International Journal of EXERCISE SCIENCE

Original Research

Impact of Occupational Footwear and Workload on Lower Extremity Muscular Exertion

ALANA J. TURNER*[1], JONATHAN C. SWAIN*[1], KATHERINE L. McWHIRTER*[1], ADAM C. KNIGHT‡[1], DANIEL W. CARRUTH‡[2] and HARISH CHANDER‡[1]

[1]Neuromechanics Laboratory, Department of Kinesiology, Mississippi State University, Starkville, MS, USA; [2]Human Performance Laboratory, Center for Advanced Vehicular Systems, Mississippi State University, Starkville, MS, USA

*Denotes undergraduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 11(1): 331-341, 2018. Footwear worn and workload performed can influence muscular exertion, which is critical in occupational environments. The purpose of the study was to assess the impact of two occupational footwear, steel-toed (SWB) and tactical (TWB) work boots, on muscular exertion when exposed to a physical workload. Eighteen healthy male participants (age: 21.27 ± 1.7 years; height: 177.67 ± 6.0 cm; mass: 87.95 ± 13.8 kg) were tested for maximal voluntary isometric contraction (MVIC) using electromyography (EMG) and pressure pain threshold (PPT) using an algometer for four lower extremity muscles prior to (pre-test) and two times after a physical treadmill workload (post-test 1 & post-test 2). Additionally, heart rate (HR), ratings of perceived exertion (RPE) at the end of the workload, and recovery were recorded along with the time spent on treadmill (TT). Results from the study revealed that PPT was significantly lowered in ankle dorsiflexors immediately following the workload and EMG mean and peak muscle activity were significantly lowered in post-test 2 session in knee extensors. No significant differences were found between footwear types in all measures. The findings could be attributed to the acute muscle soreness as a result of muscular exertion from the workload. The footwear design and mass did not impact PPT, MVIC, HR, RPE, and TT with the workload administered in the study.

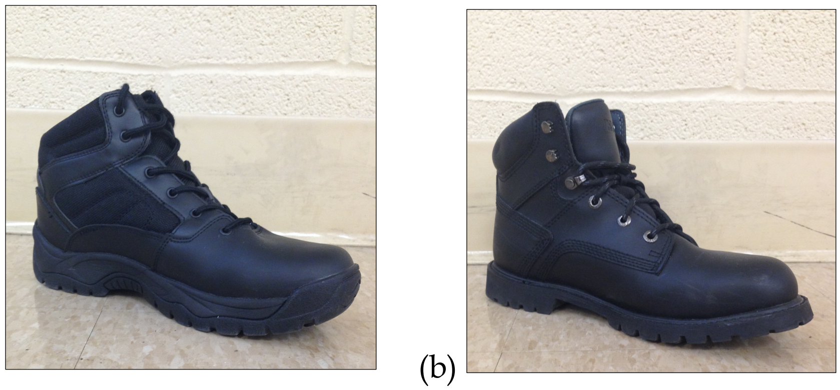
KEY WORDS: Muscular exertion, pressure pain threshold, occupational footwear

INTRODUCTION

Many physical hazards and stresses exist among occupational workers, which include lifting and carrying heavy loads, standing and walking for prolonged durations of time and usage of personal protective equipment (PPE). The primary event or exposure leading to injury and illness in occupational environments is overexertion with 376,190 cases accounting for 33 percent of all cases reported (3). Such hazards and stresses can be directly implicated to a number of health problems that have musculoskeletal, neurological and/or cardiovascular origins. A common health issue, muscular exertion and fatigue, can be defined as a gradual decrease in the force capacity of muscle and develops soon after the beginning of the sustained activity (8). This reduction in the muscular force has been implicated to a decrease in working capability and results in an internal perturbation to the motor control system thereby inducing impairment in motor coordination (19). Disturbances to the human motor control systems can result in an abated ability for efficient completions of motor tasks. The ability to perform tasks accompanied by fatigue is a hazardous condition for workers. Subjective measures of muscular exertion have been quantified using ratings of discomfort, such as visual analog scale (7) and ratings of perceived exertion (RPE) (23), and with more reliable subjective ratings, such as pressure pain threshold (PPT) using pressure pain algometry (6, 9). Objective measures of muscular exertion and fatigue have also been quantified by measuring a reduction in force production of the muscle and by identifying change in muscle activity patterns using electromyography (EMG) (8). Moreover, both these subjective and objective measures are performed before and after a period of sustained activity/workload and muscular exertion in order to identify the impact of such workload on muscular exertion (8).

In addition to intrinsic factors of the human body such as age, presence or absence of health complications, level of fitness, attentional demands, work experience, and the way a particular task is performed; many extrinsic factors (factors that are external to the human body) such as load carriage, working surface or terrain, type of task and personal protective equipment (PPE) that includes occupational footwear can influence muscular exertion and fatigue. With most of the strenuous, physically demanding occupational tasks being performed with feet on the ground, the footwear worn becomes a vital extrinsic factor in the contribution to muscular fatigue and overall human performance in occupational tasks. Footwear serves as the interface between the human foot and the ground and plays an extremely crucial role during both static and dynamic tasks. Inappropriate or incorrectly designed footwear, especially with additional physical workload and muscular exertion to the lower extremities, have been shown to have detrimental effects to human performance (4, 5). Earlier studies have shown an increase in energy expenditure and subsequently a potential faster rate of fatigue in many scenarios such as, using footwear compared to barefoot (13), using footwear that are heavier in mass compared to lighter footwear (21) and using the same footwear with its mass being increased (15). Additionally, decreased force production and increased muscular fatigue were shown with heavier footwear (firefighter rubber boots) compared to lighter footwear (firefighter leather boots) (12).

With the leading event or exposure for occupational injuries and illness being workload overexertion (3), and with footwear playing a decisive role in muscular exertion and the development of muscular fatigue, it is crucial to understand muscular fatigue that is experienced in occupational settings in order to minimize injuries and promote safety. Specifically, the impact of occupational footwear, such as steel-toed work boots and tactical work boots, in response to low intensity - long duration workload and no workload on human performance involving postural stability has been previously established (4, 5). Occupations that predominantly use these boots include the construction and manufacturing sectors, which had a total of 79,890 and 122,610 reported cases of non-fatal injuries respectively (3). However, the influence of these work boots when exposed to a high intensity - short duration workload, such as construction workers working on a roof, have not been identified, especially focusing on muscular exertion and fatigue. Therefore, the purpose of the study was to assess the impact of two types of occupational footwear; tactical work boot (TWB) and steel-toed work boot (SWB), on subjective and objective measures of fatigue, when exposed to a simulated high intensity workload. We hypothesized that the muscular exertion quantified by PPT and EMG will be greater after the workload and in the steel-toed work boot.



(a) (b)

Figure 1. Occupational footwear. (a) Tactical work boot (TWB) and (b) Steel-toed work boot (SWB).

METHODS

Participants

Eighteen healthy male participants (age: 21.27 ± 1.7 years; height: 177.67 ± 6.0 cm; mass: 87.95 ± 13.8 kg) with no self-reported history of musculoskeletal, neurological, or cardiovascular abnormalities completed the study. Participants' physical fitness status was also above recreationally trained (>3-4 days/week with consistent aerobic and anaerobic training for the at least the last 3 months). Sample size was determined a priori from similar, previous studies in the laboratory and cross checked by using G-Power statistical software with a desired power of 0.8, a desired effect size of 0.25, and at an alpha level of 0.05. As the construction and manufacturing industries have a predominant male population and due to the availability of only male size steel-toed and tactical work boots, only a male population was recruited for the study. All procedures were approved by the University's Institutional Review Board (IRB) for human subjects' research [Approval: IRB 16-388].

Protocol

The experimental protocol followed a pre-test - post-test repeated measures design consisting of two separate days of testing with an initial familiarization day. On the familiarization day, after obtaining informed consent, participants were exposed to a familiarization session that included testing methods of PPT using an algometer, especially the subjective feeling of discomfort during the PPT testing, and performing maximal voluntary isometric contractions of the lower extremity muscles. General anthropometric assessment and a physical activity readiness questionnaire (PAR-Q) were also obtained that included age, height, mass, shoe size, and general information about physical activity levels. After the familiarization day, participants were tested on two experimental testing days following the same protocol on each boot condition [TWB – mass: 0.5 kg and SWB – mass: 0.9 kg] (Figure 1) using a counter balanced design to remove order effects. Each testing session began with an initial 3-5 minute warm up consisting of walks, jogs, high knees and jumping jacks. Participants were then analyzed for maximal voluntary contraction (MVIC) and pressure pain threshold (PPT) prior (pre-test) to and two times following a simulated physiological workload separated by 15 minutes of rest (post-test 1 and post-test 2). Three trials of 5-second MVICs from knee extensors (vastus medialis-VM), knee flexors (biceps femoris-BF), ankle dorsiflexors (tibialis anterior-TA), and plantarflexors (medial gastrocnemius-MG) were collected in the mid-range of joint range of motion (ROM) using the Biopac Electromyography (EMG) system (BIOPAC Systems Inc. CA, USA). All participants were instructed to give maximal effort and maximally contract the corresponding muscles with verbal encouragement to keep going for the 5 second trials and allowed a minute of rest between each muscle group trials. Following the completion of MVIC testing, participants were assessed with three trials of PPT recorded using the FPIX-25 digital algometer with a 1 cm^2 flat tip (Wagner Instruments, CT, USA) for knee extensors (3 sites: rectus femoris, vastus medialis and vastus lateralis), knee flexors (2 sites: biceps femoris and semitendinosus), ankle dorsiflexors (1 site: tibialis anterior), and plantarflexors (2 sites: medial gastrocnemius and lateral gastrocnemius). The measurement of PPT included 3 steps based on Fisher (1987). The participant was instructed to say "yes" when they start feeling pain or discomfort. Then the rubberized end of the algometer was vertically placed on the muscle belly sites of the corresponding muscles and pressure was applied at 100 g/second increasing continuously. Finally, when the participant said "yes", the pressure was stopped and the algometer reading was noted down. Participants were not provided with any feedback during the PPT trials nor were they allowed to see or hear the algometer reading to avoid perception and anticipation of these subjective measures.

On completion of the pre-testing procedures of MVIC and PPT, participants were then directed to a treadmill to complete a physical exertion task following the standard Bruce treadmill protocol that included 3-minute stages to allow achievement of a steady state before workload was increased, starting at stage 1 at 2.74 km/h (1.7 mph) with 10% grade; stage 2 at 4.02 km/h (2.5 mph) with 12% grade; stage 3 at 5.47 km/h (3.4 mph) with 14% grade and subsequent stages of 4, 5, 6 and 7 involving the same 3 minute duration with grade increased by 2% and speed going from 6.76, 8.05, 8.85 and 9.66 km/h (4.2, 5.0, 5.5 and 6.0 mph) respectively. Participants were asked to stop the test at any point when they felt that they could not continue anymore and were given a 3 minute cool down at a self-selected slow walking speed. Heart rate (HR) and ratings of perceived exertion (RPE) were recorded at the end of the workload and following a 3 minute recovery, and the total time spent on the treadmill (TT) was also recorded. Following the physical exertional workload, participants completed the same measures of MVIC and PPT immediately after the recovery as the first of the post-test measures (post-test 1) and again following a 10 minute seated rest as the second post-test measure (post-test 2). The same testing procedures were repeated on the second boot condition based on the counter balanced boot assignment after a minimum of 72 hours from the first testing day to avoid any undue fatigue.

Statistical Analysis
All dependent variables including mean muscle activity, peak muscle activity, and PPT values were assessed using a 2 × 3 repeated measures analysis of variance (repeated measures ANOVA) [2 footwear (SWB × TWB) × 3 time (pre-test × post-test 1 × post-test 2)] to identify footwear and time differences. If a significant interaction was found, it was followed up with simple effects analysis and if a significant main effect for footwear or time was found, it was followed up with post-hoc pairwise comparisons with a Bonferroni correction. A paired sample t-test was performed to identify differences in final and recovery RPE and TT. All statistical analyses were performed with an alpha level of $p = 0.05$ using IBM SPSS 24 statistical software.

Data Analyses: EMG muscle activity raw data from the MVIC trials were filtered using a band-pass filter at 20 Hz–250 Hz and rectified using full wave rectification, before calculating mean (Mean) and peak (Peak) muscle activity (mV). PPT values were recorded in force (Newtons (N)) based on the output from the algometer. HR, RPE and treadmill time (TT) were recorded based on participant outcomes. An average of three trials during the MVIC and PPT for each muscle and each testing condition was used for further statistical comparisons.

Table 1. Muscle activity (means ± standard deviation) for pre-test, post-test 1 and post-test 2 during MVICs.

Mean Muscle	Pre-Test		Post-Test 1		Post-Test 2	
Activity (mV)	TWB	SWB	TWB	SWB	TWB	SWB
VM	0.1725 ± 0.09	0.1688 ± 0.10	0.1687 ± 0.08	0.1641 ± 0.07	0.1378 ± 0.06*	0.1239 ± 0.05*
BF	0.2925 ± 0.15	0.2358 ± 0.15	0.2617 ± 0.14	0.2576 ± 0.14	0.2408 ± 0.10	0.2033 ± 0.09
TA	0.3502 ± 0.10	0.3292 ± 0.13	0.3278 ± 0.11	0.3163 ± 0.14	0.3560 ± 0.12	0.3120 ± 0.14
MG	0.2014 ± 0.08	0.2149 ± 0.07	0.2026 ± 0.10	0.2423 ± 0.17	0.1953 ± 0.11	0.1945 ± 0.07
Peak Muscle	Pre-Test		Post-Test 1		Post-Test 2	
Activity (mV)	TWB	SWB	TWB	SWB	TWB	SWB
VM	1.2936 ± 0.69	1.3114 ± 0.79	1.2645 ± 0.52	1.3292 ± 0.72	1.0703 ± 0.44*	1.0015 ± 0.40*
BF	1.9571 ± 1.04	1.4962 ± 0.98	1.7192 ± 0.98	1.6659 ± 0.92	1.5710 ± 0.70	1.3502 ± 0.45
TA	2.3234 ± 0.79	2.1736 ± 0.95	2.2018 ± 0.67	2.0674 ± 1.01	2.3321 ± 0.85	2.0705 ± 1.03
MG	1.4443 ± 0.65	1.5653 ± 0.67	1.4154 ± 0.72	1.4982 ± 0.64	1.3983 ± 0.69	1.3623 ± 0.60

Lower extremity muscles: vastus medialis (VM), biceps femoris (BF), tibialis anterior (TA) and medial gastrocnemius (MG). * denotes significant from pre-test at $p < 0.05$

RESULTS

The repeated measures ANOVA revealed significant main effect differences for time for PPT in ankle dorsiflexors (tibialis anterior) [F (2, 34) = 4.345; $p = 0.021$, $\eta_p^2 = 0.204$] (Figure 2). Pairwise comparisons revealed significantly lower PPT in post-test 1 compared to pre-test. Significant main effect for time for knee extensors (vastus medialis) in both Mean EMG [F (2, 34) = 6.584; $p = 0.004$, $\eta_p^2 = 0.279$] (Figure 3) and Peak EMG [F (2, 34) = 4.187; $p = 0.024$, $\eta_p^2 = 0.198$] (Figure 4) were present. Pairwise comparisons revealed significantly lower post-test 2 muscle activity compared to pre-test and post-test 1 for Mean EMG and significantly lower post-test 2 muscle activity compared to post-test 1 for Peak EMG. No other significant boot main effect or boot-time interaction was found. No significant differences were found between final and recovery HR and RPE and TT between boot types.

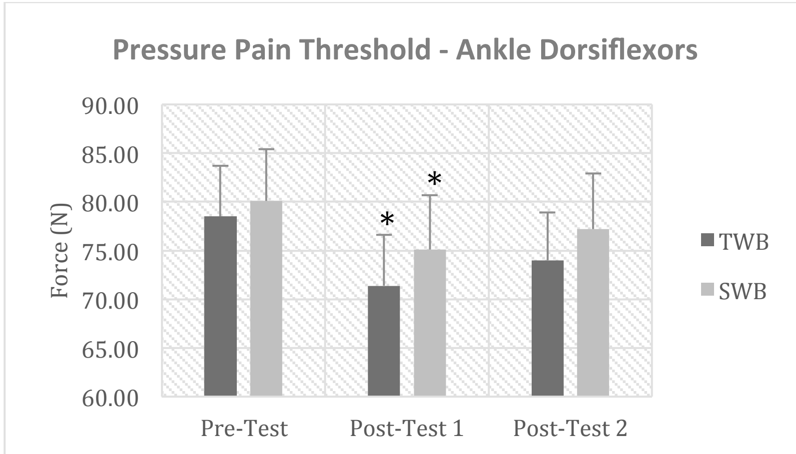


Figure 2. Pressure pain threshold (PPT) in ankle dorsiflexors (tibialis anterior muscle) for tactical work boot (TWB) and steel-toed work boot (SWB). * represents significant difference from pre-test at ($p<0.05$) and bars represent standard errors.

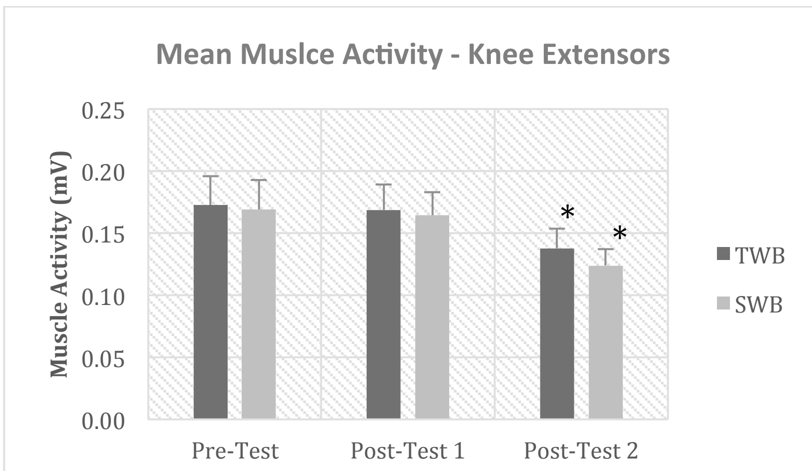


Figure 3. Mean muscle activity during maximal voluntary isometric contraction (MVIC) in knee extensors (vastus medialis muscle) for tactical work boot (TWB) and steel-toed work boot (SWB). * represents significant difference from pre-test at ($p<0.05$) and bars represent standard errors.

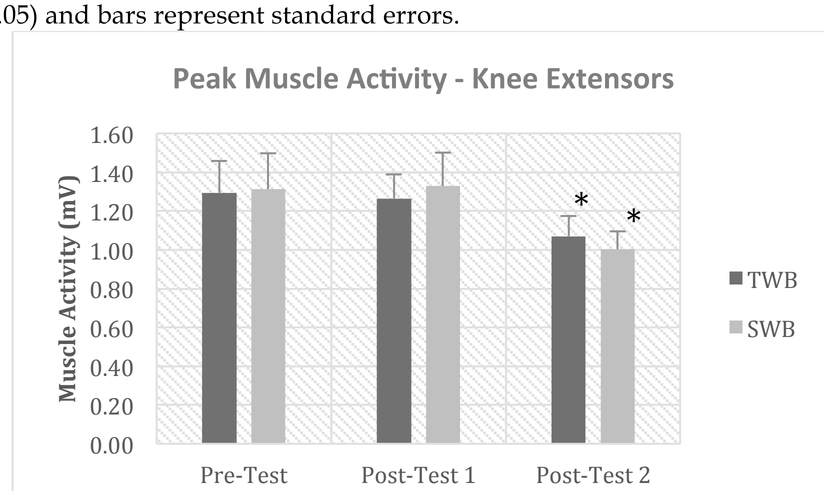


Figure 4. Peak muscle activity during maximal voluntary isometric contraction (MVIC) in knee extensors (vastus medialis muscle) for tactical work boot (TWB) and steel-toed work boot (SWB). * represents significant difference from pre-test at ($p<0.05$) and bars represent standard errors.

DISCUSSION

The purpose of the study was to assess the impact of two types of occupational footwear, TWB and SWB, on subjective and objective measures of muscular exertion when exposed to a simulated acute, high intensity workload. The findings from the study indicated significantly lower PPT immediately following the treadmill workload suggesting a lowered threshold to resist pressure induced pain, which could be attributed to acute muscle soreness. Additionally, for MVIC, significantly lower EMG mean and peak muscle activity were seen, in the post-test 2 session compared to pre-test and post-test 1, suggesting an increased muscular exertion which could be attributed to the treadmill workload, specifically after a 10 minute rest period.

However, these significant differences were limited to anterior muscles of the lower extremity, dorsiflexors and knee extensors, for PPT and MVIC, respectively. No significant differences between the footwear types were evident for PPT, MVIC, RPE (final and recovery), HR (final and recovery) and TT suggesting footwear type did not influence pressure pain threshold, muscular exertion, perceived exertion, heart rate, and time to workload task failure. Muscular fatigue represents an unavoidable occurrence during work related activity and/or daily activities (8, 22) and can be seen as one of the factors responsible for cessation of an activity or failure of a task (14). However, muscular fatigue is not seen as the point of task failure (8), but the mechanisms that lead to muscle fatigue will depend on the type of task performed (14). Most of the studies that have analyzed impact of footwear type were performed with multiple workloads generated using treadmill or stair climb protocols or both. The current study utilized the standard Bruce treadmill protocol to analyze the impact of the physical workload, a fifteen-minute rest period, and the type of occupational footwear on muscular exertion. This protocol was chosen to elicit an exhaustion type workload that resembles occupational workers climbing up ramps and inclined surfaces. Although no significant differences were seen between footwear types, significant differences existed between testing times resulting from the physical exertion workload.

In healthy adults, pain threshold has been reported to be increased during and after exercise due to the release of endogenous opioids and descending pain inhibitory mechanisms (16, 17, 18). However, a decrease in pain threshold has been reported after muscle soreness and muscle damage, especially with no intervention (1, 6). The findings from the study support previous literature in demonstrating lowered PPT (1, 6) after physical exertion. However, the significantly lower PPT was only limited to the ankle dorsiflexors (tibialis anterior muscle), only during the post-test 1 session compared to pre-test, suggesting an acute muscle soreness immediately following the physical exertion, as significant differences were not present in the post-test 2 session. Since the workload performed was the standard Bruce treadmill protocol that involves inclined stage progressions, it could be suggested that the tibialis anterior muscle exhibited acute soreness in performing greater range and forceful dorsiflexion movements at the ankle to clear the foot during the treadmill workload. Additionally, supporting previous literature, EMG mean and peak muscle activity during the MVICs were significantly lowered in the post-test 2 session for the knee extensors (vastus medialis), which could be attributed to muscular fatigue from the workload. A decrease in EMG muscle activity in MVICs following maximal muscular exertion has been reported to be due to a reduction of neural drive or motor neuron discharge from the central nervous system (2). However, the significant decrease was evident only in the post-test 2 testing session, suggesting that muscle fatigue was not immediate. A constant decrease in EMG muscle activity in muscles exposed to physically exerting workloads has been seen over multiple time points, with the greatest decline being around 24- 48 hours after the workload, suggesting delayed onset of muscle soreness (7). Although EMG during MVICs have been used to quantify muscular fatigue, a better way to identify fatigue is by measuring force production, as a decline in force production from a muscle is defined as muscular fatigue. Hence, interpretations of muscular fatigue from the current study's EMG during MVICs should be addressed with caution.

One of the primary purposes of the study was to identify if differences existed between the type of occupational footwear worn during the workload in subjective and objective measures of muscular exertion. Previously, in comparing two types of occupational footwear (leather and two types of rubber boots) among firefighters it was reported that mean increases in metabolic and respiratory variables were in the 5-12% range for every 1 kg increase in boot weight (21). Similarly, a comparison of leather and rubber boots in firefighters, showed that the heavier rubber boots demonstrated significantly greater decrements in peak torque (knee extension, flexion, ankle dorsiflexion and plantarflexion) when exposed to a workload that included two simulated fire stair climbs from the candidate physical activity test (CPAT) with a 34.04 kg load (self-containing breathing apparatus and a simulated high-rise pack) validating increased muscular fatigue (12). In the current study, the steel-toed work boot was 0.4 kg heavier than the tactical work boot for the averaged shoe size used by the participants [TWB: 0.5 kg and SWB: 0.9 kg]. However, the difference in boot mass did not elicit changes in the subjective and objective measures of muscular exertion following a physical workload. More recently, the same occupational footwear used in the current study, steel-toed work boot and tactical work boot, were assessed for balance (postural control) under acute non-fatiguing and fatiguing long duration (4 hours) walking workload. During non-fatiguing conditions, the work boots were reported to have poor balance compared to barefoot and restaurant type work shoes (5). During the 4 hour walking workload, even though balance decreased significantly over time during the workload, these work boots were reported to be better for static balance maintenance owing to their high-top above-ankle boot shaft designs (4). However, the current study did not show any significant differences between the occupational footwear types under a treadmill workload. The type of workload was a more prominent variable in this study than the footwear design characteristics. The acute muscular exertion evident by significant differences in PPT and EMG could have inhibited the footwear differences, especially since footwear differences in postural sway were seen with a low intensity workload (4) and non-fatiguing conditions (5). Finally, the lack of significance in between work boot types in PPT, EMG MVIC variables, HR, RPE, and TT could be because the lower extremity muscles were not maximally exhausted with the current study's aerobic exercise treadmill protocol. A number of physiological and cardiovascular parameters, such as oxygen consumption, energy expenditure, ventilatory and lactate thresholds, could be potential reasons for the volitional cessation of the treadmill workload. Hence, physiological parameters rather than localized muscular fatigue, may be the limiting factors in the workload.

The impact of different types of occupational footwear such as construction and manufacturing work boots, firefighter boots and military boots have been assessed under different occupational workload on both biomechanical and physiological parameters (4, 5, 12, 15). The current study adds to the body of literature in the area of occupational footwear biomechanics on the behavior of these construction and manufacturing work boots on lower extremity muscular exertion when exposed to an acute high intensity workload.

There are limitations to the current study, as no additional physiological parameters were collected during the treadmill workload. These physiological parameters may have provided more insight into how oxygen consumption and energy expenditure differed between the heavier SWB and the lighter TWB. The type of workload performed might have led to volitional cessation of the treadmill protocol due to cardiovascular and physiological parameters, rather than muscular fatigue. Additionally, assessment of intrinsic and extrinsic musculature of the foot with PPT and EMG may provide a better understanding of the foot-footwear interaction. And finally, only males were tested in the study due to the availability of the occupational footwear. Future studies should focus on the behavior of these occupational footwear under different simulated occupational workloads that involve both anaerobic and aerobic type activity. Future studies with these occupational footwear types should also focus on long duration measures after a physical workload, such as immediately after and 24 -72 hours after workload, to account for delayed onset of muscle soreness, which can be especially applied for new hires in a strenuous physically demanding occupation.

The subjective measures of PPT and objective measures of EMG muscle activity during MVIC demonstrated significant differences following the physical workload. However, these significant differences were limited due to the physical workload, rather than between occupational footwear types. PPT was significantly lowered in ankle dorsiflexors immediately following the workload, and EMG mean and peak muscle activity were significantly lowered in post-test 2 session in knee extensors, which could be attributed to the muscular exertion from the workload. The findings from the study can further contribute towards literature that focuses on human performance impacted by physical workloads and footwear types, especially in an ergonomic setting with occupational footwear. However, more research is warranted on the impact of these occupational footwear on physiological and other biomechanical measures, with exposure to different types of workloads.

ACKNOWLEDGEMENTS

There was no funding for the project. The authors wish to thank the Neuromechanics laboratory's undergraduate club members for their assistance in the data collection process.

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