

Effect of Boot Weight on Gait Characteristics of Men and Women Firefighters in Negotiating Obstacles

Sharon Chiou¹, Nina Turner², Joyce Zwiener¹, Darlene Weaver¹
William Haskell² and Marilyn Ridenour¹

¹Division of Safety Research

National Institute for Occupational Safety and Health, Morgantown WV 26505, USA

²National Personal Protective Technology Laboratory

National Institute for Occupational Safety and Health Pittsburgh, PA, 15236, USA

This study investigated the effect of boot weight on gait characteristics of men and women firefighters in negotiating obstacles. Twelve men and nine women professional firefighters, while wearing full turnout gear and different boots of varying weights, walked for five minutes while stepping over two 30-cm and two 15-cm height obstacles. The results indicated that boot weight and task duration affected firefighters' gait characteristics in negotiating obstacles. For each one kg increase in boot weight, there was a 2.8 cm decrease in toe-obstacle clearance when crossing a 30 cm obstacle. Significant decreases in toe-obstacle clearances and increases in lateral displacement of the foot were also found after 5-minute walking tasks compared to the beginning of the task. Based on these findings, firefighters may be more likely to trip over obstacles when wearing heavier boots and after walking for a period of time. Findings of this study provide useful information for firefighters and boot manufacturers in boot selection and design, as well as recommendations for preventing trips and falls.

Introduction

Firefighting is one of the most dangerous jobs in the United States with the work-related injury rate exceeding those of most occupations [Walton et al., 2003]. In 2007, an estimated 80,100 firefighter injuries occurred in the line of duty [Karter and Molis, 2008]. Fall-related injuries were the top leading cause accounting for 27.3% of the total fire ground injuries, followed by overexertion (24.4%) [Karter and Molis, 2008]. 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 a carbon

monoxide, heat, and noise. They also frequently work on roofs and ladders and the walking surfaces are often cluttered or slippery due to the existence of debris, building materials, or contaminants.

Firefighters' personal protective equipment (PPE) is designed to provide a high level of protection against extremely adverse environments. Nevertheless, the use of PPE may pose an additional load on the firefighters, restricting their movements [Adam and Keyserling, 1995], impeding job performance [Krausman and Nussbaum, 2007], and increasing the risks for slip-and-fall injuries. Firefighters have traditionally worn heavily insulated rubberized boots as protective footwear, which can add 10 pounds of extra weight to a firefighter. Previous studies have documented the evidence on the effect of PPE on firefighters' postural balance [Punakallio et al., 2004]. The heavy weight of firefighter boots has been shown to significantly increase the physiological stresses of firefighters [Turner et al., in press]. The effects of boot weight and design on firefighters' locomotion efficiency, however, are still unknown. A few articles on the evaluation of military boots were found [DoMoya, 1982; Rosenblad, 1988]. There have been little to no previous attempts to show how boot weight may affect firefighters' gait and might be an important factor in fall injuries.

Method

Subject and Boot Characteristics

The objective of this study was to investigate the effect of firefighter boot weight on firefighters' gait characteristics and risks

for fall injuries while negotiating obstacles. Twelve healthy men (28.9±5.0 years) and nine healthy women (35.3±3.1 years) professional firefighters between the age of 23 and 39 years old participated in the study. All subjects provided informed consent and were free of neuromuscular dysfunction, history of dizziness, vestibular disorders, and fall injuries in the past year. Male subjects were recruited from West Virginia, while women participants were recruited from western Maryland, northern Virginia, eastern Ohio and West Virginia.

Four models of firefighter boots conforming to National Fire Protection Association [NFPA]1971 Standards for structural firefighting were selected for the study. These boots were pull up bunker boots that were commercially available. The four models of boots represent two models of leather boots, one model of leather/fabric hybrid boots, and one model of rubber boots. The boot characteristics are shown in Table 1. The sole flexibility was determined by the Longitudinal Stiffness of Footwear Testing based on the TM 194 procedures of the UKSATRA Technology Center.

Test Protocol

The test protocol involved subjects walking along a 6.3-meter path and stepping over two 15-cm and two 30-cm obstacles. The participants, while wearing full turnout gear and randomly assigned boots, walked from one end of the walkway, stepping over four obstacles to travel to the other end. They then turned around and continued walking and crossing obstacles for five minutes at a speed of 0.57 m/sec. The walking speed was paced using a metronome. A 6-camera motion analysis system (Peak Motion Analysis System™, Vicon Inc., Centennial, CO) was used to collect 3D marker trajectory data at 60 Hz and low pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. Two ten-second trials of kinematic data were collected during the five-minute walk, one in the beginning after 30 seconds of walking and the other during the last 30 seconds of walking. Each subject was allowed to select his or her preferred limb for leading over the obstacle. A total of 8 reflective markers were placed on the subjects at the toe, heel, 5th metatarsal joint, and the ankle to monitor gait patterns and rear foot motions for both leading and trailing feet. Two markers were placed on the two ends of each obstacle to define its position in the 3D-space. The obstacles were made of light-weight PVC pipes measuring 3.5 cm diameter and one meter in length. They posed little to no risks of falls if contacted.

Table 1. Boot Characteristics by Model

Boot Model	A	B	C	D
Upper material	Leather	Leather	Leather/ Fabric	Rubber
Sole flexibility*	More Flexible	Less Flexible	Less Flexible	More Flexible
Boot wt (men)	3.1 (0.1)	2.9 (0.1)	2.5 (0.1)	3.8 (0.1)
Boot wt (women)	2.5 (0.1)	2.4 (0.1)	2.0 (0.1)	3.3 (0.04)
Boot length (men)	31.2 (0.9)	31.2 (0.8)	30.9 (0.9)	30.7 (1.0)
Boot length (women)	27.1 (0.9)	27.0 (0.8)	26.5 (1.0)	26.8 (0.6)
Boot width (men)	10.8 (0.2)	10.1 (0.2)	10.6 (0.2)	11.1 (0.3)
Boot width (women)	9.6 (0.2)	9.0 (0.2)	9.6 (0.2)	10.1 (0.2)

Note: standard deviations are shown in parenthesis; * SATRA TM 194 Testing performed Boot weights are in kg and boot length and width are in cm.

Results

The motion data were analyzed from the toe-off of the trailing foot before stepping over the first obstacle to the heel strike of the trailing foot after crossing the second obstacle. Swing foot trajectories were assessed through the examination of crossing step length, toe obstacle clearance, lead foot heel strike distance, and trail foot approach distance. The cross step length was the distance from the trailing toe-off to the leading heel contact. Toe obstacle clearance was defined as the vertical distance between the toe and the top of the obstacle at the instant when the toe was directly above the obstacle. The heel strike distance was the distance from the lead heel to the obstacle, while the trailing foot approach distance was the distance from the trailing toe to the obstacle. During testing it was observed that subjects tended to displace

their crossing limb laterally when clearing the obstacle. Therefore, the lateral position of the lead foot was quantified, which is the horizontal position of the lead toe from the stance foot at the time when it crossed over the obstacle. Data from successful trials for which the subjects stepped over the obstacle without contacting the obstacle were included in the analysis. Of all 168 trials collected, 19 (11.3%) tripping incidents occurred. All tripping over obstacles occurred with the trailing foot. Repeated Measure Analyses of Variance (ANOVAs) were performed to test the effect of gender, boot weight, boot sole flexibility, and time period (beginning vs. end of 5-min walk) on the temporal-distance variables. The effect of boot weight and time period was found to be significant on trailing foot toe-obstacle clearances for both

high and low obstacles ($p < 0.02$). As the boot weight increased, the toe-obstacle clearances decreased. For each one kg increase in boot weight, there was a 2.8 cm decrease in toe-obstacle clearance for the taller obstacle. Subjects were able to maintain a toe-obstacle clearance of 23.5 cm in the beginning of the walk (Figure 1); however, the clearance was decreased to 21.9 cm near the end of the 5-minute walk over the high obstacle ($p < 0.05$). In addition, significant differences were observed for lateral toe position by gender ($p < 0.01$) and time period ($p < 0.03$). On an average, the lead toe was initially 42 cm to the right of the stance foot when crossing the high obstacle, but it was increased to 46 cm near the end of walk. Women firefighters were found to displace the toe farther away from the stance foot than the men firefighters (Fig. 2).

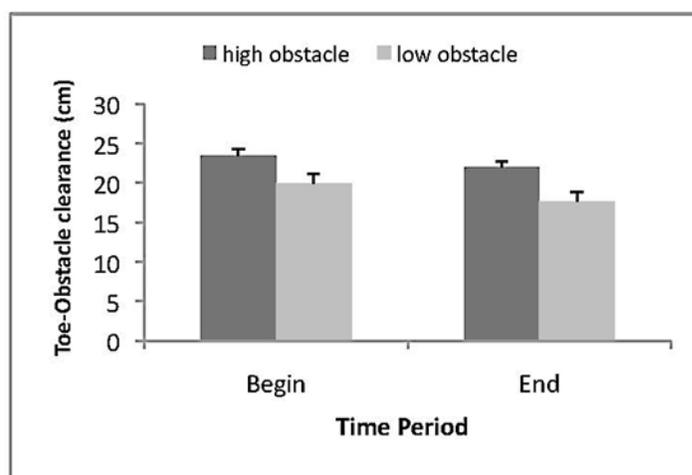


Figure 1 Mean toe-obstacle clearance for two obstacles by time period

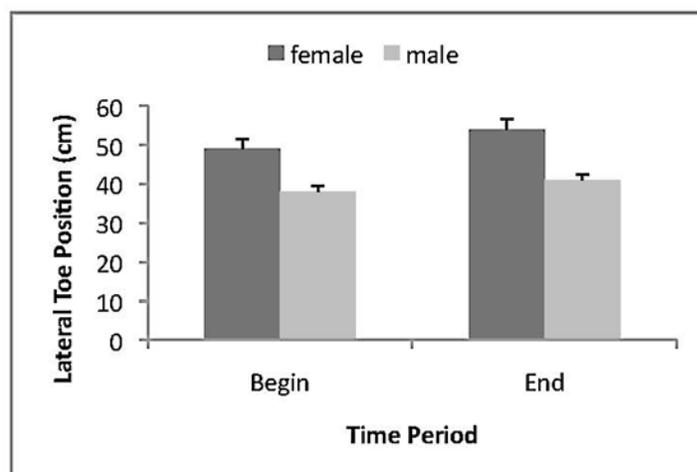


Figure 2 Mean lateral toe position by gender and time period

Summary

Successful navigation through the fire ground necessitates effective avoidance of obstacles and securing adequate footing. In this study, the toe-obstacle clearances significantly decreased as the boot weight and task time period increased. Insufficient toe-obstacle clearances often result in unsuccessful obstacle avoidance at the job site and may lead to loss of balance (Krell and Patla, 2002). Results from this study indicated that boot weight and task time period affected firefighters' gait characteristics in negotiating obstacles. Subjects were more likely to trip over obstacles when wearing heavier boots and after walking for a period of time. Men and women firefighters adopted different kinematic strategies in negotiating obstacles. By swinging the foot outward, female subjects increased the toe height to help maintain toe clearance above the obstacle. Findings from this study may provide scientific evidence for firefighters and manufacturers in boot selection and design for preventing falls on the fire ground.

The findings and conclusions are those of the author and do not necessarily represent the views of NIOSH. Mention of any products does not constitute the endorsement of NIOSH.

References

- Adams PS, Keyserling WM [1995]. The effect of size and fabric weight of protective coveralls on range of gross body motions. *Am Ind Hyg Assoc J* 56:333–340.
- DeMoya RG [1982]. A biomechanical comparison of the running shoe and the combat boot. *Mil Med* 147:380–383.
- Karter MJ, Molis JL [2008]. Firefighter Injuries for 2007. *NFPA J* November/December.
- Krausman AS, Nussbaum MA [2007]. Effects of wearing chemical protective clothing on text entry when using wearable input devices. *Int J Ind Ergon* 37:525–530.
- Krell J, Patla AE [2002]. The influence of multiple obstacles in the travel path on avoidance strategy. *Gait Posture* 16:15–19.
- Punakallio A, Lusa S, Luukkonen R [2004]. Functional, postural and perceived balance for predicting the work ability of firefighters. *Int Arch Occup Environ Health* 77:482–90.
- Rosenblad W [1988]. The design and evaluation of military footwear based upon the concept of healthy feet and user requirement studies. *Ergonomics* 31(9):1245–1263.
- Turner NL, Chiou S, Zwiener J, Weaver D, Spahr J [in press]. Physiological effect of boot weight and design on men and women firefighters. *J Occup Environ*.
- Walton SM, Conrad KM, Furner SE, Samo DG [2003]. Cause, type and workers' compensation costs of injury to fire fighters. *Am J Ind Med* 43(4):454–458.

2010 International Conference on

Fall Prevention and Protection



U.S. Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health



NIOSH



Disclaimer: These proceedings do not constitute endorsement of the views expressed or recommendations for the use of any commercial product, commodity, or service mentioned by the National Institute for Occupational Safety and Health (NIOSH). The opinions and conclusions expressed in the presentations and report are those of the authors and not necessarily those of NIOSH. All conference presenters were given the opportunity to review and correct statements attributed to them within this report. Recommendations are not final statements of NIOSH policy or of any agency or individual involved. They are intended to be used in advancing the knowledge needed for improving worker safety.



Research and Practice for Fall Injury Control in the Workplace:

Proceedings of International Conference on Fall Prevention and Protection

This document is in the public domain and may be freely copied or reprinted.

Disclaimer

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH). In addition, citations to Web sites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products.

Furthermore, NIOSH is not responsible for the content of these Web sites. All Web addresses referenced in this document were accessible as of the publication date.

Ordering Information

To receive documents or other information about occupational safety and health topics, contact NIOSH at

Telephone: 1-800-CDC-INFO (1-800-232-4636)

TTY: 1-888-232-6348

E-mail: cdcinfo@cdc.gov

or visit the NIOSH Web site at www.cdc.gov/niosh.

For a monthly update on news at NIOSH, subscribe to NIOSH eNews by visiting www.cdc.gov/niosh/eNews

DHHS (NIOSH) Publication No. 2012-103

November 2011

SAFER • HEALTHIER • PEOPLE™