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Prakriti Parijat and Thurmon E Lockhart

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Influence of localized muscle fatigue of the knee joint on gait parameters related to slip propensity

Prakriti Parijat, School of Biomedical Engineering and Sciences, Virginia Tech
Thurmon E Lockhart, Industrial and Systems Engineering, Virginia Tech

Existing epidemiological evidence suggests that localized muscle fatigue might be considered as an intrinsic risk factor that causes lack of balance control leading to falls. The goal of the study was to examine how localized muscle fatigue of the knee joint (quadriceps) alters gait parameters that are related to slip propensity. 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 three-dimensional video analysis system and force plates during both sessions. The fatigue session results indicated a substantial increase in heel contact velocity (HCV) and required coefficient of friction (RCOF), as well as a decrease in the transitional acceleration of the whole body COM (TA), walking velocity (WV), and step length (SL). In addition, a positive correlation was observed between RCOF and HCV. These findings provide new insights into the biomechanical relationship between localized muscular fatigue and gait parameters linked with slip propensity. The study concluded that localized muscular fatigue affects gait parameters and hence can be considered as a potential risk factor for slip-induced falls.

INTRODUCTION

Occupational fall accidents remain a major cause of a considerable number of injuries and fatalities among the American workforce. According to the Bureau of Labor Statistics (2003), nearly 30% of workers who sustained injuries from slips and falls missed 31 days of work or more. Further, 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 U.S. has been estimated to be in excess of 6 billion U.S. dollars (Courtney et al., 2001); the injuries are also the cause of a serious public health problem with costs expected to exceed \$43.8 billion by the year 2020 in the U.S.

Localized muscle fatigue (LMF) has been recently identified as one of the major intrinsic factors contributing to slip and fall accidents (Bentley and Haslam, 2001). Existing evidence (Lipscomb, 2006; Hsiao and Siemonov, 2001) provides convincing arguments that localized muscle fatigue (LMF) can disrupt the quality of the signal from the periphery responsible for effective balance and control. Although there has been a reduction of heavy work due to growing technological advances, some occupations such as construction and forestry still demand intense physical work. The Literature indicates that a third of the U.S. workforce exerts significant physical strength on the job and experience fatigue in the work place (Swaen et al., 2003). It has been identified in the past that changes in gait characteristics influence the risk of slips and falls (Lockhart et al.,

2003, Ferber et al., 2002). As the lower extremities are the prime movers during a gait cycle, LMF of this musculature might have detrimental effects on gait characteristics, which in turn might increase slip propensity. More specifically, the function of the knee joint has been reported in terms of producing large flexion and extension moments while recovering from a slip (Liu et al., 2006). It has been demonstrated that fatigue of the knee extensors and hip flexor muscles cause significant decreases in stabilization time compared with the fatiguing of other muscle groups (Miller et al., 1976). The quadriceps and the hamstring musculature aid in control of the knee flexion and extension, and fatiguing these muscle groups may further influence the gait characteristics. While epidemiological studies link the incidence of slip-induced falls with muscle fatigue, the relationship of LMF with slip-induced fall accidents remains unclear. The purpose of the present study was to examine how localized muscle fatigue of the knee joint (quadriceps) alters gait parameters.

METHODS

Sixteen healthy young adults (10 males and 6 females) participated in the study. Informed consent was approved by the Institutional Review Board (IRB) of Virginia Tech and was signed by all the participants. The participants (mean age 24.66 ± 3.58 years, height 174.86 ± 7.67 cm, weight 65.86 ± 10.93 Kg) did not have any lower extremity musculoskeletal injury in the past. The experiment consisted of two different sessions, fatigue

(F) and no fatigue (NF), within a period of a week. These sessions were completely randomized for all the participants. Walking trials were conducted on a linear walkway (1.5 x 15.5m) embedded with two force plates (Bertec Corporation). Twenty three reflective markers were placed over the various bony landmarks of the participants. The marker configuration of the whole body model was similar to previous studies (Lockhart et al., 2003). A six-camera ProReflex system (Qualisys Medical AB, Gothenburg, Sweden) was used to collect three-dimensional position data of the participants while walking. Uniform experimental shoes were provided to participants to minimize shoe sole differences. A fall arresting rig was used for safety. In the NF session, participants were instructed to walk at self-pace across the linear walkway for 20 minutes. Force plate and marker data were collected once the participants felt comfortable walking with the harness.

Bilateral quadriceps fatigue was induced using isokinetic exertions of the knee during the F session. 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. A special bilateral knee attachment was constructed for the Biodex which essentially worked the same as with one knee attachment. The attachment allowed the participants to extend and flex both their knees together. The extensions were performed at 60°/sec, a value consistent with earlier fatigue protocols (Kay et al., 2000). Participants were allowed to perform a 5 minute warm up on the Biodex, and then their MVE (maximum voluntary exertion) baseline measure was recorded. During the warm up session, participants were told to use both their knees equally for the extensions. After the baseline measure was recorded, participants performed bilateral knee extensions repeatedly against a resistance set at 70% of their determined maximum voluntary exertion (MVE). Visual feedback was provided to the participants for their current and target moment levels. An MVE was performed at regular intervals (5 minutes) until the participants reached 60% of their baseline MVE; this was considered as the fatigue state (within 30-50 minutes of exertions).

In the F session, participants were asked to walk on the walkway following which they were brought to the Biodex and fatigue was induced using the above method. Immediately after the fatiguing protocol (within 1 minute), the participants were asked to walk across the walkway, and data was collected to represent their fatigue walking.

The required coefficient of friction (RCOF), heel contact velocity (HCV), transitional acceleration of the whole body COM (TA), walking velocity (WV), and

step length (SL) were compared for the two different sessions to evaluate the effects of fatigue. These measures have been used as indicators of slip severity in previous studies (Lockhart et al., 2003). Fatigue status (NF and F) was the independent variable. A repeated measure one-way analysis of variance (ANOVA) was employed to predict statistical significance. A within subject design was considered where the same subjects were used before and after a treatment condition (F and NF). The descriptive and inferential statistics were performed in the JMP and SAS statistical packages. The level of significance was set at 0.05. Bivariate analysis was performed to examine the correlation between the different dependent measures.

RESULTS

The one way ANOVA indicated that the participants walked with a higher HCV in the F session ($F(1,31) = 33.86, p = 0.01$) as compared to the NF session (Figure 1). The TA in the forward direction was observed to be slower during the F session ($F(1,31) = 3.85, p = 0.04$) as compared to the NF session. Participants walked with a slower speed (WV) after fatigue exertions, but the differences were not statistically significant ($F(1,31) = 1.52, p = 0.08$) (Table 1).

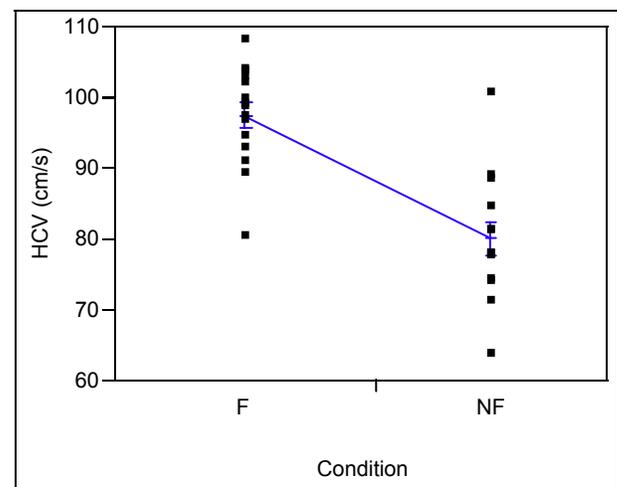


Figure 1. Heel contact velocity (HCV) during Fatigue and No Fatigue sessions

Consistent patterns of RCOF were observed during both the sessions in all the participants (Figure 2). It was also observed that the RCOF was higher during the fatigue session ($F(1,31) = 9.73, p = 0.04$) (Table 1). Participants walked with shorter SL during the F session, but the differences were not statistically significant. The mean and standard deviation with the statistical results are provided in Table 1.

Table 1. Summary of gait parameters (HCV-heel contact velocity, WV- walking velocity, RCOF-required coefficient of friction, TA- whole body COM transitional acceleration, SL- step length) * p<0.05

Variables	No Fatigue	Fatigue	ANOVA
	Mean(S.D)	Mean(S.D)	
HCV (cm/s)	81.94 (51.22)	97.83(66.67)	*
WV (cm/s)	127.02(14.42)	119.29(20.32)	N.S
RCOF	0.19(0.007)	0.22(0.005)	*
TA(cm/s ²)	199.21(41.27)	159.27(57.16)	*
SL (cm)	71.4(1.68)	69.7(1.68)	N.S

The bivariate analysis indicated that HCV and RCOF were positively correlated ($r=0.39$, $p=0.026$). In addition, there was a negative correlation between HCV and TA ($r= -0.37$, $p=0.03$). The TA in the forward direction was observed to be slower during the F session ($F(1,31) = 3.85$, $p = 0.04$) as compared to the NF session. Participants walked with a slower speed (WV) after fatigue exertions, but the differences were not statistically significant ($F(1,31) = 1.52$, $p = 0.08$).

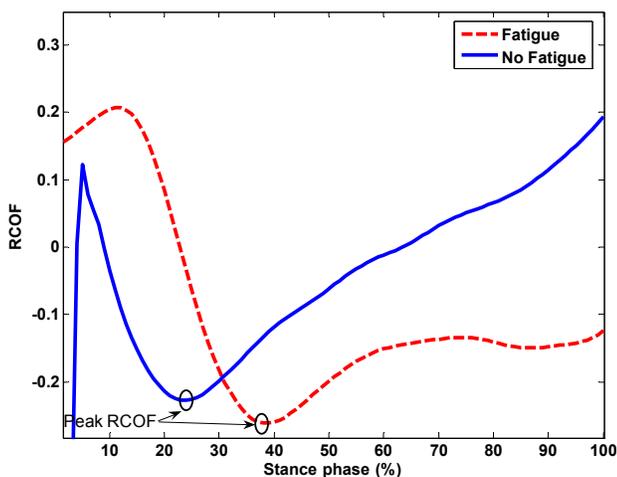


Figure 2. Ensemble average of the required coefficient of friction (RCOF) during Fatigue and No Fatigue sessions.

DISCUSSION

The purpose of this study was to examine the effects of localized muscle fatigue of the knee joint on different gait parameters and friction demand characteristics that are indicative of slip propensity. The results indicated that participants walked with a higher HCV after the fatigue trials. Heel contact velocity is considered important in terms of kinematic gait parameters as it can drastically change the friction demands while walking. It has been studied that HCV affects the required coefficient of friction (RCOF) by altering the ratio of horizontal to vertical foot forces (Lockhart et al., 2003). The

results are consistent with the study by Saggini et al (1998) who examined the effects of localized muscle fatigue on the lower extremity and concluded that fatigue increased the gait cycle time and also increased the horizontal heel velocity.

The bivariate analysis suggested a positive correlation between HCV and RCOF, indicating that the RCOF increased with an increase in the HCV. A higher heel contact velocity was considered to increase the likelihood of slip-induced falls in previous studies (Karst et al., 1999, Mills and Barrett, 2001). A likely factor influencing the higher HCV may be a decrease in the hamstring activation rate (Lockhart et al., 2003). The co-activation of hamstring and quadriceps muscles is important in heel contact dynamics. LMF of the quadriceps may influence this process and thereby increase the HCV. In this study, we did not control the walking velocity of the participants. Reduction in WV has been identified as a risk factor for slip induced falls in the elderly (Kim et al., 2005). Although implicated, no significant difference in WV was observed in this study. This might be attributed to the differences in individual strategies used to adapt gait speed after fatigue.

During an external perturbation like a backward slip, the speed of the forward momentum of the body is essential, and an inability in producing this momentum might 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 reduced. This is in agreement with past studies where it was observed that lower extremity fatigue affected the back acceleration (Yoshino et al., 2004). Lockhart et al. (2003) indicated that a reduced push-off force of the stance leg further reduced TA and increased RCOF and risk of slip initiation. This indicates that a reduction in the TA due to localized muscle fatigue is likely to increase the friction demand at the shoe floor interface of the contacting foot.

In terms of kinetic gait parameters, the results indicated a higher RCOF after the fatigue session. Previ-

ous studies have observed that the onset of lower extremity fatigue during walking changed the loading rate and increased the ground reaction forces [25]. As RCOF is dependent on the ground reaction forces (horizontal and vertical), this would mean that increased ground reaction forces due to fatigue will alter friction demand characteristics. Furthermore, Lockhart et al. (2003) indicated that a reduction in TA is likely to increase the friction demand at the shoe floor interface of the contacting foot. Increased initial friction demand (i.e., RCOF) would lead to a higher likelihood of slips associated with low coefficient of friction floor surfaces. It has been observed previously that HCV was a predictor variable for RCOF in the older adults and both TA and HCV were predictor variables for RCOF in younger adults (Kim et al., 2005). This is in accordance with the current study. Further biomechanical analysis of these parameters and other variables like joint moment and muscle activity will be required to clearly predict the relationship between LMF of the knee and slip propensity.

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. Although implicated, the assumption that 60% of baseline MVE as the fatigue state prior to testing ensured that all participants were fatigued at similar levels. Previous studies on the difference between the strength in unilateral and bilateral exertions have produced equivocal results (Khodiguian et al., 2003). However, a study by Jacobi et al. (1998) concluded that the force production is not altered during bilateral contractions. Bilateral fatigue was induced in the current study to simulate a more realistic scenario where both limbs are fatigued (i.e., walking).

The data from the results of this study can be used as preliminary information on the effects of fatigue on some specific gait parameters and fall outcomes. Some conclusions can be drawn from the study regarding which parameter was most affected by fatigue, and further in depth analysis of those parameters can be undertaken to confirm the results.

CONCLUSION

The major findings of the study concluded that localized muscle fatigue of the knee alters the important gait parameters that are linked to an increased risk of slip induced fall accidents. Future research will investigate the effects of fatigue on balance control from an actual perturbation (slip). A better understanding of potential risk factors affecting slip induced falls can facilitate in the development of fall prevention strategies (work/rest cycle schedule, fatigue monitors, exercises).

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