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Effect of Boot Weight and Sole Flexibility on Gait and Physiological Responses of Firefighters in Stepping Over Obstacles

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Objective: The authors investigated the effect of boot weight and sole flexibility on spatiotemporal gait characteristics and physiological responses of firefighters in negotiating obstacles.

Background: Falls and overexertion are the leading causes of fire ground injuries and fatalities among firefighters. There have been few in-depth studies conducted to evaluate the risk factors of falls and overexertion associated with firefighter boots.

Method: For the study, 13 female and 14 male firefighters, while wearing full turnout clothing and randomly assigned boots, walked for 5 min while stepping over obstacles. The independent variables included boot weight, sole flexibility, gender, and task duration. Spatiotemporal measures of foot trajectories and toe clearance were determined. Minute ventilation, oxygen consumption, carbon dioxide production, and heart rate were measured.

Results: Increased boot weight was found to significantly reduce trailing toe clearance when crossing the 30-cm obstacle. Significant increases in lateral displacement of the foot were found near the end of the 5-min walk compared with the beginning of the task. Increased boot weight significantly increased oxygen consumption. There were significant decreases in oxygen consumption for more flexible soles.

Conclusion: Firefighters were more likely to trip over obstacles when wearing heavier boots and after walking for a period of time. Boot weight affected metabolic variables (5% to 11% increases per 1-kg increase in boot weight), which were mitigated by sole flexibility (5% to 7% decrease for more flexible soles).

Application: This study provides useful information for firefighters and boot manufacturers in boot selection and design for reducing falls and overexertion.

Keywords: firefighter boots, obstacle negotiation, tripping, toe clearance, oxygen consumption

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INTRODUCTION

Firefighting is one of the most dangerous and physically demanding jobs in the United States, with the work-related injury rate exceeding those of most other occupations (Walton, Conrad, Furner, & Samo, 2003). The intensity of energy expended by firefighters performing firefighting tasks is generally agreed to be in the heavy–to–very heavy range (Bilzon, Scarpello, Smith, Ravenhill, & Rayson, 2001). According to the National Fire Protection Association (NFPA), an estimated 78,150 firefighter injuries occurred in the line of duty in 2009 (Karter & Molis, 2010). The top two leading causes of injury were overexertion (25.2%) and falls (22.7%). Of all 82 firefighter fatalities in 2009, 44 were the result of overexertion or stress (Fahy, LeBlanc, & Molis, 2010). In firefighting and rescuing operations, firefighters are exposed to a varied, complex, unpredictable, and rapidly changing environment. They are constantly exposed to chemical and physical hazards, such as carbon monoxide, heat, noise, and so on. They also frequently work on roofs and ladders, and the walking surfaces are often cluttered or slippery because of the existence of debris, building materials, and contaminants.

Firefighters are required to wear protective ensembles that are designed to provide a high level of protection against extremely adverse environments. Nevertheless, the use of personal protective equipment (PPE) may pose an additional load on the firefighters, restricting their movements (Adams & Keyserling, 1995; Holmer, 1999; Huck, 1988) and impeding the job performance (Krausman & Nussbaum, 2007). Firefighters have traditionally worn heavily insulated rubberized boots as protective footwear, which can add 10 pounds (4.4 kg) of extra weight to a firefighter. There are two general types of certified structural firefighting boots in use today: rubber bunker boots 30 cm to 40.6 cm (13 in. to 16 in.) and leather or leather-fabric "hybrid" boots 20.3 cm to 40.6 cm

(8 in. to 16 in.). Leather boots are now produced with either stitched (less flexible) or cement (more flexible) soles. The weight of firefighter boots has been shown to significantly increase the physiological stresses of firefighters (Huang, Garten, Wade, Webb, & Acevedo, 2009; Turner, Chiou, Zwiener, Weaver, & Spahr, 2010). During treadmill walking, a 3% to 10% increase in oxygen consumption (VO_2) per kilogram in boot weight has been observed (Turner et al., 2010).

In addition to boot or shoe weight, sole longitudinal stiffness has been shown to affect VO_2 during running (Roy & Stefanyshyn, 2006). Running shoes with low, moderate, and high longitudinal bending stiffness were investigated. The relationship observed between VO_2 and sole stiffness was described as a "U-shaped" curve, with an intermediate amount of stiffness providing the lowest oxygen consumption. Research on boot sole stiffness is scarce; however, one recent study of military boots found that greater sole stiffness had a negative impact on biomechanical gait parameters (Cikajlo & Matjacic, 2007).

It is well recognized that PPE affects postural balance (Kincl, Bhattacharya, Succop, & Scott, 2002; Punakallio, Lusa, & Luukkonen, 2003; Seliga et al., 1991; Sobeih, Davis, Succop, Jetter, & Bhattacharya, 2006). Previous research also documented that footwear affects postural balance and may be related to falls (Brecht, Chang, Price, & Lehmann, 1995; Chiou, Bhattacharya, Lai, & Succop, 2003; Menz & Lord, 1999). Since firefighters' boots are heavy and bulky, they may change firefighters' gait patterns and limit effective locomotion on the fire ground. The effects of boot weight and sole flexibility on male and female firefighters' metabolic variables, gait patterns, and ability to negotiate obstacles, however, are still unknown. In addition, previous research has documented gender as a factor influencing movement patterns during walking and running (Ferber, McClay, & Williams, 2003). The primary objective of this study was to investigate the effect of boot weight and sole flexibility on spatiotemporal characteristics and physiological responses of male and female firefighters in negotiating obstacles.

The hypotheses were as follows: (a) Toe clearances decrease and oxygen consumption increases with heavier boots when negotiating obstacles, and (b) increased boot sole flexibility positively affects gait performance and physiological responses. For gait variables, the effects of gender and task duration are of secondary interest. The following hypotheses were tested for gait variables: (a) Significant gender differences in gait patterns while stepping over obstacles exist, and (2) task duration has a negative effect on gait patterns.

METHOD

Participants

Participants in the study were 14 healthy male (age 28.4 ± 5.5 years, weight 94.6 ± 15.6 kg, height 178.5 ± 5.8 cm, and experience 8.7 ± 5.1 years; values are *M* ± *SD*) and 13 healthy female (age 33.2 ± 4.4 years, weight 67.9 ± 8.0 kg, height 166.6 ± 5.0 cm, and experience 5.9 ± 4.7 years; values are *M* ± *SD*) career firefighters between the ages of 23 and 39 years old. All participants provided informed consent and underwent a health history screening with the following exclusion criteria: history of dizziness, tremor, vestibular disorders, neurological disorders, cardiopulmonary disorders, diabetes, or chronic back pain or having experienced a fall within the past year that resulted in an injury with days away from work. Male participants were recruited from West Virginia, and female participants were recruited from western Maryland, northern Virginia, eastern Ohio, and West Virginia.

Boot Characteristics

Four models of firefighter boots conforming to NFPA standards for structural firefighting were selected for the study (NFPA, 2007). These boots were pull-up bunkers boots that were commercially available. The four models represent hybrid upper with a combination of leather and fabric upper and less flexible soles (HS), leather upper with less flexible soles (LS), leather upper and more flexible soles (LF), and rubber upper with more flexible soles (RF). Boot longitudinal stiffness testing was performed by SATRA Technology Center (Northamptonshire, UK) using SATRA TM 194 procedures to determine the sole flexibility. Boots with a maximum flex angle <50° and stiffness index >15.0 were

TABLE 1: Boot Characteristics by Model

	Boot Model			
	HS	LS	LF	RF
Upper material	Leather/fabric	Leather	Leather	Rubber
Size				
Males (*n* = 14)	11.4 (0.9)	11.4 (0.9)	11.3 (0.9)	10.9 (1.0)
Females (*n* = 13)	6.4 (0.9)	6.4 (0.9)	6.4 (0.9)	6.1 (1.3)
Boot weight (km)				
Males (*n* = 14)	2.48 (0.10)	2.93 (0.12)	3.10 (0.10)	3.82 (0.10)
Females (*n* = 13)	2.05 (0.15)	2.46 (0.12)	2.56 (0.15)	3.36 (0.10)
Sole flexibility[a]	Less flexible (SI > 15)	Less flexible (SI > 15)	More flexible (SI ≤ 15)	More flexible (SI ≤ 15)
Sole hardness[b]	75.6 (2.8)	83.8 (1.1)	68.8 (1.5)	69.3 (1.0)

Note. Standard deviations are shown in parentheses. HS = hybrid leather and fabric upper with less flexible soles; LS = leather upper with less flexible soles; LF = leather upper with more flexible soles; RF = rubber upper with more flexible soles; SI = Stiffness Index.
[a]SATRA TM 194 footwear longitudinal stiffness testing was performed.
[b]Shore A hardness was measured with the use of a Shore A durometer (Electromatic Equipment Co., Inc, Cedarhurst, NY).

classified as less flexible, whereas boots with a maximum flex angle ≤50° and stiffness index ≤15.0 were classified as more flexible. The shoe sole hardness ranged from 68.8 to 83.8 in terms of Shore A hardness. Besides boot upper and sole characteristics, special considerations were made to match other boot components, such as insulation, shin guard, toe cap, and boot height. The boot characteristics are provided in Table 1.

Experimental Procedures and Laboratory Setup

The experimental protocol was approved by the National Institute for Occupational Safety and Health Human Subject Review Board. On the day of the experiment, after providing informed consent, anthropometric data were collected. Participants then donned turnout clothing and a pair of boots, with boot model order counterbalanced to minimize any order effects. A range of sizes of turnout clothing (small to extra large) and fire boots (size 5 to 14.5) were provided to the participants. The best-fitting clothing and shoes were chosen on the basis of participants' inputs of perceived comfort and minimum restriction in motion and mobility. The participants were provided several sizes of boots to choose from, and they were asked to stand up and walk around to ensure a correct fit for arches, ball joints, heels, and toes. The participants also put on gloves, helmet, and a 10.5-kg backpack, which represents a 45-min self-contained breathing apparatus (SCBA). A total of eight reflective markers were placed on the boots at the toe, heel, fifth metatarsal joint, and the ankle for the monitoring of foot trajectories.

Participants were tested along a 12-m (40-ft.) walkway. Before the experiment started, the participants were given time to familiarize themselves with the walkway and obstacles. Each participant was allowed to select his or her preferred limb for leading over the obstacle.

A six-camera motion analysis system (Peak Motion Analysis System™, Vicon Inc., Englewood, CO) was used to collect 3-D marker trajectory data at 60 Hz and was low pass filtered with the use of a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. The participants, while carrying a 9.5-kg hose and a 10.5-kg backpack and wearing randomly assigned boots, walked from one end of the walkway, stepping over four obstacles, to travel to the other end (Figure 1). They then turned around and continued walking and crossing obstacles for 5 min at a speed of 0.57 m/s. The

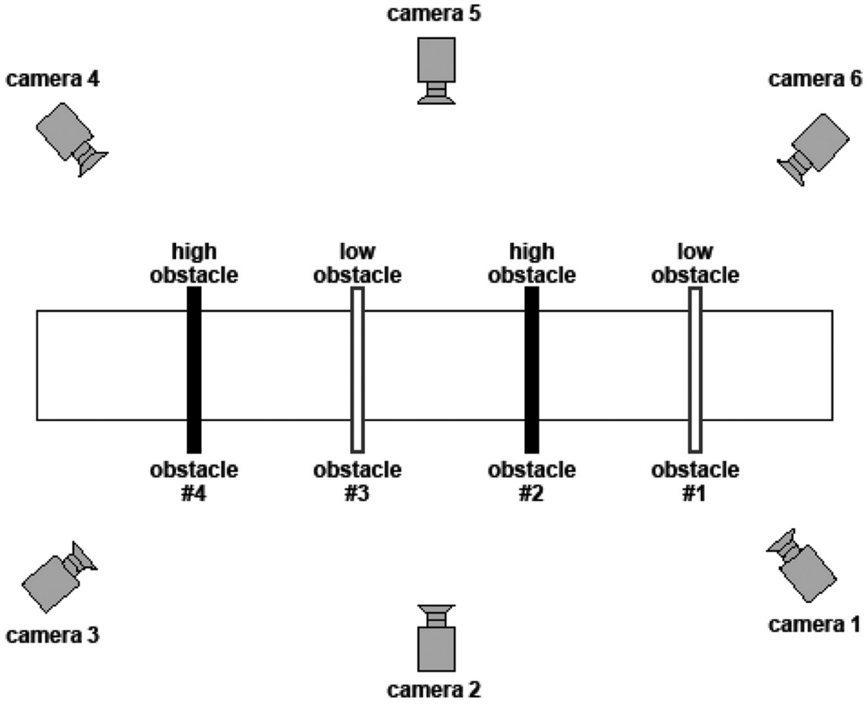

Figure 1. Laboratory setup.

walking speed was paced by a metronome and confirmed with kinematic data. During the 5-min walk, two 10-s trials of kinematic data were collected, one in the beginning within the first 30 s of walk and the other one during the last 30 s of walk. After the 5-min walk was over, the participants rested for 10 min and changed boots for the next walk.

We spaced two 15-cm and two 30-cm height obstacles equally along the walkway (Figure 1). We placed two markers on the two ends of each obstacle to define its position in the 3-D space. The obstacles were made of PVC pipes measuring 2.5 cm in diameter and 1 m in length. The pipes were light and rigid, posing little to no risk of falls if contacted. The height of the obstacles simulated common obstacle heights found on the fire ground. The 30-cm obstacle height was selected on the basis of past research (Rosengren, McAuley, & Mihalko, 1998), and the 15-cm height was selected to investigate whether boot weight effects would be significant for lower obstacles. A portable metabolic measurement system (COSMED, Italy) was used for collecting physiological data.

Dependent Variables and Data Analysis

We analyzed the motion data from the heel strike of the participant's trailing foot before he or she stepped over the second obstacle to the heel strike of the trailing foot after he or she crossed the third obstacle (Figure 1). The lead foot was the foot that crossed the obstacle first, followed by the trailing foot. Swing foot trajectories of both lead and trailing feet were measured with markers placed on the boots. The obstacle-crossing characteristics were assessed by spatiotemporal parameters, including crossing step length, preobstacle horizontal distance, postobstacle horizontal distance, lateral position of the lead foot from the stance foot, foot crossing velocity over the obstacle, and heel contact velocity. Additionally, the toe clearances of both feet when crossing the obstacle were calculated. The horizontal distance measures were determined in the anterior-posterior direction. Physiological parameters included minute ventilation (VE), oxygen consumption (VO_2, or absolute oxygen consumption, and VO_2/kg, or relative oxygen consumption), CO_2 production

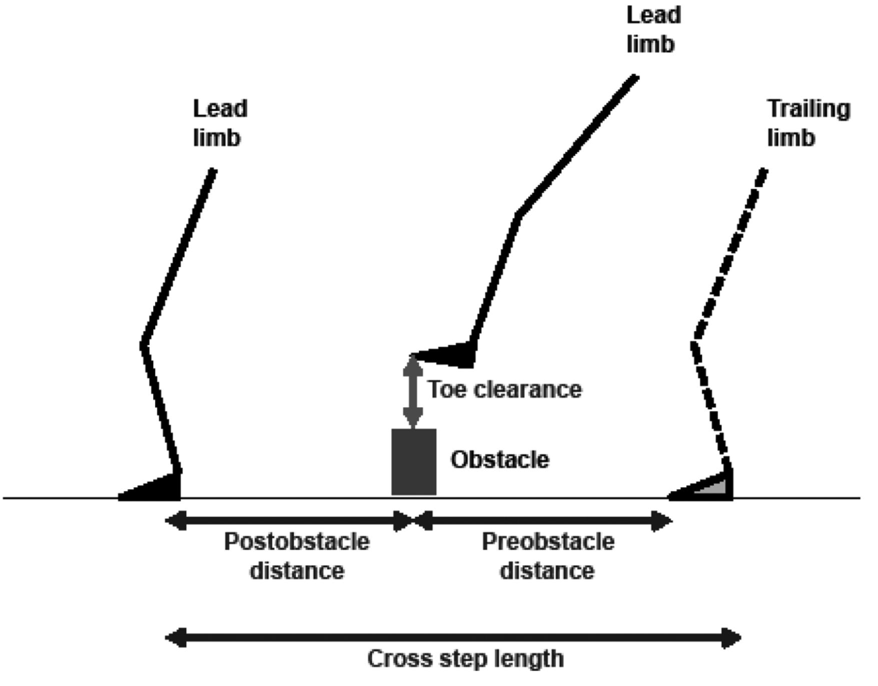

Figure 2. Illustration of step characteristics measures. Solid lines and black fill indicate the lead limb and foot. Dashed lines and gray fill indicate the trailing limb and foot.

(VCO_2), and heart rate (HR). An average of the breath-by-breath data from Minute 5 was used for analysis.

Figure 2 provides the illustration of the step characteristics measured. The cross-step length was the horizontal distance of the step involved in crossing the obstacle defined from trailing heel strike to lead heel contact. The preobstacle distance was the horizontal distance from the trailing toe to the obstacle. The postobstacle distance was the horizontal distance measured from lead heel at heel contact to the obstacle. Toe clearances of both leading and trailing limbs were calculated as the vertical distance between the toe and the top of the obstacle at the instant when the toe was directly above the obstacle. During the experiment, participants tended to displace their crossing limb laterally when clearing the obstacle. Therefore, the lateral placement of the foot was quantified, which is the mediolateral position of the lead toe with respect to the stance heel at the time when the lead foot was over the obstacle. The foot crossing velocity was the horizontal linear velocity of the lead and trailing limb when the foot was above the obstacle. The heel contact velocity was determined by the velocity of the heel marker at the event of heel strike.

Data from successful trials for which the participants stepped over the obstacle without contacting the obstacle were included in the motion data analysis. An ANCOVA, with the use of the MIXED procedure of SAS software (Cary, NC) with the level of significance set at $p < .05$, was used to test the effect of gender, boot weight (covariate), sole flexibility, and task duration (beginning vs. end of 5-min walk) on spatiotemporal variables and toe clearance variables. Preliminary analyses that included the factor of trial sequence revealed no significant main effects and interactions, implying there was no learning or carryover effect. To reduce the possible effect of body size, distance variables (i.e., cross-step length, preobstacle distance, and postobstacle distance) were also analyzed after they were normalized to leg length in the preliminary analysis. However, the results did not differ significantly from those obtained using

TABLE 2: Comparison Between Tripping and Successful Trials

Variable	Tripping Trials (n = 19)	Successful Trials (n = 149)
Cross-step length (cm)	67.1 (0.07)	66.7 (0.11)
Preobstacle distance (cm)	10.0 (0.03)	18.7 (0.05)
Postobstacle distance (cm)	24.9 (0.10)	23.4 (0.06)
Lateral distance (cm)	42.5 (0.14)	44.1 (0.14)
Lead toe velocity (m/s)	2.35 (0.22)	2.35 (0.26)
Trail toe velocity (m/s)	1.45 (0.24)	1.52 (0.32)

Note. Values are presented as means with standard deviations in parentheses.

absolute data, with an exception of the cross-step length. Physiological data from Minute 5 of each bout of obstacle crossing were used for analysis.

The MIXED procedure (SAS) with the level of significance set at $p < .05$ was used to test the effect of boot weight and sole flexibility. For all variables, estimated percentage change per 1-kg increase in boot weight, as well as estimated percentage change for more flexible compared with less flexible soles, was calculated by dividing the boot weight and sole stiffness effects predicted by the MIXED model by the means for the less flexible leather boot (LS).

RESULTS

Spatiotemporal Measures

Data for 12 of 14 males and 9 of 13 females were analyzed because of markers that either were blocked by the ensemble or were dropped on the floor during the obstacle crossing. Of all 168 trials, 19 (11.3%) tripping incidents occurred. All obstacle-induced trips occurred with the trailing foot. The incidents were observed across four-boot model. The following number of trips was found for each model: (a) HS = 6, (b) LS = 4, (c) LF = 6, and (d) RF = 3. Table 2 presents the descriptive comparisons of means and standard deviations for spatiotemporal variables between tripping incidents and successful trials. Participants had shorter preobstacle distances (10.0 cm vs. 18.7 cm) and longer postobstacle distances (24.9 cm vs. 23.4 cm) when tripping on the obstacles. The lateral distance for successful obstacle crossing was longer, with a mean of 44.1 cm compared with 42.5 cm.

Results from ANCOVA revealed a significant boot weight effect on trailing toe clearance for both obstacle heights ($p < .02$). In addition, preobstacle distance ($p < .002$) and lead heel contact velocity ($p < .05$) were found to significantly change with boot weight but only for the high obstacle. The effect of task duration was significant on four spatiotemporal measures: trailing toe clearance ($p < .05$), lateral distance ($p < .05$), lead heel contact velocity ($p < .03$), and postobstacle distance ($p < .01$, low obstacle only). Gender differences were found on lateral distance, and significance was observed for both obstacle heights ($p < .03$). There was a significant gender effect on the absolute cross-step length ($p < .05$) but not the normalized step length. As for the effect of sole flexibility, the trailing toe clearance appeared slightly larger for more flexible soles than for less flexible soles; however, the effect was not statistically significant ($p = .051$). Neither lead toe clearance nor crossing velocity was affected by gender, task duration, or boot weight. In addition, no significant interactions were found between the variables.

Table 3 presents the means and standard deviations in spatiotemporal and toe clearance parameters by boot model (boot weight effect) and obstacle height. The boot model RF was the heaviest, followed by LF, LS, and HS. Participants placed their trailing foot closer to the obstacle before crossing the high obstacle when wearing heavier boots ($p < .002$). The mean preobstacle distances for the heaviest (RF) and lightest (HS) boots were 17.3 cm and 19.9 cm, respectively. Participants also had

TABLE 3: Spatiotemporal Variables by Boot Model and Obstacle Height

	High Obstacle				Low Obstacle			
	HS	LS	LF	RF	HS	LS	LF	RF
Variable	(→ In order of increasing boot weight)				(→ In order of increasing boot weight)			
Cross-step length (cm)[c]	66.8 (7.1)	66.3 (6.3)	66.4 (7.2)	67.5 (6.3)	66.1 (5.8)	66.4 (6.8)	65.2 (7.9)	67.2 (7.1)
Preobstacle distance (cm)[a]	19.9 (2.2)	18.1 (1.7)	19.5 (1.2)	17.3 (2.4)	21.1 (1.7)	24.7 (1.3)	21.9 (1.5)	17.0 (1.4)
Postobstacle distance (cm)	23.4 (2.8)	20.9 (2.5)	23.5 (2.5)	25.7 (3.3)	22.9 (3.1)	22.7 (2.3)	23.9 (2.3)	24.9 (3.7)
Lead toe clearance (cm)	24.9 (3.3)	25.3 (3.5)	23.9 (2.7)	25.3 (2.9)	24.6 (3.4)	24.1 (2.4)	23.7 (3.6)	23.3 (2.9)
Trail toe clearance (cm)[a, b, c, f]	24.1 (4.2)	22.6 (3.2)	23.0 (3.2)	22.5 (3.0)	21.3 (4.0)	18.4 (2.7)	20.5 (3.8)	17.5 (3.8)
Lateral distance (cm)[c, d, e, f]	43.7 (5.2)	43.9 (4.3)	41.4 (5.5)	47.0 (6.1)	26.2 (3.4)	26.3 (2.0)	25.9 (3.2)	28.2 (2.8)
Lead foot crossing velocity (m/s)[c, d]	2.16 (0.27)	2.46 (0.32)	2.19 (0.24)	2.21 (0.22)	2.22 (0.25)	2.49 (0.22)	2.22 (0.20)	2.22 (0.20)
Trail foot crossing velocity (m/s)[c, d]	1.44 (0.22)	1.46 (0.26)	1.41 (0.18)	1.51 (0.25)	1.47 (0.23)	1.56 (0.20)	1.47 (0.34)	1.58 (0.33)
Lead heel contact velocity (m/s)[a]	–0.20 (0.02)	–0.15 (0.02)	–0.14 (0.02)	–0.13 (0.02)	–0.09 (0.005)	–0.08 (0.005)	–0.05 (0.008)	–0.07 (0.007)
Trail heel contact velocity (m/s)	0.51 (0.08)	0.57 (0.09)	0.49 (0.07)	0.54 (0.05)	0.45 (0.06)	0.51 (0.07)	0.52 (0.06)	0.57 (0.05)

Note. Values are presented as means with standard deviations in parentheses. HS = hybrid leather and fabric upper with less flexible soles; LS = leather upper with less flexible soles; LF = leather upper with more flexible soles; RF = rubber upper with more flexible soles.
[a] Significant effect of boot weight ($p < .02$) for high obstacle.
[b] Significant effect of boot weight ($p < .003$) for low obstacle.
[c] Significant effect of gender ($p < .05$) for high obstacle.
[d] Significant effect of gender ($p < .03$) for low obstacle.
[e] Significant effect of task duration ($p < .05$) for high obstacle.
[f] Significant effect of task duration ($p < .05$) for low obstacle.

TABLE 4: Effect Estimates and Percentage Changes in Spatiotemporal Measures per 1-kg Increase in Boot Weight by Obstacle Height

	High Obstacle		Low Obstacle	
Variable	Estimate	% Change	Estimate	% Change
Cross-step length (cm)	1.9	2.9	2.4	3.6
Preobstacle distance (cm)[a]	−4.1	−22.6	−3.5	−14.0
Postobstacle distance (cm)	1.1	5.1	2.0	8.7
Cross toe clearance (cm)	0.8	3.1	0.4	−1.6
Trail toe clearance (cm)[b, c]	−2.9	−13.4	−4.4	−14.5
Lateral distance (cm)	3.3	7.5	1.7	6.4
Lead foot crossing velocity (cm/s)	6.4	2.6	5.5	2.2
Trail foot crossing velocity (cm/s)	2.7	1.8	8.4	5.4
Lead heel contact velocity(cm/s)[d]	−5.7	−38.1	−2.6	32.5
Trail heel contact velocity (cm/s)	4.3	7.5	1.2	2.3

[a] Significant effect of boot weight ($p < .002$) for high obstacle.
[b] Significant effect of boot weight ($p < .02$) for high obstacle.
[c] Significant effect of boot weight ($p < .003$) for low obstacle.
[d] Significant effect of boot weight ($p < .05$) for high obstacle.

shorter trailing toe clearance with heavier boots. The estimated boot weight effects showed a decrease in trailing toe clearance as the boot weight increased (Table 4). For each 1-kg increase in boot weight, there was an estimated 2.9-cm and 4.4-cm decrease in trailing toe clearance for high and low obstacles, respectively. The estimated decrease in preobstacle distance was 4.1 cm for the high obstacle. Decreases in toe clearance were observed for less flexible compared with more flexible boot soles; however, these decreases were not statistically significant ($p < .051$).

In a further analysis of gender effects, comparisons between female and male groups revealed that female participants positioned their feet more laterally while crossing obstacles ($p < .03$). There were differences of 11.8 cm and 6.5 cm in mean lateral distance between the two groups for high and low obstacles, respectively. Moreover, the instantaneous velocities at lead heel contact were different between males and females. The velocity was negative, indicating the foot was moving in the rearward direction as the lead foot contacted the floor. Female participants had significantly greater impact heel contact velocity in the rearward direction immediately after the lead foot crossed the obstacle (0.25 m/s vs. 0.9 m/s for high obstacle, 0.15 m/s vs. 0.02 m/s for low obstacle, $p < .02$). A significantly greater increase in trailing heel contact velocity in the forward direction was observed for male participants (0.57 m/s vs. 0.43 m/s) for the low obstacle ($p < .04$).

The effects of task duration were examined further. Significant decreases in trailing toe clearances ($p < .05$) and increases in lateral distances ($p < .05$) and lead heel contact velocities ($p < .03$) in the rearward direction were found with the increase in walking time. In the beginning of the 5-min walk, participants maintained a trailing toe clearance of 23.6 cm over the high obstacle; however, it decreased to 22.1 cm near the end of the walk. On average, the lateral position of the lead toe was initially 42 cm to the stance foot when crossing the high obstacle, but it increased to 46 cm near the end of walk ($p < .03$). The mean postobstacle distance increased by approximately 3 cm toward the end of walk compared with the beginning.

Physiological Measures

Means and standard deviations for physiological variables are presented in Table 5. Significant boot weight effects ($p < .05$) were observed for

VE, VO_2, oxygen consumption per kg body weight (VO_2/kg), and VCO_2 in both males and females. A significant effect of boot weight on VE was seen in males only. Significant effects of sole flexibility ($p < .05$) were observed for VO_2/kg (males and females) and in VO_2 and VCO_2 (females only). Table 6 shows the estimated percentage change in metabolic and respiratory variables attributable to boot weight and sole flexibility during obstacle crossing. For the effect of boot weight on VO_2/kg, significant increases per 1-kg increase of boot weight of 8.7% for males and 7.1% for females were estimated. For less flexible compared with more flexible soles, significant changes in relative oxygen consumption of –6.1% for males and –5.0% for females were estimated. For females only, 5.0% and 6.8% decreases were estimated for VO_2 and VCO_2, respectively.

DISCUSSION

Spatiotemporal Measures

In firefighting and rescuing operations, firefighters are constantly required to navigate over a varied and cluttered environment. A successful and safe obstacle crossing requires accurate movement of the swing limb to achieve sufficient foot clearance and the stability of the body supported by the stance limb (Krell & Patla, 2002). The trajectory patterns of the lead and trail limbs during obstacle crossing have been documented to be significantly different (Patla, Rietdyk, Martin, & Prentice, 1996). In this study, all tripping incidents occurred with the trailing limb. Several factors may have contributed to the increased risk that the trailing foot would contact the obstacle. During obstacle crossing, after the lead limb has stepped over the obstacle, both the obstacle and the trailing limb are behind and outside the field of view (Patla, 1997). Participants can no longer use their vision to guide the trajectory of the trailing limb to clear the obstacle; therefore, the probability that the trailing limb may inadvertently contact the obstacle increased. Furthermore, in comparison with the leading foot, the position of the trailing foot was one foot length closer to the obstacle than the leading foot prior to crossing the obstacle. The trailing limb must achieve an adequate elevation within a shorter time, given the same crossing speed (Draganich & Kuo, 2004).

Maintaining higher toe clearance can be considered as a safety adaptation to minimize the risk that the foot may unexpectedly contact an obstacle. In the present study, the trailing toe clearance was consistently lower than that of the leading limb, with a 3-cm difference in mean toe clearance. Participants were able to maintain relatively constant lead toe clearance regardless of boot weight, whereas trail toe clearance significantly decreased, with 13.4% (high obstacle) and 14.5% (low obstacle) reduction per 1-kg increase in boot weight. To safely step over an obstacle, the human body must maintain intersegmental coordination to control the swing limb (Winter, 1991). The maintenance of adequate toe clearance is achieved by a combination of sufficient hip and knee flexion and hip elevation. Patla and colleagues (1996) suggested that elderly participants use greater vertical hip hiking to increase toe clearance. Given that increased toe clearance is achieved primarily by greater lower limb flexion, the reduced trail toe clearance observed in this study could result from insufficient knee and hip flexion because of restricted range of motion imposed by protective clothing and boot weight. Although muscle fatigue was not measured, it is probably a contributing factor to the observed decrease in trailing toe clearance from the beginning to the end of the task.

Foot placement before and after the obstacle provides valuable insights into stepping strategies, such as how participants approach the obstacle and how the foot lands after the obstacle. Poor limb placement may also increase the risk of contact with the obstacle. In this study, the preobstacle distance was significantly affected by boot weight, with a 4-cm decrease per 1-kg increase in boot weight when participants crossed the high obstacle. An earlier study reported that placing the trailing foot closer to an obstacle reduces flexion in trailing hip, knee, and ankle and increases the risk of tripping (Chou & Draganich, 1998). The reduced preobstacle distance found in this study indicated that participants tended to place the trailing foot closer to the high obstacle when wearing heavier boots, and such placement increases the risks for

TABLE 5: Physiological Variables During Obstacle Crossing at 0.57 m/s by Boot Model and Gender

	Males (n = 14)				Females (n = 13)			
	HS	LS	LF	RF	HS	LS	LF	RF
Variable	(→ In order of increasing boot weight)				(→ In order of increasing boot weight)			
VO_2 ($L \cdot min^{-1}$)	1.75^a (0.25)	1.81^a (0.26)	1.71^a (0.21)	1.89^a (0.26)	1.57^b (0.23)	1.60^b (0.23)	1.54^b (0.26)	1.61^b (0.24)
VO_2/kg ($ml \cdot kg \cdot min^{-1}$)	19.0^b (2.1)	19.6^b (2.0)	18.7^b (2.8)	20.5^b (2.6)	23.3^b (2.2)	23.8^b (2.7)	22.8^b (3.3)	23.9^b (2.4)
VCO_2 ($L \cdot min^{-1}$)	1.41^a (0.26)	1.44^a (0.24)	1.35^a (0.18)	1.53^a (0.24)	1.31^b (0.26)	1.32^b (0.22)	1.24^b (0.23)	1.33^b (0.24)
VE ($L \cdot min^{-1}$)	50.8^a (9.0)	52.1^a (8.6)	51.0^a (8.8)	54.9^a (7.0)	49.7 (8.7)	49.3 (8.1)	49.1 (9.2)	51.8 (9.0)
HR (bpm)	157 (24)	160 (24)	160 (28)	158 (23)	159 (27)	157 (20)	163 (23)	163 (20)

Note. Values are presented as means with standard deviations in parentheses. HS = hybrid leather and fabric upper with less flexible soles; LS = leather upper with less flexible soles; LF = leather upper with more flexible soles; RF = rubber upper with more flexible soles. VO_2 = absolute oxygen consumption; VO_2/kg = relative oxygen consumption; VCO_2 = carbon dioxide production; VE = minute ventilation; HR = heart rate; bpm = beats per minute.
[a] Significant effect of boot weight ($p < .05$).
[b] Significant effects of boot weight and sole flexibility ($p < .05$).

TABLE 6: Estimated Percentage Change in Physiological Variables Attributable to Boot Weight and Sole Flexibility by Gender

	Estimated % Change per 1-kg Increase in Boot Weight		Estimated % Change for More Flexible Compared With Less Flexible Sole	
Variable	Males (*n* = 14)	Females (*n* = 13)	Males (*n* = 14)	Females (*n* = 13)
VO_2	11.0[a]	6.3[a]	−7.2	−5.0[a]
VO_2/kg	8.7[a]	7.1[a]	−6.1[a]	−5.0[a]
VCO_2	13.2[a]	7.6[a]	−9.0	−6.8[a]
VE	6.9[a]	7.3	−3.8	−1.8
HR	−0.5	−0.5	1.8	1.8

Note. VO_2 = absolute oxygen consumption; VO_2/kg = relative oxygen consumption; VCO_2 = carbon dioxide production; VE = minute ventilation; HR = heart rate.
[a] Significant effect of boot weight ($p < .05$).

trail foot contact, as reflected in the reduction of toe clearance and preobstacle distance as well as the increase in number of tripping incidents.

It is interesting to note that the postobstacle distance increased at the end of the 5-min walk compared with the beginning when participants were crossing the low obstacle. However, participants maintained the preobstacle distance from beginning to end of the walk. Such strategy could be considered as a safety adaptation in providing greater toe clearance over the obstacle (Chen, Aston-Miller, Alexander, & Schultz, 1991). One drawback of this practice is that in the event of contact with the obstacle, participants may have difficulties recovering their gait because of reduced ranges of motion restricted by the turnout gear.

An additional strategy employed by firefighters to negotiate the obstacles was the lateral position of the lead toe. By swinging the foot outward, participants were able to maintain sufficient toe clearance in crossing the obstacles (Byrne & Prentice, 2003) despite the decreased joint motions imposed by the turnout clothing. Female firefighters appeared to swing even more laterally than the male participants, with an approximate 12-cm and 7-cm increase in lateral displacement for the high and the low obstacle, respectively. We observed this increased lateral displacement regardless of normalizing the displacement data by leg length. Therefore, the effect was not attributable to the fact that female participants were shorter in stature. Significantly larger lateral displacements were also found near the end of the 5-min walk for both obstacle heights compared with the beginning. After the 5-min walk with a full ensemble, the participants modified the crossing patterns by increasing the lateral displacement in crossing the obstacle.

In this study, the insignificance in foot crossing velocity over the obstacle is likely to relate to the fixed walking speed set for the experiment (0.57 m/s). The lead heel contact velocity, however, was significantly affected by gender and task duration. The increases in heel contact velocities in a rearward direction suggest that participants attempted to make the corrective action of controlling the foot motions at landing. This safety precaution was more obvious in female participants and near the end of the 5-min task.

A limitation of this study is that kinematics, muscle activity, and muscle strength information about the hips, knees, and ankles and kinetic data were not available to further examine the crossing strategies. Although such data would have been useful, the study was designed to examine firefighters in the full ensemble and gear walking and crossing obstacles. Kinematic data collected from markers attached to the bulky clothing would have been subject to errors attributable to relative movement between the body segments and the clothing. Similarly, electromyographic data collected under the bulky ensemble would not be reliable. In addition, restricting the participants to step on force plates to collect kinetic data would have caused them to deviate from their natural movement patterns since they were carrying a significant amount of weight.

Physiological Measures

The significant effect of boot weight on metabolic and respiratory variables in participants wearing heavy protective clothing and carrying equipment while stepping over obstacles was confirmed. The estimated 7% increase in VE per 1-kg increase in boot weight, observed in males during obstacle crossing, would result in an approximate 3-min decrease in service time for a typical SCBA cylinder (Turner et al., 2010). The significant 7% to 9% increase in VO_2/kg per 1-kg increase in boot weight was demonstrated in both males and females. The lack of any significant interaction between gender and boot weight indicates that the boot weight effect on metabolic variables is not influenced by the gender-dependent strategy revealed by the spatiotemporal data for this task. These results are in contrast to previous findings regarding treadmill walking while wearing firefighter boots (Turner et al., 2010). In the previous study, treadmill speed was kept constant whereas stride length was allowed to vary, which most likely accounted for the heightened effect of boot weight observed in males but not in females. In the current study, significant increases in physiologic variables attributable to increasing boot weight with a concomitant 13% decrease in trailing toe clearance were observed, leading to the conclusion that greater boot weight results in a decrease in obstacle clearance despite a greater oxygen cost.

The observed significant decreases in VO_2 attributable to greater boot sole flexibility are not well characterized, and the mechanism is unknown. The estimated 5% to 6% decreases in VO_2/kg for more flexible compared with less flexible soles were seen in both males and females, even though they were wearing heavy protective clothing and equipment. A recent study of military boots (Cikajlo & Metjacic, 2007) provided evidence that ankle joint movement and ankle power generation were significantly greater in boots with more flexible soles. The authors speculated that the increases may result in a more energy-efficient gait when walking speed remains constant, which could provide a mechanism for lower oxygen consumption.

CONCLUSION

Successful navigation through the fire ground necessitates effective avoidance of obstacles and securing adequate footing. This study demonstrated that firefighters were more likely to trip on obstacles with their trailing feet. They were also likely to trip over obstacles when wearing heavier boots and after walking for a period of time. The trailing toe clearances significantly decreased as the boot weight and task duration increased. Firefighters negotiated the obstacles by swinging their feet outward to increase the toe height and to maintain toe clearance above the obstacles. Female participants swung their feet even more outward than did the male participants. This adaptation was also observed near the end of the task after 5 min of walking. Greater boot weight caused increases in metabolic variables, which were mitigated by greater sole flexibility. Findings from this study may provide scientific evidence for firefighters and manufacturers in boot selection and design for reducing falls on the fire ground. Firefighters should consider boot weight in boot selection, as heavier boots may affect gait patterns and physiological stresses.

KEY POINTS

- Boot weight and task duration affected firefighters' gait performance in negotiating obstacles. Firefighters were more likely to trip over obstacles when wearing heavier boots and after walking for a period of time.
- For each 1-kg increase in boot weight, there was an estimated 2.9-cm and 4.4-cm decrease in trailing toe clearance for 30-cm and 15-cm obstacles, respectively.
- Boot weight affected metabolic variables, which were mitigated by sole flexibility. There was an estimated 5% to 11% increase in metabolic variables per 1-kg increase in boot weight and a 5% to 7% decrease for more flexible compared with less flexible soles.

AUTHORS' NOTE

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of the name of any company or product, or inclusion of any reference, does not constitute endorsement by the National Institute for Occupational Safety and Health.

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REFERENCES

Adams, P. S., & Keyserling, W. M. (1995). The effect of size and fabric weight of protective coveralls on range of gross body motions. *American Industrial Hygiene Association Journal*, *56*, 333–340.

Brecht, J. S., Chang, M. W., Price, R., & Lehmann, J. (1995). Decreased balance performance in cowboy boots compared with tennis shoes. *Archives of Physical Medicine and Rehabilitation*, *76*, 940–946.

Bilzon, J., Scarpello, E., Smith, C., Ravenhill, N., & Rayson, M. 2001, Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. *Ergonomics*, *44*, 766–780.

Byrne, J. M., & Prentice, S. D. (2003). Swing phase kinetics and kinematics of knee replacement patients during obstacle avoidance. *Gait and Posture*, *18*, 95–104.

Chiou, S., Bhattacharya, A., Lai, C., & Succop, P. A. (2003). Effects of environmental and job-task factors on workers' gait characteristics on slippery surfaces. *Occupational Ergonomics*, *4*, 209–223.

Chen, H. C., Aston-Miller, J. A., Alexander, N. B., & Schultz, A. B. (1991). Stepping over obstacles: Gait patterns of healthy young and old adults. *Journal of Gerontology: Medical Sciences*, *46*, M196–203.

Chou, L. S., & Draganich, L. F. (1998). Placing the trailing foot closer to an obstacle reduces flexion of the hip knee, and ankle to increase the risk of tripping. *Journal of Biomechanics*, *31*, 685–691.

Cikajlo, I., & Matjacic, Z. (2007). The influence of boot stiffness on gait kinematics and kinetics during stance phase. *Ergonomics*, *50*, 2171–2182.

Draganich, L. F., & Kuo, C. E. (2004). The effect of walking speed on obstacle crossing in healthy young and healthy older adults. *Journal of Biomechanics*, *37*, 889–896.

Fahy, R. F., LeBlanc, P. R., & Molis, J. L. (2010, July/August). Firefighter fatalities in the United States: 2009. *NFPA Journal*, pp. 75–81.

Ferber, R., McClay, D. I., & Williams, D. S. (1999). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*, *18*, 350–357.

Holmer, I. (1999). The role of performance tests, manikins and test houses in defining clothing characteristics relevant to risk assessment. *Annals of Occupational Hygiene*, *43*, 353–356.

Huang, C.-J., Garten, R. S., Wade, C., Webb, H. E., & Acevedo, E. O. (2009). Physiological responses to simulated stair climbing in professional firefighters wearing rubber and leather boots. *European Journal of Applied Physiology*, *107*, 163–168.

Huck, J. (1988). Protective clothing systems: A technique for evaluating restriction of wearer mobility. *Applied Ergonomics*, *19*, 185–190.

Karter, M. J., & Molis, J. L. (2010, November/December). U.S. firefighter injuries in 2010. *NFPA Journal*, pp. 71–76.

Kincl, L. D., Bhattacharya, A., Succop, P. A., & Scott, C. C. (2002). Postural sway measurements: A potential safety monitoring technique for workers wearing personal protective equipment. *Applied Occupational and Environmental Hygiene*, *17*, 256–266.

Krausman, A. S., & Nussbaum, M. A. (2007). Effects of wearing chemical protective clothing on text entry when using wearable input devices. *International Journal of Industrial Ergonomics*, *37*, 525–530.

Krell, J., & Patla, A. E. (2002). The influence of multiple obstacles in the travel path on avoidance strategy. *Gait and Posture*, *16*, 15–19.

Menz, H. B., & Lord, S. R. (1999). Footwear and postural stability in older people. *Journal of the American Podiatric Medical Association*, *89*, 346–357.

National Fire Protection Association (NFPA). (2007). *NFPA 1971–Standard on protective ensembles for structural fire fighting and proximity fire fighting.* Quincy, MA: NFPA.

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait and Posture*, *5*, 54–69.

Patla, A. E., Rietdyk, S., Martin, C., & Prentice, S. (1996). Locomotor patterns of the leading and the trailing limbs as solid and fragile obstacles are stepped over: Some insights into the role of vision during locomotion. *Journal of Motor Behavior*, *28*, 35–47.

Punakallio, A., Lusa, S., & Luukkonen R. (2003). Protective equipment affects balance abilities differently in young and older firefighters. *Aviation, Space, and Environmental Medicine*, *74*, 1151–1156.

Rosengren, K. S., McAuley, E., & Mihalko, S. L. (1998). Gait adjustments in older adults: Activity and efficacy influences. *Psychology and Aging*, *13*, 375–386.

Roy, J. R., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine and Science in Sports and Exercise*, *38*, 562–569.

Seliga, R., Bhattacharya, A., Succop, P., Wickstrom, R., Smith, D., & Willeke, W. (1991). Effect of work load and respirator wear on postural stability, heart rate, and perceived exertion. *American Industrial Hygiene Association Journal*, *52*, 417–422.

Sobeih, T. M., Davis, K. G., Succop, P. A., Jetter, W. A., & Bhattacharya, A. (2006). Postural balance changes in on-duty firefighters: Effect of gear and long work shifts. *Journal of Occupational and Environmental Medicine*, *48*, 68–75.

Turner, N. L., Chiou, S., Zwiener, J., Weaver, D., & Spahr, J. (2010). Physiological effect of boot weight and design on men and females firefighters. *Journal of Occupational and Environmental Health*, *7*, 477–482.

Walton, S. M., Conrad, K. M., Furner, S. E., & Samo, D. G. (2003). Cause, type and workers' compensation costs of injury to fire fighters. *American Journal of Industrial Medicine*, *43*, 454–458.

Winter, D. A. (1991). *Biomechanics and motor control of human movement*. Waterloo, Canada: University of Waterloo Press.

Winter, D. A. (1992). Foot trajectory in human gait: A precise and multi-factorial motor control task. *Physical Therapy*, *71*, 45–55.

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