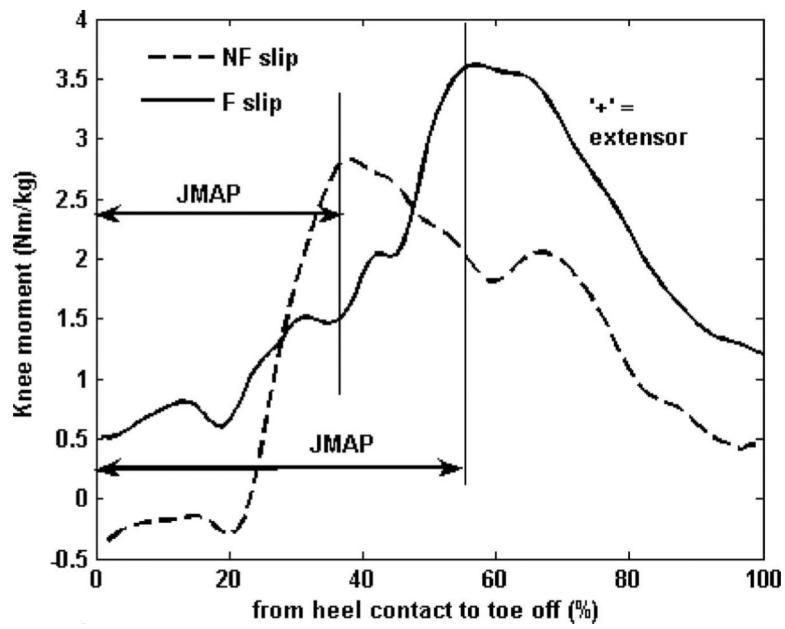
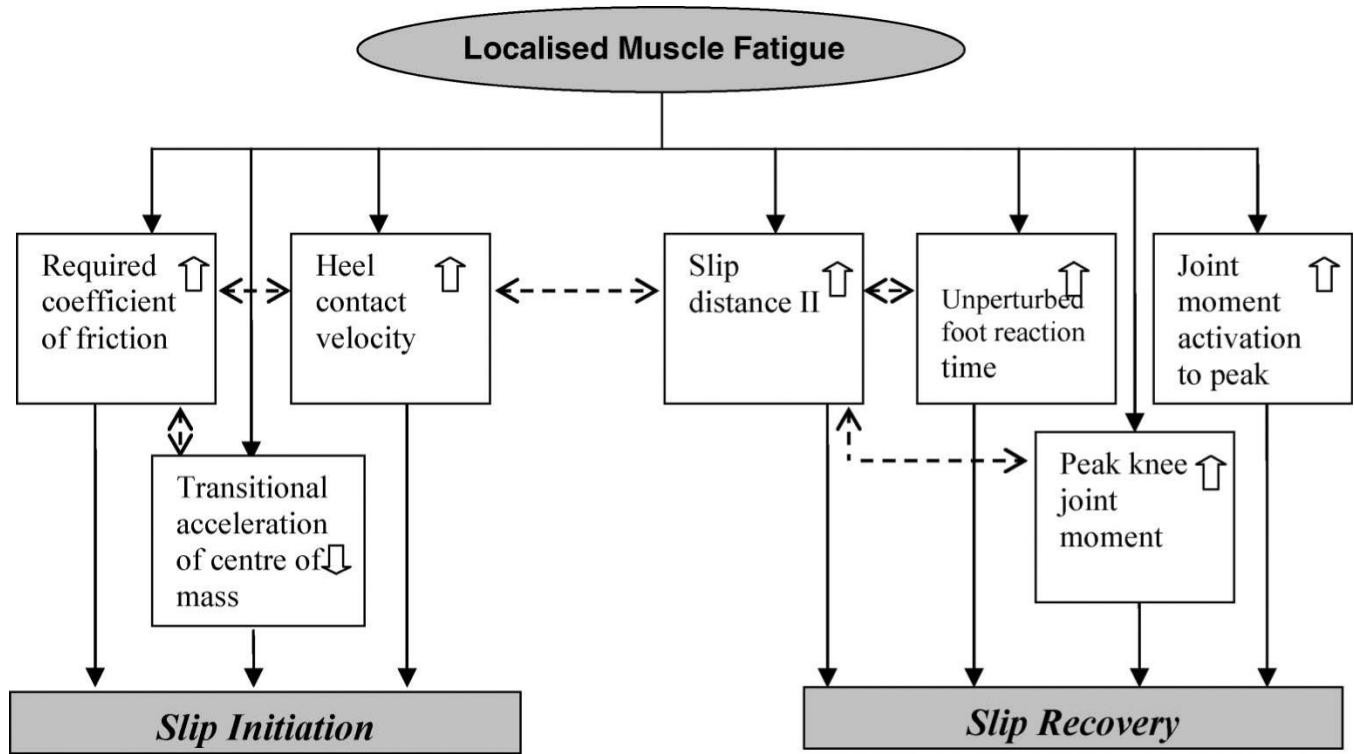


Figure 6.

Average knee joint moment profile during reactive recovery in no fatigue (NF) and fatigue (F) sessions (slip trials). JMAP = joint moment activation to peak.

**Figure 7.**

Flowchart of all the factors associated with slip initiation and slip recovery that were significantly different after fatigue. Solid line arrows indicate the changes observed; dotted line arrows indicate the correlation between the variables.

Table 1

Summary of kinematic and kinetic gait parameters.

Variables	Session		
	NF	F	ANOVA
Slip Initiation			
HCV (cm/s)	81.94 ± 51.22	97.8 ± 66.67	*
WV (cm/s)	127.02 ± 14.2	119.29 ± 20.32	NS
TA (cm/s ²)	199.21 ± 41.27	159.27 ± 57.6	*
Slip Recovery			
Unperturbed foot react time (ms)	159.70 ± 44.99	256.30 ± 58.45	**
JMAP (ms)	333.23 ± 49.8	466.48 ± 88.67	*
JMP _{slip} (Nm/kg)	3.44 ± 0.97	5.25 ± 2.8	*
SDI (cm)	3.24 ± 1.25	5.34 ± 4.06	*
SDII (cm)	12.46 ± 5.46	15.16 ± 6.34	**

HCV = heel contact velocity; WV = walking velocity; RCOF = required coefficient of friction; TA = transitional acceleration of the whole body centre of mass; JMP_{slip} = joint moment peak during slip recovery; JMAP = joint moment activation to peak; SDI and SDII = unperturbed foot reaction time and slip distances during the no fatigue (NF) and fatigue (F) walking and slip trials.

*
 $p < 0.05$

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 $p < 0.01$.