Published in final edited form as:
J Appl Biomech. ; : 1–8. doi:10.1123/jab.2019-0338.

Effects of Metatarsal Work Boots on Gait During Level and Inclined Walking

Lydia M. Kocher, **Jonisha P. Pollard**, **Ashley E. Whitson**, **Mahiyar F. Nasarwanji**
National Institute for Occupational Safety and Health

Abstract

Footwear plays an important role in worker safety. Work boots with safety toes are often utilized at mine sites to protect workers from hazards. Increasingly, mining operations require metatarsal guards in addition to safety toe protection in boots. While these guards provide additional protection, the impact of metatarsal guards on gait are unknown. This study aimed to measure the effects of 4 safety work boots, steel toe, and steel toe with metatarsal protection in wader- and hiker-style boots, on level and inclined walking gait characteristics, during ascent and descent. A total of 10 participants completed this study. A motion capture system measured kinematics that allowed for the calculation of key gait parameters. Results indicated that gait parameters changed due to incline, similar to previous literature. Wader-style work boots reduced ankle range of motion when ascending an incline. Hip, knee, and ankle ranges of motion were also reduced during descent for this style of boot. Wader-style boots with metatarsal guards led to the smallest ankle range of motion when descending an inclined walkway. From these results, it is likely that boot style affects gait parameters and may impact a miner's risk for slips, trips, or falls.

Keywords

safety; footwear; mining

Footwear is the primary interface between the worker and the work environment and plays a critical role in worker safety.[1] Safety toe footwear is often used to protect workers from the hazards typically encountered in work environments, such as mining, and is thereby required personal protective equipment at all mine sites. All underground coal mine operators in the State of West Virginia, and many other mine operators, require additional foot protection in the form of boots with metatarsal guards. As required in ASTM International standard F2413–18, metatarsal protective footwear meets the requirements for impact and compression resistant footwear and includes a metatarsal impact guard that is positioned partially over the protective toe cap and extends to cover the metatarsal bones. While

Kocher (LKocher@cdc.gov) is corresponding author.
The authors are with the Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health, Pittsburgh, PA, USA.

metatarsal protection may be effective at protecting a greater portion of the foot from injuries, the effect of this protection on gait is unknown.

Some characteristics of footwear have been previously found to affect gait, balance, and stability.[2–4] Sensory feedback from the feet plays a critical role in balance and locomotion and can be altered by standing and walking on different surfaces.[5,6] Nurse et al[5] found that textured insoles affect ankle kinematics and lower limb muscle activation patterns when compared with smooth insoles. Robbins et al[7] investigated the balance effects of midsole hardness and midsole thickness of footwear. In their evaluation of men walking on balance beams, thin hard soles provided superior stability compared with thick soft soles, resulting in less falls from the beam. Menant et al[3] examined the effects of shoe heel height, collar height, and sole stiffness on walking stability in young and older adults. They reported more conservative walking with longer time spent in double support when the shoe heel height was increased and found increased sole softness to result in impaired medial/lateral balance control in both young and older subjects.

Along with common footwear features, safety work boots have other features that may negatively affect gait, balance, and the distribution of ground reaction forces through the lower limbs.[8,9] Mobile mining equipment operators identified metatarsal footwear as contributing to slips, trips, and falls during ingress and egress because the boots are more bulky and not as flexible.[10] A recent literature review conducted by Dobson et al[2] included 18 research papers examining features of work boots and their effects on gait, kinematics, kinetics, motion, and electromyography. The authors identified shaft height, shaft stiffness, boot weight, and sole flexibility as key features of work boots that affect gait.

Shaft height was found to significantly affect ankle and foot range of motion (ROM) and stability in several studies.[11–13] Park et al[12] examined the effects of different styles of firefighter boots on ankle and ball of foot ROM when compared with running shoes during walking trials. The authors believed that the inflexible boot shaft found in firefighter boots could hinder ROM in the sagittal plane, and the slip-on style could increase ROM in the frontal plane due to reduced ankle support. Pull-on wader-style boots were found to reduce ball of foot flexion/extension and ankle plantar/dorsiflexion ROM in the sagittal plane. Increased foot abduction/adduction and ankle inversion/eversion in the frontal plane were found when participants wore the higher shafted firefighting boot. Another study examining the effects of shaft height on balance in construction workers walking on narrow planks in a virtual reality construction environment, found that boots with higher shaft heights significantly reduced the participants' perceived stability.[13] A study utilizing an agility course found boots with higher shaft heights resulted in slower completion times due to restricted ankle motion influencing shank movement.[11]

Ankle ROM has also been shown to be significantly reduced when the shaft stiffness of hiking and military boots is increased.[11,14] While some restriction in ankle ROM is necessary to protect against lateral ankle sprains, excessive restriction negatively impacts the knees and hips.[15,16] Reduced ankle ROM also leads to abnormal walking patterns and may be especially hazardous when traversing stairs, inclined walkways, and unlevel surfaces, which are commonly encountered in mining and may increase the risk of tripping.[12,17,18]

Boot weight was shown to affect heel contact velocity and toe clearance. In an investigation of firefighters performing step-over activities, boots with higher weights resulted in increased heel contact velocities and reduced toe clearances.[19] Moreover, increased boot weight increased muscle fatigue in firefighters, leading to a decreased torque generation at the knees and ankles.[20] These results are like those found when changing sole flexibility of boots. Firefighters wearing boots with more flexible soles showed increased trailing limb toe clearances.[19] Military boots with stiffer soles, compared with athletic shoes, resulted in increased tibial internal rotation, ankle eversion, and impact loading in males.[21]

The design of metatarsal boots with a larger, rigid portion over the forefoot could restrict motion of the metatarsals, potentially affecting the ROM of the foot and ankle. Moreover, the added weight may contribute to fatigue and affect heel contact velocities. A recent investigation by Pollard et al[1] examined the impact of metatarsal protection versus steel toe only protection on toe clearance during stair ascent while participants wore hiker-style boots. Although no statistically significant differences in toe clearance were found, the authors did not examine any other measures such as ROM or heel contact velocities. They also failed to examine inclined walking, which has been shown to amplify the effects of changes in footwear characteristics and slip risk.[13,22] Furthermore, research has tied larger stride lengths, larger foot–floor angles, and increased cadence to hazardous slips when walking on a slippery surface.[4] To the authors' knowledge, it is unknown how inclined walking or work boot style affects these gait characteristics.

The influence of work boot features varies depending on walking surface and tasks performed.[2] To determine the impact of metatarsal protection on slip, trip, and fall risks in mining, representative mining activities and walkway materials must be examined. The researchers hypothesized that metatarsal protection (compared with steel toe only) would result in statistically significant changes in stride length, foot–floor angle, foot velocity, and lower limb ROM, for descending and ascending level and inclined walking surfaces.

Methods

Study Population

Convenience sampling was used to recruit participants from the National Institute for Occupational Safety and Health (NIOSH, Pittsburgh, PA). Interested individuals were screened for different criteria, including age and known balance disorders (e.g., vertigo), cardiovascular disease, diabetic neuropathy, and inability to stand or walk unassisted. If qualified, they read and signed an informed consent document approved by the NIOSH Institutional Review Board. A total of 12 participants were recruited; however, one participant did not complete the study, and an additional participant's data were not included in the final analysis of the study. The excluded participant did not complete 1 full gait cycle in each trial. Overall, the study examined the gait styles of 10 participants (8 men and 2 women; age 28.6 [6.0] y; body mass 86.9 [19.0] kg; height 1.82 [0.077] m), consistent with previous research in this area.[1,2,22]

Instrumentation

Trials were recorded using a motion capture system with 18 cameras and passive retroreflective markers affixed to the participant's body and boots (Kestrel; Motion Analysis Corp, Rohnert Park, CA). A total of 22 markers were placed on the body, and 12 additional markers were placed on the boots, with 6 on each boot. The marker set was created from a modified Coda pelvis (Charnwood Dynamics Ltd, Rothley, United Kingdom), body placements outlined in Visual 3D documentation, and boot locations as described by Pollard et al.[1,23] Locations included the sternum, bilateral acromions, elbows, and wrists, an offset marker on the left inferior scapula, bilateral markers on the anterior and posterior superior iliac spines, superior iliac crests, lateral and medial femoral epicondyles, and anterior portion of the thigh and shank. Boot markers were placed on the boots at predetermined boot landmarks according to the boot size to mimic estimated locations of the foot and ankle bony landmarks.[1] Participants were paired with fitting boots, specific to style, to simulate proper locations (ie, different boot sizes may be worn by the same participant based on size differences between styles), and boot marker locations were identified and labeled to ensure repeatable placement.

There were 4 styles of boots selected for this study. In total, 2 of the pairs were hiker-style boots that have laces and a shorter shank. One pair of the hiker-style boots featured a safety toe construction (Dr. Martens® Men's Ironbridge Steel Toe, Model DMR12721001) and was referred to as hiker style with steel toe (HS). The second style of hiker boots included the added protection of a metatarsal guard (Dr. Martens® Men's Ironbridge ST Met Guard Heritage Boot, Model DMR14403001) and was referred to as hiker style with metatarsal (HM). The other 2 pairs of boots were wader-style boots that slip onto the foot and have a taller shank. Wader-style boots were folded down to allow for stable shank marker placement on the body. Like hiker-style boots, there were steel toe, wader-style boots (LaCrosse® 16″ Premium Knee Boot SM/ST, Model 00101110) and metatarsal guard boots that also have a steel toe (LaCrosse® 16″ Meta Safety Toe Met Guard Work Boots, Model 00228260), referred to as wader style with steel toe (WS) and wader style with metatarsal (WM), respectively (Figure 1). These specific boot brands were selected because the styles were nearly identical except for the type of foot protection within hiker-style and wader-style boots.

Participants performed trials on an adjustable walkway with metal grating and handrails similar to that used by Pollard et al.[22] Level and inclined grated metal walkways are often used at mines to prevent the accumulation of water and debris on the walkways.[22] The walkway could be adjusted to any inclination level, but set levels included 0° (level walkway), 10°, and 20°. Pollard et al[22] found these levels to increase the risk of slipping on inclined walkways. A forklift was used to raise and lower the walkway, and pegs were inserted at each level to ensure accurate degrees of inclination for each trial and participant.

Procedures

After eligibility was confirmed and informed consent was obtained, each participant selected and tried on all 4 pairs of boots to find the correct size. Occasionally, different sizes were worn between hiker style and wader style. Again, this improved the accuracy of estimated bony landmark retroreflective markers applied to the boot. After boot size selection, the participant was assigned a random order of boots and conditions. Incline order was randomized within each boot style. After all levels were completed for that boot style, the participant changed boots.

Participants were not told which style they were wearing, whether it was steel toe or metatarsal. Each participant was asked to walk around the lab to familiarize himself or herself with the boots for a few minutes. Once they reported feeling comfortable walking in the boots, the participant was instructed to ascend the walkway, turn around at the top, and then descend the walkway. Participants were asked to walk at a normal comfortable pace and to only use the handrails if they were needed for that specific trial. To encourage a natural gait pattern, leading leg was not controlled for different trials. Each condition was repeated 3 times before the incline was changed. In total, each participant completed 3 trials for each incline level (0°, 10°, and 20°) in each boot (HM, HS, WM, and WS). The last trial from each condition was used for analysis.

Data Analysis

Data analysis was performed in Visual 3D (version 6; C-Motion Inc, Germantown, MD). Calculated variables included joint ROM, stride length, horizontal foot velocity at foot strike, and foot–floor angle, all of which have been associated with changes in gait when investigating footwear.[2,4,11–19] ROM was calculated for the hip, knee, and ankle as the maximum flexion through maximum extension, in the sagittal plane, of the supporting leg. Stride length was calculated from foot strike through foot strike, with foot velocity recorded at the first foot strike of the cycle in the walking direction. Foot strike was used for velocity, instead of heel strike, to account for the 20° incline where the first contact was often at the toe. Foot–floor angle was the angle between the foot and the walkway at the first foot strike. All variables were calculated during 1 full gait cycle (with first foot strike, toe-off, and second foot strike) that occurred in the middle of the walkway. Each variable was calculated during that gait cycle for each foot separately. A skeletal model was generated in the software using motion capture data and estimated anatomical landmarks and used to calculate joint angles. Furthermore, a foot velocity algorithm was used to identify foot strike and toe-off gait cycle events for the right and left foot.[24] This information, along with the skeletal model, calculated stride length and horizontal foot velocity in the forward direction. Finally, walkway markers and foot center of gravity were used to calculate the foot–floor angle at foot strike.[25]

Statistical Analysis

Statistical analysis was conducted in IBM’s SPSS (IBM SPSS Statistics Subscription; Armonk, NY). A 2-way repeated-measures analysis of variance was used to compare the effects of boot style and level of incline. Each foot was calculated independently because leading leg was not controlled during this study. Gait parameters included in the analysis were stride length, foot–floor angle at foot strike, foot velocity at foot strike, and joint ROM for the left and right sides when ascending and descending. Data violating Mauchly test of sphericity were corrected using the Greenhouse–Geyser correction, and degrees of freedom were adjusted accordingly. The Bonferroni correction was applied for post hoc analysis. A P value of $P \leq .05$ was used to determine statistical significance.

Results

The results of the 2-way repeated-measures analysis of variance indicated that boot style and change in incline level had statistically significant effects on the measures of interest. Boot style and level of incline showed significant main effects as well as one significant interaction (Table 1). The level of incline showed significant main effects on stride length (in meters), foot velocity at foot strike (in meters per second), foot–floor angle (in degrees from the horizontal), and lower limb joint ROM (in degrees). Boot style primarily affected lower limb ROM.

No significant main effects were observed for the different boot styles for stride length during ascent or descent (Table 1). Level of incline showed significant main effects on stride length during ascent and descent (Table 1). Bonferroni post hoc tests revealed a significant decrease in stride length on the left and right side during ascent between 0° and 20° and 10° and 20° (Figure 2). Stride length significantly decreased during descent on the left and right side as incline level increased (Figure 2). Testing revealed a significant interaction between incline and boot style exclusively on the left side during ascent ($P = .02$). Interaction was not further tested, as significance is likely due to leading leg variance and sample size.

Boot style significantly affected foot velocity during ascent on the right side exclusively ($P = .03$; Table 1); however, post hoc tests did not reveal statistically significant differences between specific boot styles. Boot style did not appear to affect foot velocity at foot strike during descent. Level of incline showed significant main effects on foot velocity at foot strike in the horizontal direction of movement during ascent and descent (Table 1). Bonferroni post hoc tests revealed a significant decrease in velocity at foot strike on the left and right sides during ascent and descent between 0° and 20° and 10° and 20° (Figure 3). There was a downward trend in velocity during ascent as the incline increased. In comparison, velocities at 10° were slightly higher compared with 0° during descent; however, the increase did not reach significance (Figure 3). No interactions were found between incline level and boot style for foot velocity at foot strike.

Boot style did not significantly affect foot–floor angle at foot strike, during ascent or descent (Table 1). Level of incline showed significant main effects on foot–floor angle only during ascent on the left and right side (Table 1). The left- and right-side foot–floor angles significantly decreased with increased levels of incline during ascent (Figure 4). It is noteworthy that at 20°, the toe often made contact with the walkway first and not the heel, which is represented as a negative value in Figure 4. Testing did not reveal interaction between incline level and boot style for foot–floor angle.

Boot style only impacted ankle ROM during ascent (Table 1). During ascent, on the left and right sides ankle ROM was lower for the wader-style boots (WM and WS) as compared with the hiker-style boots (HM and HS) (Figure 5A). During descent, boot style had a significant main effect on hip, knee, and ankle ROM for the left and right side (Table 1). During descent, Bonferroni post hoc tests revealed that WM had lower ROM as compared with WS for the left hip, HM and HS for the left and right knee, HM and HS for the left ankle, and HS for the right ankle (Figure 5B). Ankle ROM for WS was also significantly lower than HM on the left and HS on the right during descent (Figure 5B).

During ascent, the level of incline significantly affected the hip and ankle ROM (Table 1). Left and right hip ROM increased as the level of incline increased for ascent (Figure 6A). Left and right ankle ROM was higher for 20° as compared with 0° and 10° during ascent (Figure 6A). During descent, the level of incline significantly affected the hip, knee, and ankle ROM (Table 1). There were significant decreases in the hip ROM on the left and right side as level of incline increases and a significant increase in the ankle ROM on the left and right side as level of incline increases during descent (Figure 6B). Knee ROM was significantly lower at 0° as compared with 10° and 20° on the left and right sides during descent (Figure 6B). No significant interaction was found between incline level and boot style for lower limb ROM during ascent or descent.

Discussion

This study aimed to determine the effect of metatarsal protection and boot style on gait characteristics for level and inclined walking. Results indicated that boot style affected lower limb joint ROM when ascending and descending the walkway, regardless of incline level. Ankle ROM was the one variable affected by boot style during ascent. Ankle ROM was generally larger for the hiker-style boots (HS and HM) when compared with the wader-style boots (WS and WM), with significant changes between hiker versus wader rather than steel toe versus metatarsal. Within the hiker style, HS did have a marginally larger ROM compared with HM; however, these results were not statistically significant.

Boot style significantly changed hip, knee, and ankle ROM during descent. Hip ROM was significantly smaller for WS compared with HM. This trend only existed on the left side, which suggests that the results may be due to the small study sample size and not controlling for the leading leg. Knee ROM differed between both hiker-style boots and WS. WM had the smallest knee and ankle ROM of all boots. Again, the ankle ROM was significantly different from both hiker-style boots. These results suggest that changes in ROM may be due to shaft height or perhaps limited specifically by the WM boot tested. The smaller ROM in this style of boot could negatively affect other lower limb joints and lead to abnormal walking patterns. These changes due to boot style could lead to an increased risk of slip, trip, or fall on level or inclined walking.[18]

The effects of work boot style on gait parameters was the primary interest of this study. However, the effects of incline level were also significant. Stride length, velocity, and foot–floor angle decreased as the degree of incline increased when a participant ascended the walkway. During descent, stride length decreased as incline level increased. These results indicate that participants took the longest strides when walking on level ground and stride length did not depend on boot style. The slowest horizontal velocity of the foot occurred at 20° when ascending and descending. In addition, the center of gravity of the foot was closest to the walkway when ascending the 20° inclination. This decreased foot–floor angle could lower foot clearance and increase the risk of more severe slips, as cited in previous literature.[4] These changes in foot–floor angle are likely a result of the effects of incline level on lower limb ROM.

Level of walkway inclination affected hip and ankle ROMs during ascent and hip, knee, and ankle ROMs during descent. Hip and ankle ROM increased as the incline of the walkway increased. The largest hip and ankle ROMs occurred at 20° during ascent. During descent, hip ROM decreased with increasing incline levels, with largest hip ROM occurring during level walking. This angle was similar to the ROM of level walking during the ascent trial. Ankle ROM increased with higher inclines during descent, with the largest ROM at 20° incline for the walkway. Similarly, knee ROM increased at higher incline levels. These results suggest that higher levels of inclination may increase a worker’s risk of slips, trips, or falls which is consistent with previous research by Pollard et al.[22]

This study had a few limitations. The findings may be limited to the specific conditions and boots tested; however, conditions tested are those commonly encountered at mines.[22] The leading leg was not controlled for; however, data are reported for both sides with similar trends on the 2 sides. The sample size is small, but similar to other comparable research.[1,2,22] In addition, the effect size for significant conditions was high, indicating that the sample size was adequate to identify differences (Table 1). Finally, other factors such as comfort, muscle activity, or required coefficient of friction were not considered, which could be included in future work.

The goal of this research was to examine the effects of steel toe versus steel toe plus metatarsal protection on gait parameters during level and inclined walking. While inclined walking did alter many gait parameters, boot style was the primary focus of this study. The presence of metatarsal protection did not have any effects on the gait parameters. However, there were significant differences between the boot styles (ie, hiker vs wader). Boot style altered the ROM while ascending and descending a level and inclined walkway. Ankle ROM was smaller for the wader-style boots during ascent, suggesting that the shaft height or increased flexibility of the shaft may play a role in reducing ROM regardless of toe protection style. Similar trends were observed for descent; however, the WM boot had the smallest ROM. It is possible that this specific style of boot decreased ankle ROM when descending high inclinations, leading to abnormal gait patterns. These trends may only apply to the boots tested and may not be generalizable to all wader-style boots or hiker-style boots with metatarsal protection; for application in the mining industry, additional styles of boots should be tested. Ultimately, the wader-style boots tested during this study reduced lower limb joint ROM and could increase slip, trip, or fall risks for mine workers who frequently walk on inclined or unlevel surfaces.

Acknowledgments

The authors would like to thank Mary Ellen Nelson for constructing the experimental setup and operating the forklift during all data collections. Her contributions were integral to the completion of this work. The authors would also like to thank Dr Patrick Dempsey for his statistical support and manuscript reviews and NIOSH, Pittsburgh employees for volunteering their time and effort during data collections. The authors have no conflicts of interest to disclose.

References

1. Pollard JP, Merrill J, Nasarwanji MF. Metatarsal boot safety when ascending stairs. Paper presented at: IIE Annual Conference. Proceedings, Pittsburgh, PA; 2017.
2. Dobson JA, Riddiford-Harland DL, Bell AF, Steele JR. Work boot design affects the way workers walk: a systematic review of the literature. Appl Ergon. 2017;61:53–68. doi:10.1016/j.apergo.2017.01.003 [PubMed: 28237020]
3. Menant JC, Perry SD, Steele JR, Menz HB, Munro BJ, Lord SR. Effects of shoe characteristics on dynamic stability when walking on even and uneven surfaces in young and older people. Arch Phys Med Rehabil. 2008;89(10):1970–1976. doi:10.1016/j.apmr.2008.02.031 [PubMed: 18760402]
4. Moyer BE, Chambers AJ, Redfern MS, Cham R.Gait parameters as predictors of slip severity in younger and older adults. Ergonomics. 2006;49(4):329–343. doi:10.1080/00140130500478553 [PubMed: 16690563]
5. Nurse MA, Hulliger M, Wakeling JM, Nigg BM, Stefanyshyn DJ. Changing the texture of footwear can alter gait patterns. J Electromyogr Kinesiol. 2005;15(5):496–506. doi:10.1016/j.jelekin.2004.12.003 [PubMed: 15935961]
6. Wu G, Chiang JH. The significance of somatosensory stimulations to the human foot in the control of postural reflexes. Exp Brain Res. 1997;114(1):163–169. doi:10.1007/PL00005616 [PubMed: 9125462]
7. Robbins S, Waked E, Gouw GJ, McClaran J. Athletic footwear affects balance in men. Br J Sports Med. 1994;28(2):117–122. doi:10.1136/bjsm.28.2.117 [PubMed: 7921911]
8. Majumdar D, Banerjee PK, Majumdar D, Pal M, Kumar R, Selvamurthy W. Temporal spatial parameters of gait with barefoot, bathroom slippers and military boots. Indian J Physiol Pharmacol. 2006;50(1):33–40. [PubMed: 16850901]
9. Redfern MS, Cham R, Gielo-Perczak K, et al. Biomechanics of slips. Ergonomics. 2001;44(13):1138–1166. doi:10.1080/00140130110085547 [PubMed: 11794762]
10. Pollard J, Kosmoski C, Porter WL, Kocher L, Whitson A, Nasarwanji M. Operators' views of mobile equipment ingress and egress safety. Int J Ind Ergon. 2019;72:272–280. doi:10.1016/j.ergon.2019.06.003
11. Hamill J, Bensel CK. Biomechanical Analysis of Military Boots: Phase 2 Volume 2 Human User Testing of Military and Commercial Footwear. Technical Report, Natick, MA: U.S. Army Natick Research; 1996 Report No: NATICK-TR-96/011-VOL-1.
12. Park H, Kim S, Miles M, Bauer A, Stull J, Trejo H. Impact of firefighter gear on lower body range of motion. Int J Clothing Sci Technol. 2015;27(2):315–334. doi:10.1108/IJCST-01-2014-0011
13. Simeonov P, Hsiao H, Powers J, et al. Footwear effects on walking balance at elevation. Ergonomics. 2008;51(12):1885–1905. doi:10.1080/00140130802562625 [PubMed: 19034784]
14. Cikajlo I, Matjačić Z. The influence of boot stiffness on gait kinematics and kinetics during stance phase. Ergonomics. 2007; 50(12):2171–2182. doi:10.1080/00140130701582104 [PubMed: 17886013]
15. Böhm H, Hösl M. Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. J Biomech. 2010;43(13):2467–2472. doi:10.1016/j.jbiomech.2010.05.029 [PubMed: 20541206]
16. Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol. 1986;55(6):1369–1381. doi:10.1152/jn.1986.55.6.1369 [PubMed: 3734861]
17. Andriacchi TP, Andersson GB, Fermier RW, Stern D, Galante JO. A study of lower-limb mechanics during stair-climbing. J Bone Joint Surg Am. 1980;62(5):749–757. doi:10.2106/00004623-198062050-00008 [PubMed: 7391098]
18. Benson LC, Cobb SC, Hyngstrom AS, Keenan KG, Luo J, O'Connor KM. Identifying trippers and non-trippers based on knee kinematics during obstacle-free walking. Hum Mov Sci. 2018;62:58–66. doi:10.1016/j.humov.2018.09.009 [PubMed: 30245267]
19. Chiou SS, Turner N, Zwiener J, Weaver DL, Haskell WE. Effect of boot weight and sole flexibility on gait and physiological responses of firefighters in stepping over obstacles. Hum Factors. 2012; 54(3):373–386. doi:10.1177/0018720811433464 [PubMed: 22768640]

20. Garner JC, Wade C, Garten R, Chander H, Acevedo E. The influence of firefighter boot type on balance. Int J Ind Ergon. 2013;43(1):77–81. doi:10.1016/j.ergon.2012.11.002

21. Sinclair J, Taylor PJ. Influence of new military athletic footwear on the kinetics and kinematics of running in relation to army boots. J Strength Cond Res. 2014;28(10):2900–2908. doi:10.1519/JSC.0000000000000477 [PubMed: 24714532]

22. Pollard JP, Heberger JR, Dempsey PG. Slip potential for commonly used inclined grated metal walkways. IIE Trans Occup. 2015;3(2):115–126. [PubMed: 26779388]

23. C-Motion. Marker set guidelines. 2017 http://www.c-motion.com/v3dwiki/index.php?title=Marker_Set_Guidelines. Accessed July 3, 2018.

24. O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. Automatic detection of gait events using kinematic data. Gait Posture. 2007;25(3):469–474. doi:10.1016/j.gaitpost.2006.05.016 [PubMed: 16876414]

25. Vette AH, Watt JM, Lewicke J, et al. The utility of normative foot floor angle data in assessing toe-walking. Foot. 2018;37:65–70. doi:10.1016/j.foot.2018.07.003

Figure 1 —.
Four styles of work boots worn by participants during the study, including (left to right): Hiker style with metatarsal, hiker style with steel toe, wader style with metatarsal, and wader style with steel toe.

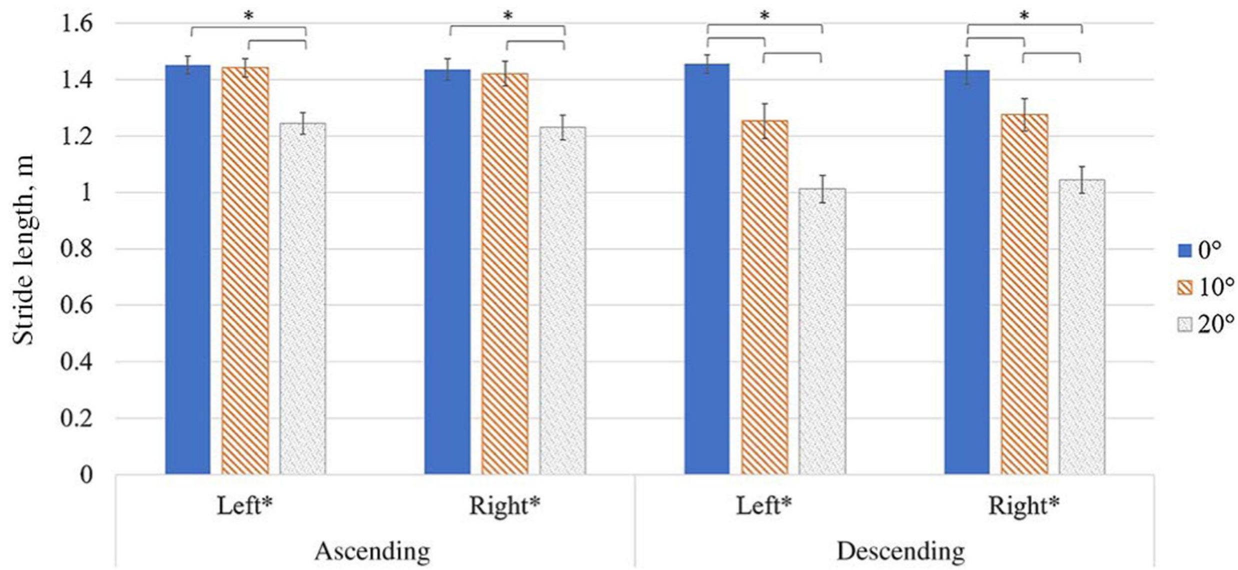

Figure 2 —.
Stride length by incline level and side when ascending and descending the walkway across boot styles. Error bars show SEs of the mean. *Significant main effects or post hoc comparisons.

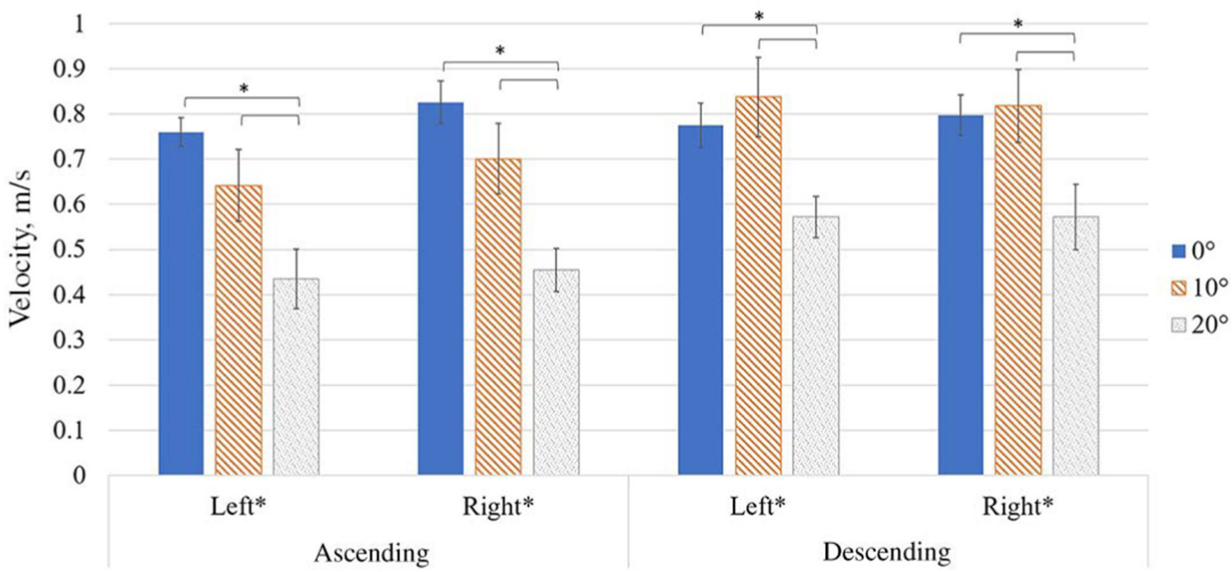

Figure 3 —.

Foot velocity by incline level and side when ascending and descending the walkway across boot styles. Error bars show SEs of the mean. *Significant main effects or post hoc comparisons.

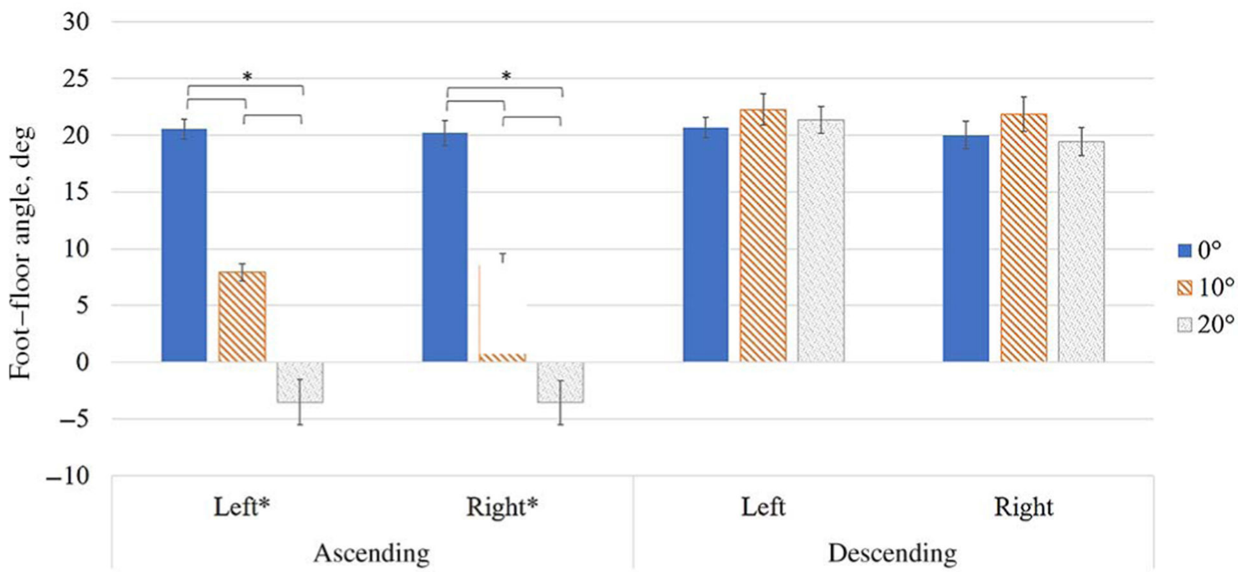

Figure 4 —.

Foot angle by incline level and side when ascending and descending the walkway across boot styles. Negative values indicate the toe contacted the walkway first. Error bars show SE of the mean. *Significant main effects or post hoc comparisons.

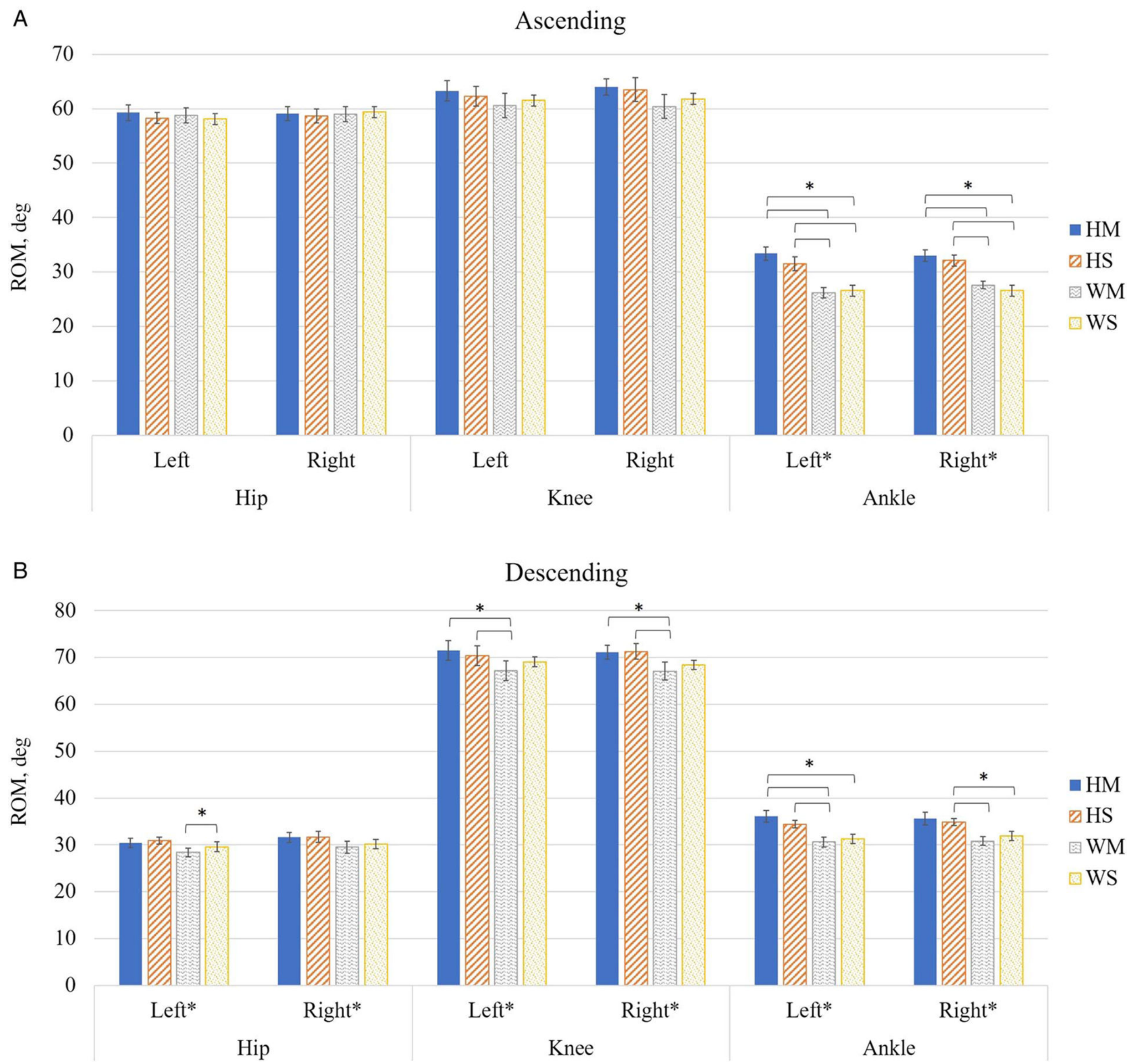

Figure 5 —.
Lower limb ROM by boot style and side when (A) ascending and (B) descending the walkway across incline level conditions. Error bars show SEs of the mean. HM indicates hiker style with metatarsal; HS, hiker style with steel toe; ROM, range of motion; WM, wader style with metatarsal; WS, wader style with steel toe. *Significant main effects or post hoc comparisons.

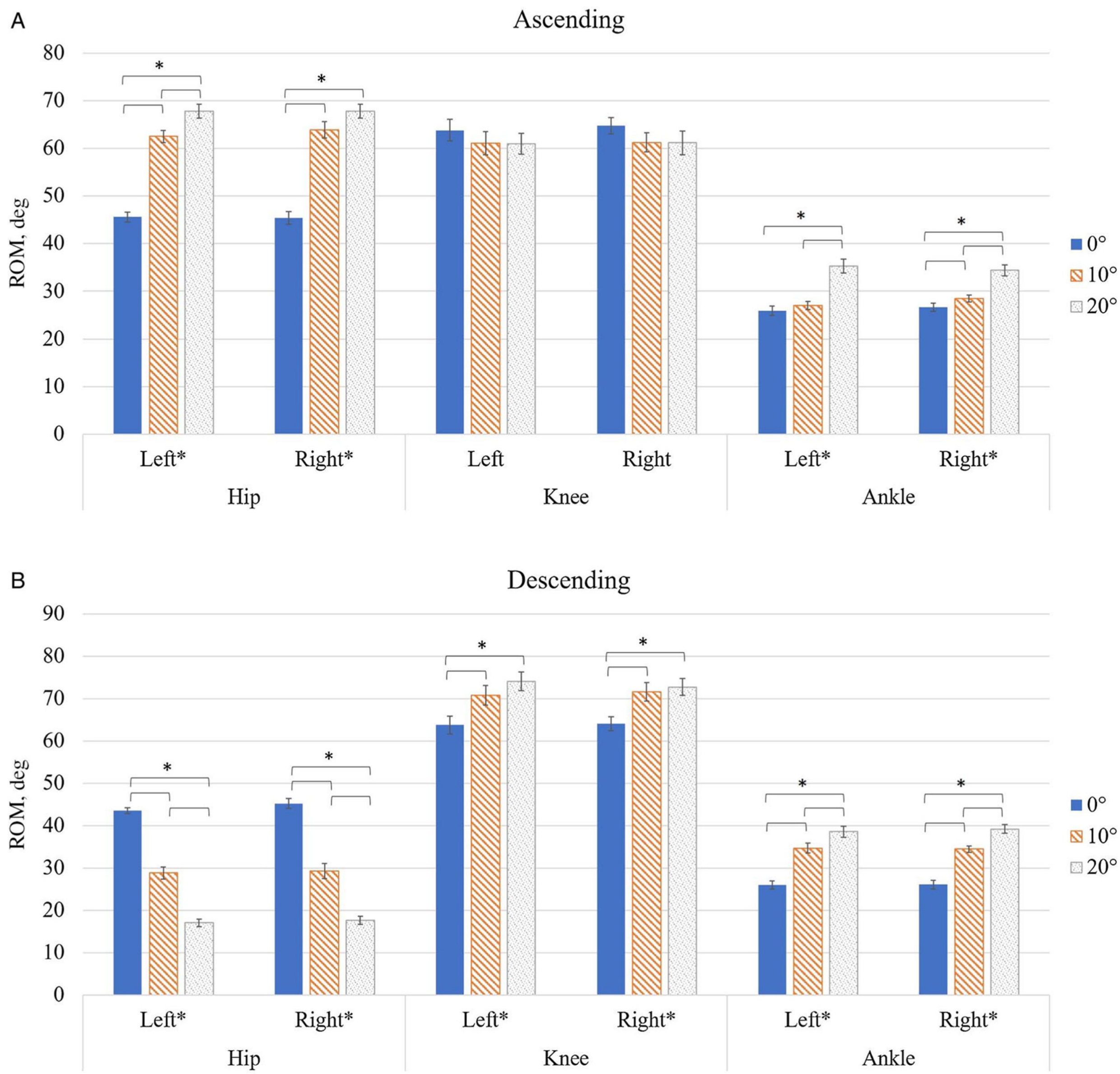

Figure 6 —.

Lower limb ROM by incline level and side when (A) ascending and (B) descending the walkway across boot styles. Error bars show SEs of the mean. ROM indicates range of motion. *Significant main effects or post hoc comparisons.

Table 1

Summary Statistics of Main Effects and Interactions on All Measured Variables

		Ascending						Descending					
		Left			Right			Left			Right		
Measured variable	**Tested condition**	***F***	***P***	**Effect size**	***F***	***P***	**Effect size**	***F***	***P***	**Effect size**	***F***	***P***	**Effect size**
Stride length	Boot style	0.939	.41	0.095	1.375	.27	0.132	2.603	.07	0.224	1.438	.25	0.138
	Incline level	**30.233**	**<.001**	**0.771**	**22.330**	**<.001**	**0.713**	**60.899**	**<.001**	**0.871**	**38.056**	**<.001**	**0.809**
	Level × style	**2.670**	**.02**	**0.229**	0.488	.82	0.051	0.706	.65	0.073	1.090	.38	0.108
Velocity	Boot style	0.849	.48	0.086	**3.461**	**.03**	**0.278**	0.674	.58	0.070	0.455	.72	0.048
	Incline level	**13.355**	**<.001**	**0.597**	**18.200**	**<.001**	**0.669**	**13.360**	**<.001**	**0.597**	**13.732**	**<.001**	**0.604**
	Level × style	1.283	.29	0.125	1.159	.34	0.114	0.632	.70	0.066	1.115	.36	0.110
Foot angle	Boot style	0.407	.62	0.043	0.864	.47	0.088	0.674	.58	0.070	0.686	.57	0.071
	Incline level	**76.516**	**<.001**	**0.895**	**73.826**	**<.001**	**0.891**	**0.882**	**.43**	**0.089**	1.329	.29	0.129
	Level × style	1.147	.35	0.113	1.727	.13	0.161	0.223	.97	0.024	0.571	.75	0.060
Hip ROM	Boot style	0.475	.70	0.050	0.109	.87	0.012	**5.360**	**.005**	**0.373**	**4.463**	**.01**	**0.331**
	Incline level	**182.688**	**<.001**	**0.953**	**110.561**	**<.001**	**0.925**	**334.713**	**<.001**	**0.974**	**332.432**	**<.001**	**0.974**
	Level × style	0.917	.49	0.092	1.461	.21	0.140	1.530	.19	0.145	0.357	.90	0.038
Knee ROM	Boot style	1.289	.30	0.125	2.727	.06	0.233	**9.978**	**.004**	**0.526**	**10.972**	**.005**	**0.549**
	Incline level	1.144	.34	0.113	2.956	.08	0.247	**31.401**	**<.001**	**0.777**	**26.105**	**<.001**	**0.744**
	Level × style	0.436	.71	0.046	2.147	.15	0.193	1.620	.16	0.153	1.956	.09	0.179
Ankle ROM	Boot style	**31.371**	**<.001**	**0.777**	**19.786**	**<.001**	**0.687**	**21.255**	**<.001**	**0.703**	**9.451**	**<.001**	**0.512**
	Incline level	**45.306**	**<.001**	**0.834**	**29.978**	**<.001**	**0.769**	**113.703**	**<.001**	**0.927**	**163.096**	**<.001**	**0.948**
	Level × style	2.036	.08	0.184	1.300	.27	0.126	0.996	.44	0.100	0.893	.44	0.090

Abbreviation: ROM = range of motion.

Note: Significance is reported at $P \leq .05$ and indicated by bold.