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Original Article

The Interaction of Cognitive Interference, Standing Surface, and Fatigue on Lower Extremity Muscle Activity

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ABSTRACT

Background: Performing cognitive tasks and muscular fatigue have been shown to increase muscle activity of the lower extremity during quiet standing. A common intervention to reduce muscular fatigue is to provide a softer shoe-surface interface. However, little is known regarding how muscle activity is affected by softer shoe-surface interfaces during static standing. The purpose of this study was to assess lower extremity muscular activity during erect standing on three different standing surfaces, before and after an acute workload and during cognitive tasks.
Methods: Surface electromyography was collected on ankle dorsiflexors and plantarflexors, and knee flexors and extensors of fifteen male participants. Dependent electromyography variables of mean, peak, root mean square, and cocontraction index were calculated and analyzed with a 2 × 2 × 3 within-subject repeated measures analysis of variance.
Results: Pre-workload muscle activity did not differ between surfaces and cognitive task conditions. However, greater muscle activity during post-workload balance assessment was found, specifically during the cognitive task. Cognitive task errors did not differ between surface and workload.
Conclusions: The cognitive task after workload increased lower extremity muscular activity compared to quite standing, irrespective of the surface condition, suggesting an increased demand was placed on the postural control system as the result of both fatigue and cognitive task.

1. Introduction

The dangers due to hazardous work conditions and the physical demands placed on the human body in an occupational and industrial work settings increase the risk of occupational falls [1]. In 2016, fall-related events accounted for 19% of all occupational injuries, while 17% of all fatal occupational injuries were the result of a fall [2]. In industrial work environments, destabilizing forces from both external and internal sources are constantly imposed on the human body. These jeopardize the integrity human postural control system and affect upright balance maintenance, which are required to safely perform occupational activities and prevent falls [3].

Primarily, postural perturbations affect the muscles of the lower extremity, and the maintenance of upright standing requires a low amount of muscular effort. However, increasing the demand on the postural control loop increases the likelihood of a fall and potential injury [3]. The disruption of internal, human factors has been linked to a decrement in proprioceptive feedback and motor unit firing rate in lower extremity muscles [4,5]. Previous studies have demonstrated that fatiguing occupational workloads increase lower extremity muscle exertion and disrupt the ability to maintain upright stance [3,6–8].

External factors such as high-collared and heavy footwear have been shown to increase dorsiflexor and plantarflexor muscle activity [9,10]. Utilizing standing surfaces of various elastic properties has

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been shown to alter lower extremity muscle activation and balance performance [9,11,24]. Workplace settings with softer antifatigue floorings consistently report a reduction in lower extremity discomfort; however, floors that lack some rigidity fail to produce this effect [12,13]. Contrasting findings have been noted in regard to standing surface and lower extremity muscle activation [9,14]. The usage of over-the-shoe antifatigue covers has also demonstrated some promising results in reliving whole-body discomfort [15]. Currently, no studies have examined how antifatigue shoe covers on balance and lower extremity muscles activity.

In addition to these factors, an increase in cognitive load has been shown to alter balance performance [16,17]. Testing the changes in postural control using a dual-task procedure divides the attention of the subject on a primary task (postural control) and secondary task (cognition interruption) [17]. However, when the combination of the primary and secondary tasks becomes too difficult, performance on the secondary task is reduced [18,19]. Cognitive task engagement has been shown to increase muscle activation times compared to quiet standing [20]. An additional study demonstrated decreased plantarflexor and dorsiflexor activity in response to balance perturbations while performing cognitively difficult math problems [21].

In occupational settings, employees are typically involved in long periods of standing along with performing some type of task that involves mental acuity. To date, no study has investigated the interaction between surface, cognitive task, and workload. Being that all three of these factors affect workers in occupational settings, it is imperative that the contributions of each factor to postural control be examined. Also, no study has examined how over-the-shoe antifatigue covers affect lower extremity muscle activation during static balance. Thus, the purpose of this study was to evaluate muscle exertion during static standing on occupational surfaces with and without a cognitive task, preceding and after a fatiguing workload.

2. Materials and methods

All experimental procedures for this study received University Institutional Review Board approval before data collection. Fifteen healthy males completed this study (age: 21.5 ± 1.74 years, height: 174.85 ± 5.6 cm, mass: 88.32 ± 14.46 kg, shoe size: 11.14 ± 1.23, leg dominance: right). These participants were free of musculoskeletal, vestibular, visual, and neural abnormalities and participated in a training regime that consisted of 150 minutes of aerobic training 3–4 days/week and resistance exercises at least 2 days/week over the past three months. All participants read and signed the informed consent document and also filled out the physical activity readiness questionnaire to rule out any of the aforementioned health complications and cleared for participation in the study.

Muscle activity was measured using the Noraxon TelemyoTM T2400 G2 wireless EMG system (Scottsdale, Arizona, USA) at 1500 Hz. The cognitive interference task was prepared using Microsoft Power Point (Seattle, Washington, USA) and was displayed on 40-inch television, 3m from the participant standing area, at the eye level. Muscle activity was collected on each participant's dominant leg tibialis anterior (TA), medial gastrocnemius (G), vastus medialis (Q), and medial hamstring (H). Bipolar electrodes with an inter-electrode distance of 2 cm were placed on shaved and abraded skin over the muscle bellies of each muscle. Raw EMG data were band-pass filtered (20-250 Hz) and full-wave rectified before analysis. Mean and root mean squared muscle activity for each muscle was calculated by averaging the three trials within each surface and task conditions. Cocontraction between muscle pairs was calculated using the cocontraction index (CCI) for agonist–antagonist pairs (CCI Q/H, CCI TA/G) during all static standing conditions using the following equation [22]:

$$(EMG_{Least} + EMG_{Most})xEMG_{Least} \ / \ EMG_{Most} \quad (1)$$

The cognitive interference task for this study consisted of a modified visual Stroop task and basic arithmetic problems. The Stroop task was arranged in sentences with each word featuring a different color. The participants were asked to read aloud the color of the word in each sentence. Each slide featured a total of three sentences with a total twenty-four words per slide. The subsequent slide featured ten mathematic problems featuring addition, subtraction, multiplication, and division arranged in a 2 × 5 matrix. Participants were asked to solve each problem and then move to the next problem on the left. All problems solution equaled to whole and positive numbers. The cognitive task lasted the duration of the static standing trial (20 sec). The task alternated from visual Stroop to arithmetic problems every ten seconds or when the participant completed the presented task. All tasks were randomized for each participant.

The lower extremity workload followed the same order and procedure for all participants and lasted until volitional failure on each task. First, four bouts of wall sits were conducted in which the participant lowered themselves into a seated position, braced against a wall, until their knees reached 90-degree knee flexion. This was followed by four sets of split squats lunges on both the left and right lower extremities. Verbal encouragement was provided for all exercises. The rating of perceived exertion was accessed using the Borg Scale (6-20) at the end of the workload [23].

Three different surfaces were utilized in this study. The solid surface was the metal top of an AMTI force platform (Watertown, MA. USA). The antifatigue mat was a 60.96 cm × 91.44 cm × 1.905 cm Imprint CumulusPRO Anti-Fatigue Mat (hardness: Shore A75) that was used to cover the entirety of the solid surface. Shoe size equivalent ErgoMates (Belleville, Ontario) (hardness: Shore A70) served as the over-shoe antifatigue covers which are displayed in Fig. 1.

The first day included the assessment of height, body mass, administrative paperwork, and the performance of an abbreviated version of the cognitive task by the participant, which occurred 48 hours before testing. The subsequent testing session was conducted in a counterbalanced, repeated measure design in which all participants' muscle activity was assessed during static standing on three surfaces, including flat solid surface, antifatigue mat, and ErgoMates. Each participant received a pair standardized slip-resistant low-top shoes in the appropriate shoe size, which were worn throughout the testing session.

Participants performed three trials of 20-second static bilateral standing in one of the standing surface conditions. Following these

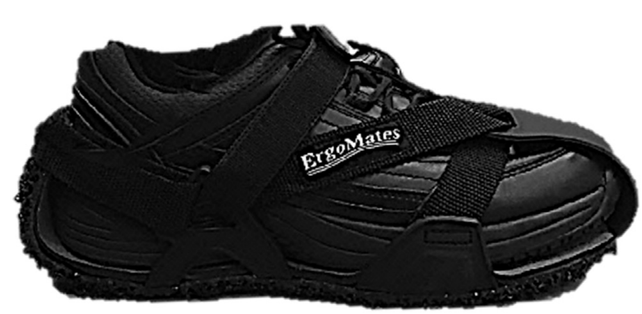

Fig. 1. The footwear displayed was outfitted with over-shoe attachment of ErgoMates. Velcro attachments sites were secured over the top of the laces and at the heel of the footwear.

trials, three more trials of 20-second static bilateral standing on the same surface was conducted as the participant performed the cognitive interference task. This was repeated for all standing surfaces. After the acute assessment of static standing, participants then performed the lower extremity workload, followed by the same static standing assessments with counter balance surface assignment.

EMG-dependent variables were analyzed with a 2 × 2 × 3 [2 Time (Pre-workload, Post-workload) × Task (Static standing × Cognitive task) × Surface (Soild surface × Anti-fatigue mat × ErgoMates)] repeated measures analysis of variance. Errors on the cognitive inference task were analyzed using a 2 × 2 [2 Time (Pre-workload, Post-workload) × Surface (Solid surface × Anti-fatigue mat × ErgoMates)] repeated measures analysis of variance. If a significant interaction was found, main effects were ignored and a test of simple effects was conducted with a Sidak Bonferroni correction. All analyses were conducted using SPSS 25 (IBM, Armonk, New York, USA) with an a priori alpha level of 0.05.

3. Results

3.1. Mean muscle activity

A significant task by time interaction was detected for G ($F_{(1,12)} = 17.147$, $p = 0.001$ $\eta^2 = 0.551$) and H ($F_{(1,12)} = 10.557$, $p = 0.006$ $\eta^2 = 0.43$). H demonstrated significantly higher muscle activity after workload during the cognitive task than pre-workload muscle activity during the cognitive task ($p = 0.001$), post-workload muscle activity was significantly higher than pre-workload muscle activity ($p = 0.012$), and post-workload muscle activity during the cognitive task was significantly higher than pre-workload muscle activity without the cognitive task ($p < 0.001$) (Fig. 2). G demonstrated significantly higher muscle activity after workload during the cognitive task than pre-workload muscle activity during the cognitive task ($p = 0.011$) (Fig. 3). A significant main effect was detected for TA ($F_{(1,12)} = 16.405$, $p = 0.001$ $\eta^2 = 0.16$) and Q ($F_{(1,12)} = 6.046$, $p = 0.028$ $\eta^2 = 0.302$). Pairwise comparisons for both TA and Q revealed muscle activity during the cognitive interference task was significantly higher than that with no cognitive interference task (Figs. 4, 5). No significant differences were detected for surface condition in TA ($p = 0.496$), G ($p = 0.553$), Q ($p = 0.165$), and H ($p = 0.444$).

3.2. Peak muscle activity

A significant time main effect was detected for H ($F_{(1,12)} = 7.427$, $p = 0.016$ $\eta^2 = 0.347$). Post-workload peak muscle activity was significantly higher than pre-workload muscle activity. No significant differences were detected for surface condition in TA ($p = 0.906$), G ($p = 0.139$), Q ($p = 0.747$), and H ($p = 0.640$).

3.3. Root mean square muscle activity

A significant main effect for task was detected for H ($F_{(1,12)} = 5.333$, $p = 0.034$ $\eta^2 = 0.591$). Static standing with the cognitive task displayed significantly higher muscle activity than static standing with no cognitive task. A significant main effect for time was detected for H ($F_{(1,12)} = 5.333$, $p = 0.028$ $\eta^2 = 0.283$). Post-workload RMS muscle activity was significantly higher than pre-workload muscle activity. No significant differences were detected for surface condition in TA ($p = 0.423$), G ($p = 0.855$), Q ($p = 0.147$), and H ($p = 0.986$).

3.4. Cocontraction index of mean muscle activity

A significant task by time interaction was detected for Q/H CCI ($F_{(1,12)} = 5.102$, $p = 0.04$ $\eta^2 = 0.267$). Test of simple effects revealed no significant differences. No significant differences were detected for the TA/G CCI.

3.5. Workload performance

The time to failure for each of the four sets of wall sits is reported in Table 1. The average number of repetitions and time to failure for each of the four sets of split squat lunges are depicted in Table 2.

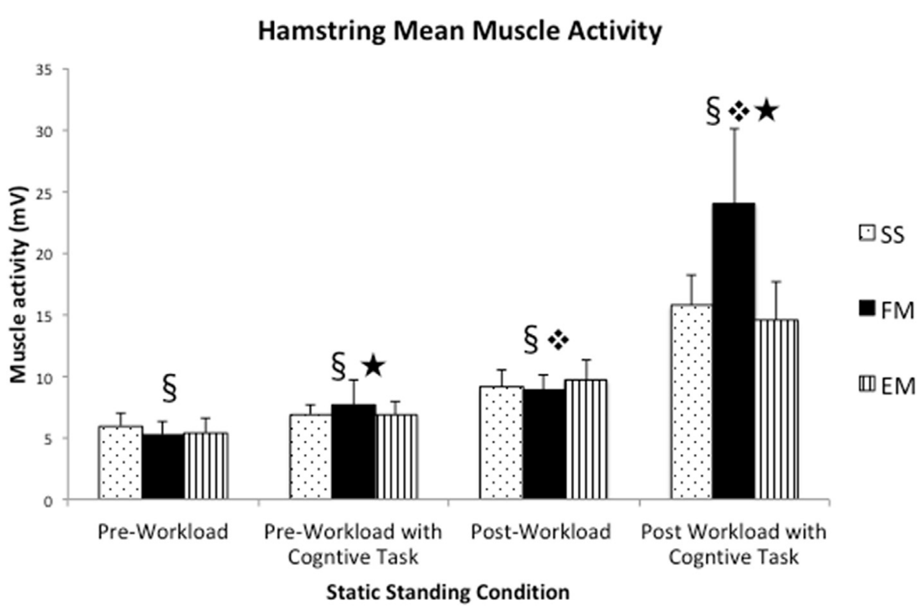

Fig. 2. Pre- and post-workload mean muscle activity for the hamstring with and without the cognitive task on the three standing surfaces (SS, solid surface; FM, fatigue mat; EM, ErgoMates). ❖Significant task time interaction simple effect, where greater mean muscle activity was found in post-workload cognitive task than pre-workload quite standing muscle activity. ★ Significant task time interaction simple effect, where greater mean muscle activity was found in the in post-workload cognitive task than pre-workload cognitive task. § Significant main effect for time, where greater muscle activity was found after workload than before workload.

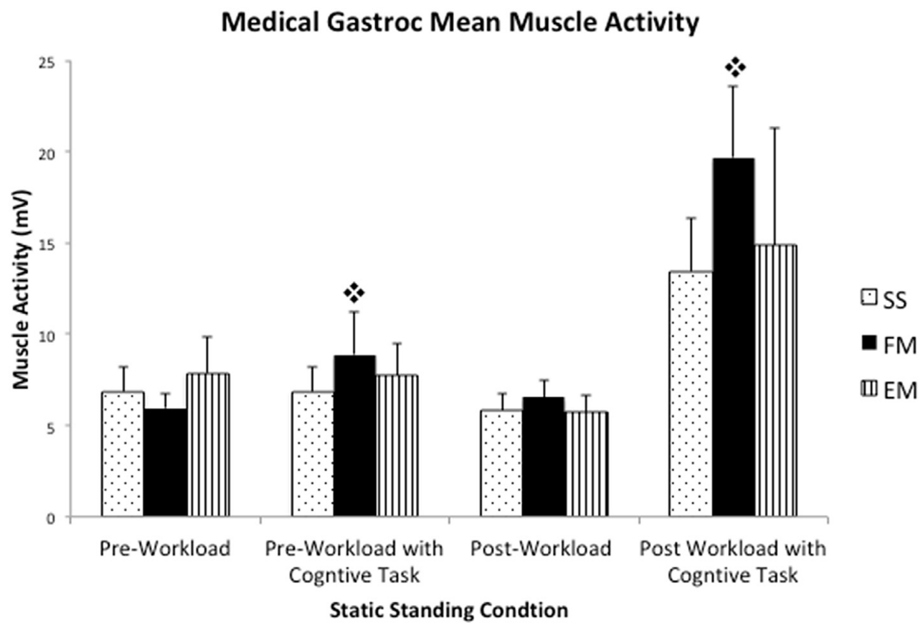

Fig. 3. Pre- and post-workload mean muscle activity for the quadricep with and without the cognitive task on the three standing surfaces (SS, solid surface; FM, fatigue mat; EM, ErgoMates). ❖Significant task time interaction simple effect, where greater mean muscle activity was found in post-workload cognitive task than pre-workload cognitive task muscle activity.

3.6. Rate of perceived exertion

The average rating of perceived exertion for the lower extremity workload was 16.23 ± 1.83.

3.7. Cognitive interference task performance

No significant differences were found for cognitive interference task performance across all surfaces ($F_{(1,13)} = 0.477$, $p = 0.625$ $\eta^2 = 0.033$) and workload conditions ($F_{(1,13)} = 1.130$, $p = 0.306$ $\eta^2 = 0.075$).

4. Discussion

The purpose of this study was to determine the effects of three different standing surfaces on static muscle exertion while performing a cognitive task, in an acute fatigued condition. These results demonstrate that while performing a cognitive task and after a workload, there is increased muscle activity during static standing, regardless of the standing surface.

This study compared a solid surface with two alternatives: an antifatigue mat and ErgoMates that attached to the participant's footwear. No differences were found between all surface conditions. Madeleine et al.(1998) had participants stand for a prolonged

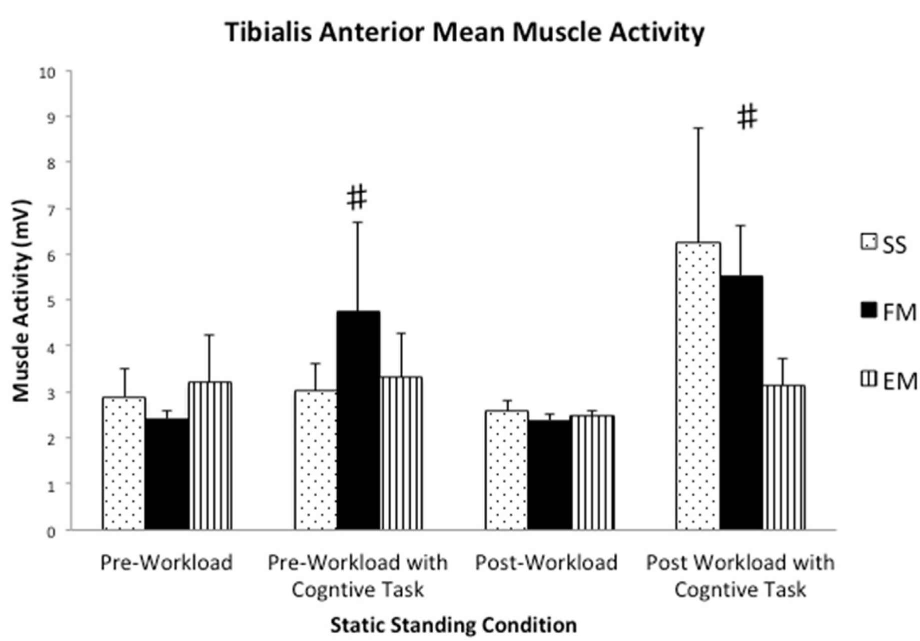

Fig. 4. Pre- and post-workload mean muscle activity for the tibialis anterior with and without the cognitive task on the three standing surfaces (SS, solid surface; FM, fatigue mat; EM, ErgoMates). ♯Significant task main effect, where greater muscle activity was found during the cognitive task than during quiet standing.

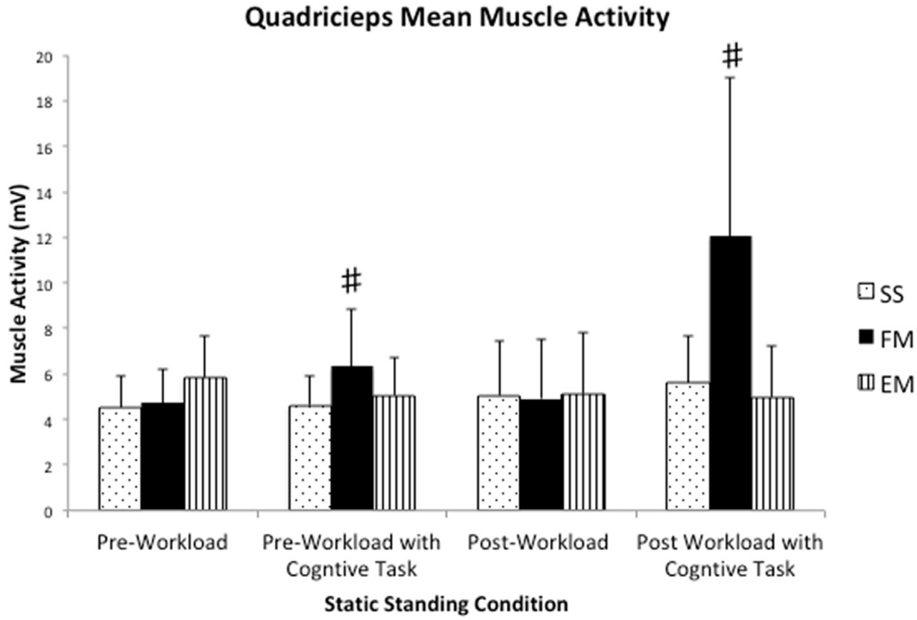

Fig. 5. Pre- and post-workload mean muscle activity for the quadricep with and without the cognitive task on the three standing surfaces (SS, solid surface; FM, fatigue mat; EM, ErgoMates). ♯Significant task main effect where greater muscle activity was found during the cognitive task than during quiet standing.

Table 1
Wall-sit performance

Variable	1WS (sec)	2WS (sec)	3WS (sec)	4WS (sec)
Mean	114.4	62.4	61.2	55.5
SD	56.1	20.0	23.9	20.7

Table 1 displays the Wall-sit (WS) average (mean) and standard deviations (SD) values for time to failure in seconds (sec) for each of the four wall-sit trials.

periods on a hard and soft surface and found the soft surface elicited more muscle exertion from the ankle dorsiflexors and decreased activation in the plantarflexors. The current findings in this study could be the results of the duration of the workload utilized. Previous studies have noted the workload duration affects both static balance performance and muscle activity differently than acute workloads [10,25]. Thus, the short workload utilized in this study may not have caused subsequent differences in surface conditions seen in other studies.

Previous studies have demonstrated alterations to footwear properties affect lower extremity muscle activation [9,10,26,27]. The ErgoMates utilized in this study were attached around the participants' low-top footwear and created an antifatigue surface interfacing with the ground. Unlike the previously mentioned studies that examined footwear variations, the ErgoMates did not substantially modify the footwear, thus had a limit effect on lower extremity muscle activation. Previous studies have noted softening footwear midsoles changes sensory receptors behavior in the base of the foot [28,29]. The ErgoMates did not directly interact with the sensory receptors at the base of the foot like most footwear. Although the overall shoe-surface interface is softer, with this lack of a direct contact to the bottom of the foot, the ErgoMates may not affect the cutaneous sensory information being relayed to lower extremity muscles. Bracing by high-collar footwear has been shown to decrease muscle activity of the plantarflexors and dorsiflexors [9,10]. All the muscles measured in this study were not obstructed by either the low-top footwear or the ErgoMates; thus, the effects on proprioceptive feedback by either may have been limited.

Muscle activity increased in the accessed musculature during the cognitive task particularly after the workload. The effects of fatigue and cognitive tasks on lower extremity muscle activity have been well documented throughout the literature [4, 5, 16, 17]. In conjunction, muscular fatigue and the cognitive tasks increased muscle exertion by increasing the demand on the postural control loop to maintain upright stance. These results are most analogous to those of Vuillerme et al. (2002), who found increased center of pressure displacements after a lower extremity fatigue protocol while performing a cognitive dual-task. However, this study did not have a condition in which static standing was performed without the task. Thus, the strength of the current study is the ability to distinguish between the effects of fatigue and cognitive dual-task on muscle activity. Interestingly, the performance of the cognitive task was maintained after the workload, thus the decline in the secondary task performance was not observed, which has

Table 2
Split squat lunges performance

Variable	1 RL lunges (SEC)	1 LL lunges (SEC)	1 RL lunges REPS	1 LL lunges REPS	2 RL lunges (SEC)	2 LL lunges (SEC)	2 RL lunges REPS	2 LL lunges REPS	3 RL lunges (SEC)	3 LL lunges (SEC)	3 RL lunges REPS	3 LL lunges REPS	4 RL lunges (SEC)	4 LL lunges (SEC)	4 RL lunges REPS	4 LL lunges REPS
Mean	78.9	56.8	31.1	22.6	48.0	39.8	23.1	19.2	38.6	30.6	19.4	14.9	36.3	30.46	19.6	15.3
SD	40.8	25.9	14.7	9.9	17.3	16.0	7.0	6.5	9.5	7.9	6.3	5.9	8.7	10.8	9.1	5.7

Table 2 displays the average (mean) and standard deviations (SD) values for time to failure in seconds (SEC) and number of repetitions (REPS) for of the four sets of split squat lunges for both the right leg (RL) and left leg (LL).

documented by other studies [18,19]. This may suggest the cognitive task used in this study was not as cognitively demanding as some other tasks utilized in the previously mentioned studies.

Several limitations are featured in this study. Muscle activity was only recorded on the right lower extremity. The workload protocol primarily focused on the proximal musculature of the lower extremity rather than the more distal muscles.

5. Conclusions

This study demonstrated that increasing cognitive load and inducing lower extremity muscular fatigue increases muscle activity, despite the standing surface. Softening the shoe-surface interface does not seem to be an adequate means of reducing muscular exertion after an acute fatiguing workload, especially when engaged in a cognitive task. Thus, when creating interventions seeking to decrease muscle exertion, other options such as footwear alterations and reducing cognitive and physical workloads should be explored. Future studies should examine the effects of a prolonged fatigue protocol on the dependent variables described in this study.

Conflicts of interest

The authors declared no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2019.06.002.

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