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1-1-2017

Work boot design affects the way workers walk: A systematic review of the literature

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Recommended Citation

Dobson, Jessica; Riddiford-Harland, Diane L.; Bell, Alison F.; and Steele, Julie R., "Work boot design affects the way workers walk: A systematic review of the literature" (2017). *Faculty of Science, Medicine and Health - Papers: part A*. 4601.

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Work boot design affects the way workers walk: A systematic review of the literature

Abstract

Safety boots are compulsory in many occupations to protect the feet of workers from undesirable external stimuli, particularly in harsh work environments. The unique environmental conditions and varying tasks performed in different occupations necessitate a variety of boot designs to match each worker's occupational safety and functional requirements. Unfortunately, safety boots are often designed more for occupational safety at the expense of functionality and comfort. In fact, there is a paucity of published research investigating the influence that specific variations in work boot design have on fundamental tasks common to many occupations, such as walking. This literature review aimed to collate and examine what is currently known about the influence of boot design on walking in order to identify gaps in the literature and develop evidence-based recommendations upon which to design future research studies investigating work boot design.

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Dobson, J. A., Riddiford-Harland, D. L., Bell, A. F. & Steele, J. R. (2017). Work boot design affects the way workers walk: A systematic review of the literature. *Applied Ergonomics: human factors in technology and society*, 61 53-68.

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Running Head: Work boots affect walking

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November, 2016

ABSTRACT

Safety boots are compulsory in many occupations to protect the feet of workers from undesirable external stimuli, particularly in harsh work environments. The unique environmental conditions and varying tasks performed in different occupations necessitate a variety of boot designs to match each worker's occupational safety and functional requirements. Unfortunately, safety boots are often designed more for occupational safety at the expense of functionality and comfort. In fact, there is a paucity of published research investigating the influence that specific variations in work boot design have on fundamental tasks common to many occupations, such as walking. This literature review aimed to collate and examine what is currently known about the influence of boot design on walking in order to identify gaps in the literature and develop evidence-based recommendations upon which to design future research studies investigating work boot design.

Keywords:

Work boot design, walking, gait, biomechanics

1. Introduction

Safety boots provide an interface between the foot and the ground, protecting the foot from undesirable external stimuli, particularly in harsh work environments. Occupational environments and the tasks performed by workers vary widely among different industries, necessitating a variety of work boot designs to match unique workplace safety requirements. There is a reoccurring issue, however, as occupational footwear appears to be designed more for occupational safety at the expense of functionality and comfort.

Standards exist specifying the design, construction and classification of safety boots (e.g. Australia/New Zealand Standard, 2010). The design features focus on reducing injuries to the feet resulting from contact with objects, objects piercing the sole or upper, friction or pressure blistering, hazardous material contact and slipping (Australia/New Zealand Standard, 2010). Hence, some of the primary design features that differ among work boot styles include the materials from which boots are made, the need for waterproofing, the height of the shaft, whether a steel safety cap and/or closures are required and the stiffness and design of the sole (see Figures 1 and 2). Even within a single occupation, such as the military, boots are often task and environment specific (e.g. a combat boot versus a jungle boot; Hamill and Bensel, 1996). Despite numerous design variations among work boots, there is a paucity of published research systematically investigating the influence these variations have on even fundamental tasks common to most occupations, such as walking.

<insert Figure 1 and Figure 2 about here>

Walking often constitutes a large component of the day-to-day activity in occupations that require safety work boots (Marr, 1999; Smith et al., 1999; Dobson et al., 2016). In such occupations it is imperative that an individual's work boots meet the demands placed on their lower limb while walking and when performing other working tasks. Otherwise, the risk of these workers incurring a lower limb injury is increased, whether it is an acute injury, such as

a sprain/strain due to slipping/tripping, or a chronic injury, such as overuse due to prolonged walking (Böhm and Hösl, 2010; Smith et al., 1999; Hamill and Bense, 1996; Marr, 1999; Marr and Quine, 1993). Lower limb injuries are prevalent in occupations that involve prolonged walking (WorkCover, 2010). In underground coal mining, an industry where workers spend an average of 8 hours walking per shift (Dobson et al., 2016), 700 serious lower limb injuries were reported annually. Of these serious lower limb injuries, ankle injuries alone contributed to a median workers compensation cost of \$5800 and 4.4 weeks off work (Personal communication, Safe Work Australia, 2016).

It has been postulated that abnormal loading of the lower limb at the shoe-to-surface interface while walking can partly contribute to this high incidence of lower limb injuries (Böhm and Hösl, 2010; Hamill and Bense, 1996). Boot design can alter the way the foot moves while walking, affecting the way the ground reaction forces are distributed throughout the lower limb (Redfern et al., 2001). If the lower limb is forced to move in a way that opposes its natural structural alignment, excess strain can be placed on the supporting anatomical structures, such as the ligaments, tendons and muscles, to maintain equilibrium (Böhm and Hösl, 2010; Hamill and Bense, 1996; Neely, 1998). For example, when normal ankle range of motion is restricted, the knee is forced to compensate for loads that the ankle is unable to absorb, increasing the risk of sustaining knee strain injuries (Böhm and Hösl, 2010). Indeed, decreased eccentric loading at the ankle joint but increased eccentric loading at the knee joint was displayed when 15 healthy young men (mean age = 29 ± 5 years) walked over a coarse gravel surface while wearing a hiking boot that restricted their ankle range of motion (Böhm and Hösl, 2010). Even with this increased lower limb injury risk associated with changes to joint motion and loading caused by footwear, very little systematic research has investigated the effects of work boot design on lower limb motion or loading during walking.

Traditionally, studies that examined the effects of work boot design during walking predominantly focused on the boot-surface frictional properties in an attempt to minimise slip-related injuries (Ramsay and Senneck, 1972). Slip-related injuries alone only account for approximately 14% of all labourer and related worker injury claims annually (WorkCover, 2010). It is therefore necessary to systematically investigate other aspects of boot design in order to determine how they affect the way workers walk in their occupational environment and, in turn, the risk of lower limb injuries that are not slip-related.

Interactions among the supporting surface, shoe and human body create a three-part system whereby changes in footwear can influence walking (Frederick, 1986). Substantial research exists documenting how different non-work related footwear types influence biomechanical variables that characterise walking, such as kinematics (joint ranges of motion, segmental alignment and temporal-spatial patterns), kinetics (ground reaction forces, joint moments and plantar pressure distributions) and electromyography (muscle activity patterns). For example, numerous studies have identified differences in variables characterising walking between shod and barefoot conditions (Bishop et al., 2006; Bonacci et al., 2013; Shakoor and Block, 2006), shoes of varying sole hardness/texture (Demura and Demura, 2012; Hardin et al., 2004; Kersting et al., 2005; Nigg et al., 2003; Nurse et al., 2005; Wakeling et al., 2002), differences between standard and athletic shoes (Bourgit et al., 2008; Kong et al., 2009; Lee et al., 2011) and unstable footwear (Myers et al., 2006; Nigg et al., 2006; Scott et al., 2012). However, research quantifying how work boot design influences walking biomechanics is much more sparse and lacking conclusive results. Hence, the purpose of this review article is to collate and examine the existing literature related to how boot design characteristics can influence walking. The results of this review will allow us to identify gaps in the literature and to provide evidence-based recommendations upon which to design future research studies investigating work boot design.

2. Literature Search Strategy

An initial search, limited to English and including all available years, was conducted in August 2016 using MEDLINE (1964+), Scopus (1960+) and Web of Science (1965+) to identify journal articles associated with the effects of boot design on biomechanical variables characterising walking (see Figure 3). Several searches were conducted combining the keyword 'boot' with the terms "walk*" AND "gait" AND "?motion", "kinematics" AND "kinetics", "electromyography" OR "EMG". Gait was selected as a search term as walking is a form of gait in which at least one foot remains in contact with the ground. Searches across the three databases returned 342 papers with 15 papers identified for review. Papers were only included in this review if they examined how boot design affected walking. Papers relating to rehabilitation boots (sometimes also referred to as walking boots) were excluded because these boots are designed specifically for recovery from injury or pathology rather than performing occupational tasks. Shoes and other footwear were not included unless they had design features similar to that of boots and/or were directly compared to boots. Additional relevant published papers were then obtained from the reference lists of the sources located in the databases. A total of 18 papers were suitable for review (see Table 3). Although these 18 papers were systematically reviewed, additional articles have been included to help explain and support information presented throughout the review.

<insert Figure 3 about here>

3. Quality Assessment

Methodological quality of the reviewed studies was assessed using the Quality Index (Downs et al., 1998) and performed by the primary author (see Table 1). The Quality Index is a reliable and validated checklist designed to evaluate randomised and non-randomised studies of health care interventions (Downs et al., 1998). The Quality Index was previously used in a review of the effect of children's shoes on gait because it was considered appropriate in

rigour with shoes treated as a 'health intervention' (Wegener et al., 2011). To determine the index, a potential overall score of 32 is calculated across 27 items organised into five subscales. Ten items assess study reporting (including reporting of study objectives, outcomes, participants characteristics, interventions, confounders, findings, adverse events and probability); three items assess external validity (the ability to generalise the results); seven items assess internal validity - selection bias (bias in the measurement of the intervention); six items assess internal validity - confounding (bias in the selection of study participants); and one item assesses study power (whether negative findings from a study could be due to chance; Wegener et al., 2011). The papers in the current study scored an average of 21 out of 32 where blinding of experimental conditions and participant/task selection caused a consistent loss in points (see Table 1).

<insert Table 1 about here>

4. Boot Design and Walking

The 18 studies investigating the effect of boot design on walking focused on comparing different boots relative to one another and other types of footwear rather than systematically comparing boot design features in isolation relative to a standard boot (see Table 2). The study by Majumdar et al. (2006) exemplifies the difficulties created in terms of understanding the influence of boot design on lower limb motion during walking. The gait of eight healthy infantry soldiers (26.7 ± 2.7 years of age; 59.3 ± 5.1 kg mass; 164.8 ± 4.4 cm height) was analysed when the study participants walked barefoot, while wearing bathroom slippers and while wearing military boots (see Figure 4). Although significant between-condition differences were found in the temporal-spatial variables characterising walking, the footwear conditions were too different to provide meaningful insight into the influence the military boot design had on walking. Despite this limitation, the reviewed studies highlight some key features of boot design that appear to influence walking and therefore warrant further

consideration. These key boot design features (shaft height, shaft stiffness, boot mass and sole flexibility) and how they appear to influence variables of gait, are summarised below.

<insert Table 2 about here>

4.1 *Shaft Height*

A defining feature of work boot design is the height of the boot shaft (see Figure 1). The main purpose of a high shaft is to provide protection to a large area of the shank. In an occupation such as underground coal mining, a high boot shaft is mandatory as miners work in an environment where mud and moveable rocks are likely to contact the leg below the knee if there is no protective cover (personal communications with industry).

4.1.1 *Shaft height can influence the risk of instability and falls*

Studies directly examining the effect of variations in shaft height on walking are limited. One of the few studies in this field revealed shaft height could influence an individual's foot and ankle range of motion thereby altering lower limb mobility while walking. Walking in pull-up bunker firefighting boots (see Figure 4), compared to low-cut running shoes, significantly reduced ball of foot flexion-extension and ankle plantar flexion-dorsiflexion range of motion (in both directions) in the sagittal plane (8 male and 4 female firefighters; Park et al., 2015). Ball of foot and ankle range of motion are vital during walking as these movements facilitate push-off for pre-swing, clearing the ground during mid-swing and absorption of the ground reaction force during initial contact (Whittle, 2007). Limited range of motion during these phases could lead to an abnormal walking pattern where stumbling and falling are likely to occur, particularly on uneven surfaces typically seen in occupations where high shafted work boots are mandatory (Park et al., 2015). Conversely, the higher shafted firefighting boot led to increased ball of foot abduction-adduction and ankle inversion-eversion range of motion in the frontal plane compared to when the participants wore the running shoe (Park et al., 2015). Increased motion in these directions is associated

with a higher risk of lateral ankle sprains, particularly during initial contact on uneven surfaces (Park et al., 2015; Wright et al., 2000). The different result in foot and ankle range of motion in the sagittal plane compared to the frontal plane is most likely explained by the design of the firefighting boot. Due to barriers required for thermal protection and the puncture and collision protection of a metal shank, the firefighting boot shaft is relatively inflexible (Park et al., 2015). The inflexible boot shaft could hinder range of motion in the sagittal plane, whereas the slip-on nature of the firefighting boot could lead to less ankle support than the lace-up running shoes in the frontal plane, hence explaining the increased range of motion (Park et al., 2015). Unfortunately, due to equipment error, the authors discarded the condition involving the higher shafted but laced leather boot, leaving this theory as speculation. Nevertheless, changes in ball of foot and ankle range of motion imply boot shaft height can alter normal foot motion, leading to adjustments in walking and an increased risk of instability and falls.

4.1.2 The influence of shaft height on ankle stability and foot mobility is context specific

Lateral balance, a key factor contributing to falls risk in construction workers also appears to be influenced by boot shaft height (Simeonov et al., 2008). The main mechanism for this association is thought to be via changes in foot motion because altering medio-lateral foot placement is the most effective strategy to control lateral stability while walking (Simeonov et al., 2008). Boots with a higher shaft, compared to boots with a lower shaft (see Figure 4), significantly decreased trunk accelerations and rearfoot angular velocities and increased perceptions of stability when 24 male construction workers (39 years of age; 86.4 ± 12.6 kg mass; 178.3 ± 6.9 cm height) walked on a narrow plank under virtual reality conditions that recreated a construction site (Simeonov et al., 2008). It was assumed the higher boot shaft reduced the need for large corrective trunk and foot adjustments by providing more timely and accurate proprioceptive information about ankle joint motion and body orientation

(Simeonov et al., 2008). This proprioceptive information assisted individuals to maintain stability by helping to keep their centre of gravity well within the limits of their base of support (Simeonov et al., 2008). Indeed, introducing a boot with a higher shaft, compared to a boot with a lower shaft, reduced the amount of ankle injuries incurred by Royal Marine recruits (8,329 attendees to the Commando Training Centre Royal Marines sickbay), further supporting the notion of boot shaft height influencing ankle stability (Riddell, 1990).

The influence of boot shaft height on ankle stability, however, appears to be context specific. For example, elevating and tilting the narrow plank, in the study by Simeonov et al. (2008) described above, increased the participants' rearfoot angular velocities, which were unexpectedly more pronounced while participants wore boots with a higher shaft compared to boots with a lower shaft height (Simeonov et al., 2008). The authors speculated this unexpected result was caused by an interaction of the higher boot shaft with the ankle joint when the plank was tilted, resulting in additional moments and lateral forces being generated, leading to instability. It was suggested that a higher boot shaft with more flexibility might dampen the generation of additional moments and lateral forces so when a boot shaft is tilted at an angle, i.e. when walking on a sloped surface, it would not have such a direct impact on ankle joint motion (Simeonov et al., 2008). Indeed, military and work boots with a higher boot shaft, compared to footwear with a low shaft, have been shown to limit ankle dorsiflexion, restricting ankle range of motion and, in turn, leading to slower times when study participants completed an agility course (Hamill and Bensele, 1996). Restricted ankle motion was thought to influence shank movement, therefore leading to slower performance times when participants planted their foot to change direction (Hamill and Bensele, 1996).

Although Simeonov et al. (2008) used a robust study design, study participants were required to wear footwear typically worn in the construction industry while walking on an elevated, narrow plank tilted to 14°. Comparing results from this study to those obtained

while participants walk on other occupation-specific surfaces would not be ecologically valid, particularly considering the significant differences between the footwear conditions relating to shaft height only depended on the angle of plank tilt. The results are also different to standing balance trials where boot shaft height (40 cm, 29 cm and 17 cm) had no significant main effect on stability (Yang et al., 2015), further highlighting context specificity. Moreover, the test footwear used by Simeonov et al. (2008) also had multiple design variations; the average mass of the low shaft and high shaft footwear conditions differed by approximately 270 g. As discussed in Section 4.3, boot mass appears to have an overriding effect on variables characterising walking and, therefore, it should not be concluded that changes in shaft height were solely responsible for the observed differences in stability. The addition of electromyographic data and more detailed kinematic and kinetic data would support or refute the author's claim that changes in proprioception associated with differences in boot shaft height caused the changes in lower limb biomechanics influencing stability when walking (Simeonov et al., 2008).

Evidence is available that implicates boot shaft height influences foot mobility, and consequently stability, when individuals walk. Again, differences in boot design features other than shaft height were present and only limited biomechanical variables characterising walking were collected (see Table 2). For example, when 30 young participants (15 men; 25.5 ± 5.6 years of age; 77.8 ± 13.7 kg mass; 1.78 ± 0.06 m height and 15 women; 22.5 ± 1.6 years of age; 64.4 ± 4.1 kg mass; 1.63 ± 0.08 m height) marched and ran in several different types of work and leisure boots with varying shaft heights, footwear had a significant effect on the mobility of their feet (see Figure 4; Hamill and Benseal, 1996). When the participants wore a Nike cross trainer boot or a Reebok Pump boot they displayed significantly greater movement of their centre of pressure than when they wore other boot types (combat military boot, jungle military boot and Red Wing work boot). In terms of design differences, the Nike

(12.1 cm high shaft) and Reebok boots (15.4 cm high shaft) had much shorter shafts compared to the other boots (~10 cm less shaft height than the 26 cm combat military boot shaft). The authors speculated the shorter shaft height enabled the ankle to move more freely, in turn allowing a greater centre of pressure excursion (Hamill and Benseal, 1996). Unfortunately, the authors of the study (Hamill and Benseal, 1996) did not specify in which direction the observed centre of pressure movements occurred and, without other measures characterising walking, it is unknown whether movement of the foot was due to increased ankle range of motion or, instead, some other factor.

More detailed analyses of centre of pressure excursions in other research has revealed that occupational footwear with a low shaft led to significantly increased postural sway in the anterior-posterior and medial-lateral directions when compared to two high shafted boots worn by 14 healthy adult males (23.6 ± 1.2 years of age; 89.2 ± 14.6 kg, 181 ± 5.3 cm; Chander et al., 2014). Regrettably, in addition to variations in shaft height, the high shafted boots (18.5 cm shaft; 0.9 kg mass) weighed double that of the low shafted shoes (9.5 cm shaft; 0.4 kg mass), again confounding any effect of shaft height. Furthermore, the experimental protocol comprised a standing balance test and it is unknown whether the same results would be replicated during a dynamic task such as walking. Nevertheless, excessive medio-lateral displacement of the centre of pressure can reflect lateral instability, which has been significantly related to lateral falls in construction workers (Simeonov et al., 2008). Movement of the centre of pressure in the forefoot from lateral to medial during initial contact has also been correlated with exercise-related lower limb pain (Willems et al., 2006). Therefore, future research investigating the effects of variations in shaft height on centre of pressure excursion while individuals walk is warranted.

4.1.3 Higher boot shafts can increase plantar pressures: Implications for stress fractures

In addition to centre of pressure excursions, boot shaft height is thought to also influence peak plantar pressures generated during walking. Wearing combat assault boots (see Figure 4) led to significantly higher peak pressures (kPa) being generated under metatarsals 2-5 and higher peak loading rates (kPa ms^{-1}) under all metatarsal heads compared to wearing a gym trainer while running (seven injury-free physically active males; 18.3 ± 0.4 years of age; 81.1 ± 8.2 kg mass). The plantar pressure changes were attributed to a significant reduction and earlier occurrence of ankle dorsiflexion and greater ankle joint stiffness during stance due to the combat assault boots support above the ankle, compared to the gym trainer (Nunns et al., 2012). These increased plantar pressures during walking are a risk factor for metatarsal stress fractures, particularly when covering long distances on foot in occupations such as the military (Nunns et al., 2012). However, the test footwear also differed in mass and midsole hardness, with the combat assault boot weighing three times that of the gym trainer and having almost double the midsole hardness (Nunns et al., 2012). Although boot shaft height has been implicated in the occurrence of metatarsal stress fractures, further research is required to confirm the role of variations in shaft height in the development of these injuries and whether alterations in ankle stiffness associated with higher boot shafts is a contributing factor.

4.1.4 Shaft height future research recommendations

Overall, boot shaft height appears to significantly influence ankle range of motion and, in turn, postural sway and plantar pressure variables while walking. Based on the current literature, however, exactly how shaft height affects these and other variables characterising walking is not known. Previous studies have used experimental footwear that simultaneously altered shaft height in combination with confounding boot design features, such as shaft stiffness, boot mass and sole flexibility, rather than modifying shaft height in isolation.

Interestingly, the influence of shaft height varies depending on the surface and task performed but a lack of comprehensive biomechanical data characterising the effects of shaft height on walking leaves many questions unanswered. Future studies need to systematically alter boot shaft height in isolation with all other boot design features kept consistent. Particular attention needs to be paid to keeping boot mass constant when changing shaft height because the reviewed studies highlighted it is difficult to find boots with different shaft heights that have the same mass. Comprehensive biomechanical data then needs to be collected while individuals perform a variety of work specific tasks on relevant surfaces to better understand the sensitivity of lower limb function to changing boot shaft height while walking. Investigating the interaction of boot shaft height with the other boot design features, especially shaft stiffness, also warrants future investigation.

<insert Figure 4 about here>

4.2 *Shaft Stiffness*

In addition to protecting the shank, a boot shaft should provide sufficient stiffness to support the ankle and, in particular, restrict excessive ankle joint inversion (Böhm and Hösl, 2010; Cikajlo and Matjajić, 2007). Enclosing the ankle and shank with a stiffer boot shaft can create a protective effect in the lateral direction, which minimises lateral ligament ankle sprains, the most common injury associated with walking (Blake and Ferguson, 1993; Böhm and Hösl, 2010). Boot shaft stiffness is determined by the material a boot is made out of (i.e. rubber is more flexible (less stiff) than leather), the amount of reinforcing built into the shaft, the addition of a thick liner and the shaft height (see Figure 1). Load-deformation curves obtained with equipment such as strain gauges (Arndt et al., 2003), robot manipulators (Cikajlo and Matjajić, 2007) and load cells (Böhm and Hösl, 2010) are used to quantify boot shaft stiffness.

4.2.1 Shaft flexibility affects ankle range of motion

Manipulation of shaft stiffness in hiking boots (Böhm and Hösl, 2010; Cikajlo and Matjacić, 2007), military boots (Hamill and Bense, 1996) and basketball boots (Robinson et al., 1986) has been found to significantly alter ankle range of motion. A more flexible shaft increased ankle range of motion during walking and a stiffer shaft reduced it. The amount of ankle range of motion allowed by a boot shaft appears crucial to both efficient biomechanics, as well as reducing lower limb injury occurrence. Although adequate ankle range of motion is vital to efficient gait, excessive ankle motion is potentially problematic because it causes the joint to rely on secondary anatomical structures, such as the muscles and ligaments, for support (Böhm and Hösl, 2010; Hamill and Bense, 1996), increasing the risk of lower limb sprain/strain injuries (Neely, 1998).

4.2.2 Restrictions in ankle range of motion can negatively affect the knee

There is relatively strong evidence suggesting that restricted ankle joint motion during walking can have negative implications for the more proximal joints of the lower limb, such as the knee. For example, a lace-up hiking boot (see Figure 4), with 50% less passive shaft stiffness, decreased eccentric energy absorption at the ankle joint when healthy male participants (29 ± 5 years of age; 77 ± 8 kg mass; 177 ± 5 cm height) walked on a simulated gravel surface (Böhm and Hösl, 2010). Eccentric energy absorption at the knee and co-contraction of the vastus lateralis and semitendinosus muscles were simultaneously increased, indicating the ankle joint's ability to absorb the ground reaction force was impaired and the knee joint had to compensate via increased contraction of the primary muscles supporting the joint (Böhm and Hösl, 2010). Interestingly, despite a large difference in shaft stiffness between the two hiking boots, the between-condition difference in ankle range of motion was only 1.4° . It is therefore questionable whether the subtle difference in ankle motion caused the change in vastus lateralis and semitendinosus activity. Alternatively, the participants

could be reacting to differences in how the boot shaft felt when pressing against their shank. Increased proprioception acuity and trends towards more active ankle stiffness have resulted when circumferential ankle pressure was applied to the ankle, although this was applied using a blood pressure cuff and it is unknown whether a boot shaft would yield the same result (You et al., 2004). Dobson et al. (2015) reported similar increases in quadriceps and hamstring muscle activity when participants wore a leather lace-up work boot with a stiff shaft compared to a gumboot (flexible shaft; see Figure 4). Joint moments and ankle muscle activity were not recorded in this study preventing a direct comparison with the results reported by Böhm and Hösl (2010).

Although boot shaft stiffness appears to play a role in regulating the amount of muscle activation required to stabilise a joint, the influence of changes in proprioception caused by variations in boot shaft stiffness is less clear (Müller et al., 2012; Noé et al., 2009). Research consistently shows that when the demand placed on the lower limb is increased, muscle activity increased (Blackburn et al., 2003; Greensword et al., 2012; Mika et al., 2012; Nigg et al., 2006; Romkes et al., 2006). Similarly, when the demand placed on the lower limb is reduced, perhaps as a result of increased mechanical support provided by a boot, muscle activity is likely to decrease.

In contrast, Dobson (2013) found that when participants wore leather lace-up coal mining work boots (see Figure 4) that provided more stability and ankle support, relative to gumboots, they displayed increased activity of the muscles that cross the knee joint. The most likely reason for these contradictory results is the overriding influence of boot mass on lower limb motion (discussed below) irrespective of changes in boot support (Chiou et al., 2012). It was also postulated that regardless of stability, a stiffer boot shaft has more of an influence when walking on surfaces that require additional muscular activity and joint motion

to adapt the foot to an uneven surface, such as an inclines and declines, compared to walking on level surfaces (Dobson, 2013).

4.2.3 How altered ankle range of motion affects hip biomechanics is unknown

Restricting ankle joint motion is also thought to affect the hip by causing individuals to rely on hip motion changes to maintain balance (Horak and Nashner, 1986). Boots that restricted ankle range of motion led to increased hip range of motion when participants walked through an 8 cm deep pit of gravel (Bohm and Hosl, 2010). This increase in hip range of motion, however, was not statistically significant and several other studies have reported no change in hip range of motion in response to changing footwear design (Cikajlo and Matjacić, 2007; Hamill and Bense, 1996; Nigg et al., 2006). These previous studies involved participants traversing either level walkways or artificial gravel surfaces so it is unknown whether the resulting perturbations were large enough to require a full postural control strategy in response to subtle changes in work boot design (Horak and Nashner, 1986; Dobson et al. 2013). However, when participants walked on sloped, uneven surfaces wearing two underground coal mining work boots with different shaft stiffness, no significant difference in hip range of motion was evident (Dobson et al., 2015). This latter study, however, did not report the difference in shaft stiffness between the two boot conditions and the measurement of hip range of motion was restricted to a simplistic two-dimensional method. It therefore remains unknown whether differences in boot shaft stiffness were insufficient to illicit changes in hip range of motion while walking or, conversely, whether a two-dimensional model was not sensitive enough to detect any changes between the two footwear conditions.

4.2.4 Increased shaft flexibility can increase power generation at the ankle joint

A military boot (see Figure 4) with a softer, more flexible shaft that allowed more ankle range of motion was shown to increase power generation during push-off at the ankle joint by 33% compared to when participants wore a military boot with a stiffer shaft (Cikajlo and

Matjacić, 2007). The increase in power generation promoted a more efficient gait, evident by an increase in step length and gait velocity when nine men (24.7 ± 2.1 years of age; 73.9 ± 4.1 kg mass; 178.6 ± 5.7 cm height) walked along a 7 m runway (Cikajlo and Matjacić, 2007). Sufficient power generation at the ankle is necessary to attain adequate walking velocity and, therefore, is important to achieve efficient forward motion during walking (Requião et al., 2005). Previous studies have shown that changes in ankle range of motion can alter muscle activity and possibly power generation, particularly at more proximal lower limb joints such as the knee (Böhm and Hösl, 2010; Dobson et al., 2015). Cikajlo and Matjacić (2007) did not report using electromyography to quantify muscle activity during their study. Therefore, whether more muscle activity was required at the ankle to produce this increase in power generation or, alternatively, whether the more flexible boot shaft allowed more efficient use of the stretch shortening cycle is unknown. Although Cikajlo and Matjacić (2007) confirmed that boot shaft stiffness influenced ankle range of motion and consequently kinematic and kinetic variables characterising walking, optimal boot shaft stiffness cannot be derived from this study. The differences in shaft stiffness between the two test military boots were not uniform across all conditions with one boot type displaying 64% lower stiffness, relative to the second boot type, when the participants walked down a low incline (Cikajlo and Matjacić, 2007). When the inclination was increased to 15°, however, the second boot type showed increased shaft stiffness compared to the first boot type (Cikajlo and Matjacić, 2007), again highlighting the complex interaction among footwear type, surface characteristics and walking biomechanics.

4.2.5 Shaft stiffness future research recommendations

Given the lack of studies pertaining to controlled variations in boot shaft stiffness and the potential for shaft stiffness to decrease over time with wear, further research that alters this parameter in a systematic manner and examines effects of these variations on variables that

characterise walking is required. These future studies should systematically alter shaft stiffness in a standard boot, holding all other boot design parameters consistent to ensure the specific effects of shaft stiffness on walking can be identified. Testing of the boot shafts would also have to be repeated throughout testing to ensure that shaft stiffness is not reduced over time due to wear and, in turn, confound the results. Shaft stiffness should be varied over a large range to determine how sensitive changes in lower limb motion and muscle activity are to alterations in shaft stiffness and how both proximal and distal joints of the lower limb are affected. Collecting ankle range of motion inside the boot combined with questionnaires pertaining to participants' perceptions of tightness of boot shaft fit and proprioceptive measures, would help determine the extent to which changes in ankle range of motion and/or proprioception influence biomechanical parameters characterising walking. Boot designers should also quantify the amount of ankle range of motion required for individuals to efficiently perform specific work tasks (on surfaces encountered in the work environment) and whether work boot shaft stiffness can be optimised to enhance ankle joint efficiency and reduce the incidence of lower limb injuries incurred by workers.

4.3 Boot Mass

Boot mass is the most variable element of work boot design and can typically range between 1 and 4 kg (Chiou et al., 2012; Dobson et al., 2015; Garner et al., 2013; Nunns et al., 2012). The mass of a work boot is dependent on a multitude of design features such as the boot material, presence of a steel cap, height of the shaft, type of sole and other boot design features illustrated in Figure 1. Changing just one of these design features, even slightly, can have a substantial impact on boot mass, explaining the high variability in this design parameter.

Similar to previous studies investigating shaft height and shaft stiffness, research investigating the effects of boot mass on walking typically include footwear in which boot

design features other than boot mass have differed between the test boot conditions (see Table 2). For example, 37 soldiers (1 women; 29 years of age; 81.5 kg mass, 177.8 cm height) displayed increased tibialis anterior muscle activity when they walked on a treadmill wearing the heaviest footwear condition, a combat boot (see Figure 4) that was almost double the mass of all other test footwear (Shulze, 2011). The muscle activity values, however, were similar to those recorded when the participants walked wearing a dress shoe and two different types of athletic footwear. Although the four test footwear differed substantially in mass, shaft height and sole flexibility also varied among the footwear, again making it difficult to attribute the observed increase in tibialis anterior activity to one specific design feature such as increased boot mass. Furthermore, Schulze et al. (2011) did not collect kinematic or kinetic data to help explain their electromyography data and so whether the increased lower limb muscle activity displayed when wearing the heavier boot was due to differences in shank and/or foot motion or increased effort required to move the heavier boot is not known.

4.3.1 Heavier boots increase heel contact velocity and oxygen consumption while decreasing trailing limb toe clearance

Nevertheless, heavier footwear has been shown to alter the way individuals walk, particularly kinematic parameters characterising walking and oxygen consumption (Jones et al., 1984; Majumdar et al., 2006). Increased heel contact velocities and reduced trailing limb toe clearances were found when 14 healthy male (28.4 ± 5.5 years of age; 94.6 ± 15.6 kg mass; 178.5 ± 5.8 cm height) and 13 healthy female (33.2 ± 4.4 years of age; 67.9 ± 8.0 kg mass; 166.6 ± 5.0 cm height) firefighters stepped over obstacles wearing heavier (3.98 kg) compared to lighter (2.93 kg) firefighter boots (see Figure 4; Chiou et al., 2012). Measures of metabolic and respiratory cost (minute ventilation, absolute and relative oxygen consumption and carbon dioxide production) were also increased in this study when participants wore the heavier boots compared to the lighter boots (Chiou et al., 2012). Increases in boot mass

therefore appeared to cause a loss of control at initial contact and mid-swing, as well as requiring more energy to move the heavier boot (Chiou et al., 2012). These results are concerning because slips are more likely to occur at initial contact when foot placement is not controlled (Tang et al., 1998) and trips occur when the foot contacts an object mid swing (Austin et al., 1999). Combined with the increased energy cost and possible associated fatigue (Garner et al., 2013), heavier work boots could be a serious trip/slip hazard in occupations that require prolonged walking on uneven surfaces.

4.3.2 Heavier boots require increased muscle activity

An increase in lower limb muscle activity appears to be a mechanism by which the slip/trip risk in heavier boots can be compensated for while walking. Increased vastus lateralis and biceps femoris muscle activity during initial contact and pre-swing, respectively, occurred when participants (20 males; 33 ± 12 years of age) walked in heavier leather lace-up boots (mass = 3.1 kg) compared to lighter gumboots (mass = 2.7 kg; see Figure 4) on uneven surfaces (Dobson et al., 2015). Considering the stance and swing timing was the same regardless of which boot was worn, the increased muscle activity at initial contact and pre-swing can be seen as a slip and trip prevention strategy by ensuring the heavier boot was adequately decelerated at initial contact, preventing a slip and the foot cleared the ground during pre-swing, preventing a trip (Dobson et al., 2015). Walking on a treadmill in a heavier combat boot (1 kg) also led to increased vastus medialis muscle activity over a 30 min time period when compared to a rain boot (0.80 kg) and Converse sneaker (0.71 kg; see Figure 4; Kim et al., 2015). In agreement with Dobson et al. (2015), the authors (Kim et al., 2015) speculated this increased vastus medialis activity occurred to allow a normal walking pattern to continue despite now having to account for more mass distally. However, with only root mean square electromyography data reported and no breakdown of the phases of walking this concept requires further investigation before it can be confirmed or refuted.

Electromyographic data are also needed to further investigate why wearing a heavier firefighter boot increased heel contact velocities and decreased trailing limb toe clearance (Chiou et al., 2012), because this result is in direct contrast to the findings of Dobson et al. (2015) and Kim et al. (2015). It is possible the firefighter boot was too heavy and the participants were not able to generate enough muscle activity to control their lower limbs, particularly considering the heaviest firefighting boot was 880 g heavier than the leather lace-up boot used in Dobson et al.'s (2015) study and almost 3 kg heavier than the combat boot used in Kim et al.'s (2015) study. It is also possible that these between study differences in results were due to different experimental protocols, whereby participants in the Chiou et al. (2012) study stepped over obstacles whereas participants in the other two studies were simply walking. Future research studies combining kinematic and electromyographic data are required to establish whether heavier work boots are a risk factor for slipping and/or tripping when walking, particularly in occupations that require workers to step over objects. A recommended maximum boot mass, after which injury risk is too high due to compromised walking technique, would be important information boot manufacturers could use when designing work boots.

4.3.3 Increased boot mass can increase muscle fatigue

Energy expenditure while walking can increase by 0.7-1% for every 100 g increase in footwear mass (Jones et al., 1984). Increased muscle activity can be an indicator of muscular fatigue, but is not the most reliable method. Peak torque on the other hand is a more reliable measure of localised fatigue at an associated joint and is therefore a useful variable to confirm whether increased muscle activity associated with heavier footwear does in fact lead to fatigue (Garner et al., 2013). Significant decreases in peak torque at the ankle and knee, as measured by an isometric seated strength test, were found when 12 professional male firefighters (33.4 ± 6.8 years of age) performed a simulated firefighter stair climb test while

wearing heavier rubber boots (2.93 ± 0.24 kg) compared to lighter leather boots (2.44 ± 0.21 kg). This reduction in peak torque coincided with significant performance reductions in static postural sway tasks, revealing a negative implication associated with the reported muscular fatigue (Garner et al., 2013). The authors of the study noted the mass of the rubber boots (see Figure 4) was 500 g greater than the leather boots, providing the most likely reason for the observed results. Increased postural sway is a leading cause of falls (Lord et al., 2003), thereby implicating greater boot mass as a potential cause of the high incidence of fall-related injuries reported in labouring occupations.

Although boot mass differences are the most likely explanation for the reduced performances in postural sway reported by Garner et al. (2013), other boot design features such as differences in boot materials cannot be discounted as potential contributing factors. As discussed in previous sections of this paper, a rubber boot has a more flexible shaft than a leather boot. This between-boot difference in shaft stiffness can influence ankle motion and/or proprioception at the ankle joint and, in turn, influence lower limb mediated responses to postural sway. Furthermore, boot effects associated with static postural sway tasks and isometric seated strength tests are not directly applicable to a dynamic task such as walking.

4.3.4 Boot mass future research recommendations

Although research related to boot mass predominantly focuses on negative implications associated with heavier work boots, no study has investigated whether a work boot could be too light. Future studies need to alter boot mass in a systematic manner, while ensuring other boot design features such as shaft stiffness and sole flexibility do not confound the changes in mass. Identifying a range of boot mass that minimises worker fatigue while reducing the risk of fall-related injuries could guide boot designers when selecting new materials from which to manufacture work boots.

4.4 *Sole Flexibility*

Sole flexibility is the ability of the sole of a shoe to flex. The amount of flexibility in a work boot sole is primarily determined by the materials used to construct the layers of the sole, which will also determine its thickness, elasticity, texture and padding (Nigg et al., 2003; Nurse et al., 2005). An abundance of literature has documented the influence of variations in shoe sole flexibility on variables characterising gait (Demura and Demura, 2012; Hardin et al., 2004; Kersting et al., 2005; Nigg et al., 2003; Nurse et al., 2005; Wakeling et al., 2002) and oxygen consumption (Roy and Stefanyshyn, 2006). Literature pertaining to work boot sole flexibility, on the other hand, is sparse and lacking conclusive results due to confounding boot design differences.

Firefighting boots with a more flexible sole (stiffness index ≤ 15) have been associated with greater trailing limb toe clearances when firefighters stepped over obstacles compared to when they wore boots with a stiffer sole (stiffness index > 15 ; Chiou et al., 2012). This difference was not statistically significant but boot mass and sole flexibility were simultaneously altered such that the experimental boots with a more flexible sole had a heavier mass and the experimental boots with a stiffer sole had a lighter mass. Boot mass was found to significantly alter lower limb toe clearance, whereby heavier boots reduced toe clearance and lighter boots increased toe clearance (Chiou et al., 2012). It is plausible, therefore, that sole flexibility alone could significantly alter lower limb toe clearance when not confounded by boot mass, although this notion requires further investigation.

4.4.1 *Increased sole flexibility can reduce walking effort*

Despite differences in boot mass, firefighter boots with a more flexible sole have been shown to result in significant reductions in absolute and relative oxygen consumption and carbon dioxide production when participants stepped over obstacles compared to when wearing a boot with a less flexible sole (Chiou et al., 2012). The authors of the study speculated that a

more flexible sole enhanced ankle joint movement and, subsequently, power generation, which ultimately reduced metabolic and respiratory cost. Dobson et al. (2015) also found that participants who walked in a boot with a more flexible sole required less muscle activity to maintain the same walking pattern than when they walked wearing a boot with a stiffer sole. These boots, however, again differed in mass, with the stiffer soled boot weighing more than the flexible soled boot (Dobson et al., 2015). Further research is therefore warranted to investigate the influence of variations in boot sole flexibility and its interaction with boot mass, on variables characterising how participants walk.

4.4.2 A stiffer boot sole can increase metatarsal flexion

It is speculated that forefoot stiffness in certain work boots requires increased metatarsal flexion to accomplish enough power generation at toe-off to propel the body forward during walking (Hamill and Benseal, 1996). Walking, marching and running in military and other work boots with stiffer soles led to increased metatarsal flexion compared to when participants wore other test footwear with more flexible soles (Hamill and Benseal, 1996). This repeated metatarsal flexion, typically required during continuous walking, could be a risk factor for plantar fasciitis. However, apart from differences in sole flexibility, the footwear tested by Hamill and Benseal (1996) also differed in mass and shaft height, confounding interpretation of the results. The military and work boot footwear conditions also caused significant changes to ankle dorsiflexion during walking, marching and running, compared to the other footwear types, implicating restricted ankle motion due to a higher boot shaft as another explanation for the increased metatarsal flexion rather than changes in sole flexibility.

4.4.3 Stress fractures of the second metatarsal are linked to flexible boot soles

The remaining studies that have investigated effects of variations in boot sole flexibility on gait have focused on loading properties and implications for lower limb shock absorption.

An example is a study conducted by Arndt et al. (2003) who investigated the introduction of a military boot (see Figure 4) with a more flexible sole for Swedish military recruits. The study authors hypothesised that a military boot with a more flexible sole would increase comfort by not restricting natural foot motion while walking. Introducing a military boot with a more flexible sole, however, was correlated with an increased incidence of second metatarsal stress fractures (Arndt et al., 2003). Upon further testing, involving the study participants walking on a treadmill, the effects of the increase in sole flexibility were most notable underneath the metatarsophalangeal joint. Consequently, a significant increase in dorsal tension under the second metatarsal was found when participants wore the new boot with a more flexible sole compared to the old stiffer soled boot. Boot sole flexibility was therefore implicated in the occurrence of the overuse injury of second metatarsal stress fractures (Arndt et al., 2003).

4.4.4 Sole flexibility can affect lower limb loading: Implications for overuse injuries

The sole flexibility of army boots has further been associated with the occurrence of other lower limb overuse injuries. Compared to two athletic shoes (a cross-trainer and a running shoes), significantly greater impact loading was generated when participants wore an army combat boot with a stiffer sole (see Figure 4; Sinclair and Taylor, 2014). This greater impact loading in the army boot was accompanied by increased ankle joint eversion and tibial internal rotation. These kinematic variables that were associated with higher impact loading, ankle joint eversion and tibial rotation, have been identified as risk factors for developing musculoskeletal injuries such as plantar fasciitis and iliotibial band syndrome when individuals perform repetitive activities like prolonged walking and marching (Neely, 1998; Sinclair and Taylor, 2014).

The army boots were further associated with increased knee flexion at initial contact, which the authors speculated attenuated the additional impact loading (Sinclair and Taylor,

2014). However, in another study comparing the same test footwear conditions, the military boots were associated with increased patellofemoral load when compared to the two athletic shoes (Sinclair et al., 2015). It is therefore possible the higher shaft of the army boot, compared to the other two low-cut athletic footwear conditions, restricted the participants' ankle range of motion, forcing them to compensate at the knee, which is consistent with the findings of Böhm and Hösl (2010) discussed earlier. More comprehensive biomechanical data (e.g. muscle activity and joint angles) would help to clarify how the participants adjusted their gait to account for the increased impact loading.

Lin et al. (2007) found that different boot sole properties influenced lower limb muscle activity and joint angles when 12 healthy female students (24.2 ± 1.9 years of age; 52.0 ± 5.8 kg mass; 1.6 ± 5.8 m height) walked along a 6 m walkway while wearing three different footwear conditions (see Figure 4). The three test boots in Lin et al.'s study (2007) varied in elasticity and shock absorption at both the heel and metatarsals, again making it difficult to exclusively attribute the results to just changes in sole flexibility. The female participants also differed to the participants in the other reviewed studies, which predominantly used male participants who were substantially heavier and taller, so it is unknown how applicable these results are to demographics more typical of workers in heavy industry such as coal mining.

4.4.5 Boot sole flexibility future research recommendations

None of the previous studies investigating the effects of variations in sole flexibility on walking have tested the effects of changes in footwear while participants walked across more challenging surfaces, such as gravel or inclines, which are frequently encountered in occupations like mining. Inclined surfaces have been shown to amplify the effects of design differences among boots (Simeonov et al. 2008; Dobson et al. 2015). Therefore, it is recommended that future research studies examine the effects of variations in boot sole

flexibility on variables characterising walking under ecologically valid environmental conditions, rather than treadmill walking and while participants perform a variety of working tasks in order to understand the sole flexibility requirements for a work boot.

5. Conclusions and Directions for Future Research

This systematic review of the literature has confirmed that there is a paucity of research examining the influence of work boot design on walking, despite the potential for occupation specific work boots to reduce the incidence of work-related lower limb injuries. Most previous studies have focused on a range of footwear, rather than just work boots and compared vastly different footwear designs, making valid conclusions on the influence of specific design features difficult. Boot shaft height and stiffness, boot mass and boot sole flexibility appear to be specific boot design features that are likely to contribute to walking efficiency in the work place, but further research is needed to support this notion.

Based on this review of the literature it is recommended that future research studies investigating work boot design consider the factors outlined below.

1. Boot design features in test footwear should be systematically altered and controlled.

From the literature it is evident that differences in boot designs can influence an individual's gait. It is often unknown, however, which design feature is influencing which specific variable characterising walking and at what point do changes in the variable occur. Controlling boot features for confounding variables will enable a better understanding of the influence of individual design features on how individuals walk. The interaction between design features should also be explored to determine how they influence walking.

2. More comprehensive evaluations of the effects of variations of boot design parameters on walking are required. Previous studies have tended to focus on relatively superficial variables characterising walking, making interpretation of the

data difficult. The effects of variations in boot design parameters on kinematic, kinetic and electromyography variables that more comprehensively characterise walking are needed to fully understand the alterations in walking that occur as a result of changes to boot design.

3. Recording foot and ankle motion and muscle activity inside the boot is necessary. Most literature pertaining to the influence of boot design on the kinematics and kinetics of gait assumed that gait alterations were a result of changes in ankle range of motion. The specific changes in ankle range of motion, however, are rarely measured directly. A similar scenario occurs in regards to muscle activity, where it is assumed that changes in muscle activity at more proximal segments, such as the knee, occur to compensate for a decrease in muscle activity at the ankle. Again, this notion remains unproven. The lack of quantitative data relating to the ankle in the current literature is in part due to difficulties in designing apparatus that can fit inside a boot and accurately measure ankle range of motion and muscle activity without the signals being contaminated with excessive noise. With the size of measurement devices decreasing and different modes of data collection (i.e. wireless) becoming more common, recording ankle motion and muscle activity inside a boot is now feasible and is recommended in future studies.
4. Participant perceptions of boot comfort should be assessed. Biomechanical variables should be collected in conjunction with questionnaires regarding participants' perceptions of boot comfort, including tightness of fit. This would help identify the influence perceived tightness of fit at the ankle/shank has on the control of lower limb motion and provide insight into the influence of proprioception.
5. Occupational specific testing of footwear effects should occur. A large variety of unique work boot designs are available in order to try and accommodate for

individual workplace requirements. It is evident from the literature that the influence boot design features have on the lower limb change depending on the task performed and the supporting surface. Any work boot-related testing therefore needs to be specific to the environment and task performed by that worker. Future studies examining the effects of variations in boot design features on walking should ensure participants walk across surfaces that truly simulate the demands of relevant work environments.

More detailed research into the influence specific boot design features have on walking could lead to the development of work boots that meet the demands placed on the lower limb during a variety of occupational settings. Results from such studies have the potential to increase the efficiency of performing fundamental occupational tasks, such as walking, while reducing the high incidence of work boot-related lower limb injuries in labouring occupations.

Source of funding

This study was funded by the Coal Services Health and Safety Trust.

Conflict of interest

None

Acknowledgement

The authors wish to acknowledge the contribution of our industry partner, Illawarra Coal, for their assistance with information.

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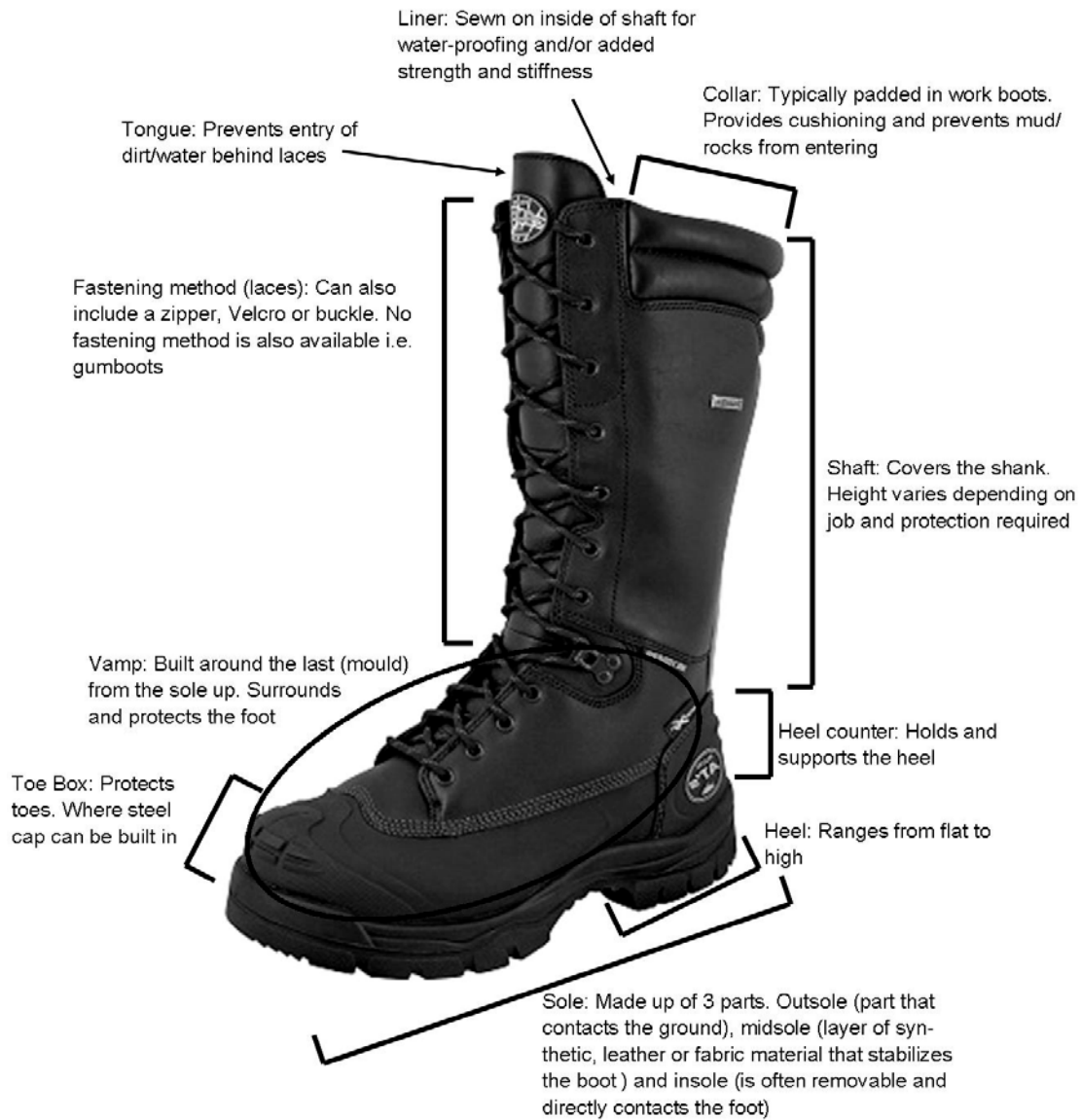


Figure 1: Distinct design features of work boots (adapted from hotboots.com/bootinfo/terms.html and oliver.com.au).



Figure 2: Blundstone® work boots displaying different design features (blundstone.com.au).

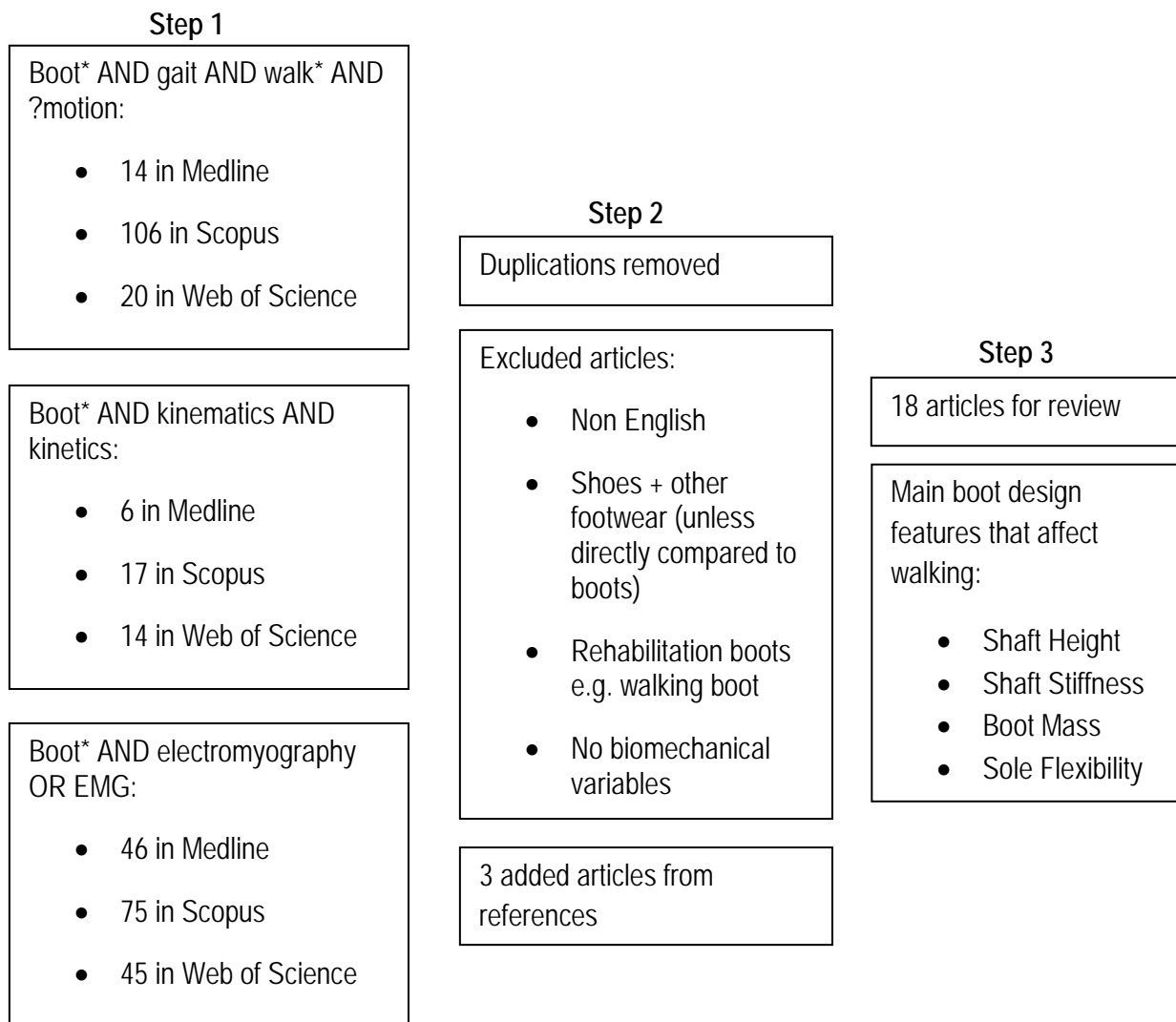


Figure 3: Literature search strategy.

<p>Arndt et al. (2003)</p>  <p>M 59</p>  <p>M 90</p>	<p>Böhm and Hösl (2010)</p>  <p>Chiou (2012) Park et al. (2015)</p> 	<p>Majumdar et al. (2006)</p>  <p>Lin et al. (2007)</p> 	<p>Chander et al. (2014)</p>  <p>Tactical Boot</p>  <p>Work Boot</p>
<p>ikajlo and Matjacic (2007)</p>  <p>Footwear 1</p>  <p>Footwear 2</p>	<p>Hamill & Bensel (1996)</p>  <p>Combat Boot</p>  <p>Jungle Boot</p>  <p>Cross Trainer</p>  <p>Work Boot</p>  <p>Reebok Pump</p>  <p>Hiking Boot</p>	<p>Dobson et al. (2015)</p>  <p>Gumboot</p>  <p>Leather Lace-up Boot</p>	
<p>Garner et al. (2013)</p>  <p>Rubber Boot</p>  <p>Leather Boot</p>	<p>Simeonov et al. (2008)</p>  <p>Work Boot</p>  <p>Safety Boot</p>  <p>Tennis Shoe</p>  <p>Basketball Shoe</p> <p>Sinclair and Taylor (2014) Sinclair et al. (2015)</p>  <p>Yang et al. (2015)</p> 	<p>Kim et al. (2015)</p>  <p>Converse Sneaker</p>  <p>Rain Boot</p>  <p>Combat Boot</p> <p>Nunns et al. (2012) Schulze et al. (2011)</p> 	

Figure 4: Summary of the boots tested in the reviewed studies

Table 1: Quality Index assessment of the 14 studies selected for detailed review.

Author	Reporting (score/11)	External Validity (score/3)	Bias (score/7)	Confounding (score/6)	Power (score/5)	Total (score/32)
Arndt et al. (2003)	5	0	4	1	1	11
Böhm & Hösl (2010)	8	1	5	5	5	24
Chander et al. (2014)	8	0	5	3	5	21
Chiou (2012)	8	1	5	2	5	21
Cikajlo & Matjacic (2007)	9	0	5	4	5	23
Dobson et al. (2015)	9	2	5	4	5	25
Garner et al. (2013)	6	1	4	4	5	20
Hamill & Bense (1996)	8	2	5	5	5	25
Kim et al. (2015)	6	1	5	3	5	19
Lin et al. (2007)	7	0	5	5	5	22
Majumdar et al. (2006)	6	0	5	3	5	19
Nunns et al. (2012)	9	1	5	3	4	22
Park et al. (2015)	8	1	5	4	5	25
Schulze et al. (2011)	6	1	5	3	5	20
Simeonov et al. (2008)	9	2	5	4	5	25
Sinclair and Taylor (2014)	9	0	5	3	5	22
Sinclair et al. (2015)	7	0	5	4	5	21
Yang et al. (2015)	7	0	5	3	5	20

Table 2: Summary of the variables characterising walking that have been measured and the boot design features investigated in the reviewed studies

Reference	Gait Variable	Boot Design Features
Arndt et al. (2003)	Stance phase in-shoe pressure (force time integrals under the heel, metatarsal heads, midfoot, hallux and remaining toes)	Sole flexibility
Böhm and Hösl (2010)	Stance phase kinetics (ground reaction force (GRF); ankle knee and hip concentric and eccentric joint energies) kinematics (spatio-temporal; ankle knee and hip joint range of motion) and electromyography (muscle co-contraction index of muscle antagonistic pairs at the knee and ankle joints)	Shaft stiffness
Chander et al. (2014)	Standing balance in-shoe pressure (centre of pressure used to calculate sway parameters of average sway velocity and root mean square in the anterior-posterior and medial-lateral directions)	Mass, shaft height, sole flexibility
Chiou (2012)	Whole gait cycle kinematics (spatio-temporal; toe clearance)	Mass, sole flexibility
Cikajlo and Matjacic (2007)	Stance phase kinematics (ankle, knee and hip joint angles; trunk and pelvis tilt) and kinetics (ankle, knee and hip joint moments and powers)	Shaft stiffness
Dobson et al. (2015)	Initial contact and pre-swing kinematics (knee and hip joint angles; stance and swing timing) and electromyography (quadriceps and hamstring muscle intensity)	Mass, shaft stiffness, sole flexibility
Garner et al. (2013)	Standing balance in-shoe pressure (centre of pressure used to calculate sway velocity in the anterior-posterior and medial-lateral directions) and kinetics (knee flexor/extensor and ankle flexor/extensor peak torque)	Mass
Hamill and Benseal (1996)	Whole gait cycle kinetics (GRF), kinematics (spatio-temporal; rearfoot movement; ankle, knee, hip and metatarsal maximum joint angles, velocity and time to maximum flexion/extension) electromyography (thigh and lower leg muscle burst duration) and in-shoe pressure (peak heel pressure, peak forefoot pressure and centre of pressure excursion)	Mass, shaft stiffness, sole flexibility
Kim et al. (2015)	Whole gait cycle electromyography (leg root mean square)	Mass
Lin et al. (2007)	Whole gait cycle kinetics (GRF), kinematics (lumbar, ankle, knee and hip maximum flexion/extension joint angles) and electromyography (muscle amplitude of lumbar region and leg)	Sole flexibility

Majumdar et al. (2006)	Whole gait cycle kinematics (spatio-temporal)	Mass, shaft stiffness, sole flexibility
Nunns et al. (2012)	Stance phase kinematics (ankle joint angles), kinetics (GRF; ankle joint moments and stiffness) and in-shoe pressure (peak pressure, impulse, peak loading rate and timing of peak pressure under each metatarsal head)	Shaft height
Park et al. (2015)	Whole gait cycle kinematics (hip, knee, ankle and ball of foot range of motion in the sagittal, frontal and transverse planes)	Mass, shaft height, shaft flexibility
Schulze et al. (2011)	Whole gait cycle electromyography (leg amplitude, peak and integral)	Shaft height, mass
Simeonov et al. (2008)	Stance phase kinematics (trunk and rearfoot angular displacements)	Shaft height
Sinclair and Taylor (2014)	Stance phase kinetics (GRF) and kinematics (spatio-temporal; ankle, knee and hip joint angles)	Sole flexibility
Sinclair et al. (2015)	Stance phase kinetics (knee extensor and abduction moment; patellofemoral contact force, loading rate and pressure)	Sole flexibility
Yang et al. (2015)	Standing balance Romberg's test (limits of stability) following walking fatigue protocol	Shaft height

Table 3: Summary of the literature pertaining to the influence of boot design on walking

Reference	Study Aim	Participants	Study Type	Procedures	Main Outcome	Boot
Arndt et al. (2003)	Understand the underlying loading factors responsible for metatarsal II deformation	Experiment 1: 2 men of distinctly different mass (participant 1 = 31 yr; 90 kg, participant 2 = 35 yr; 70 kg). Experiment 2: 6 participants (45 ± 12 yr; 79 ± 15 kg)	Cross-over, controlled comparison	Flexible vs stiffer soled boot. Experiment 1: walking on a level treadmill (3.5 km/h) for 3 h carrying a backpack of 45% bodyweight. Experiment 2: treadmill walking (3 km/h) with 20 kg backpack, 30-60min (depended on voluntary fatigue)	More flexible sole = ↑ metatarsal II dorsal tension	Military
Böhm and Hösl (2010)	Investigate the influence of boot shaft stiffness on gait performance on uneven surface	15 healthy men (29 ± 5 yr; 77 ± 8 kg; 177 ± 5 cm)	Cross-over, randomised, controlled comparison	Walking (controlled self-selected) on gravel in two different hiking boots varying by 50% in passive shaft stiffness	Stiffer shaft = ↓ weight acceptance time, ↓ ankle range of motion, ↑ knee and ↓ ankle eccentric energy absorption and ↑ vastus lateralis and semitendinosus co-contraction	Hiking
Chander et al. (2014)	Examine differences in balance while participants walked for extended durations wearing different types of occupational footwear	14 healthy men (23.6 ± 1.2 yr; 89.2 ± 14.6 kg; 181 ± 5.3 cm)	Cross-over, randomised, controlled comparison	Standing balance tests (NeuroCom Equitest) performed prior to walking (self-selected) on a vinyl floor and every 30 minutes until 240 th minute in 3 types of occupational footwear (low-cut shoe, tactical boot, work boot)	Low-cut shoe = ↑ postural sway	Work
Chiou (2012)	Investigate the effect of boot weight and sole flexibility on spatio-temporal characteristics and physiological responses of male and female firefighters in	14 healthy experienced male (28.4 ± 5.5 yr; 94.6 ± 15.6 kg; 178.5 ± 5.8 cm) and 13 healthy experienced female (33.2 ± 4.4 yr; 67.9 ± 8.0 kg;	Cross-over, counter-balanced, controlled comparison	Walking (controlled) and stepping over 4 obstacles (2 high + 2 low) on a 12 m long walkway in firefighter boots varying in mass and sole flexibility while wearing work gear and carrying a hose	↑ boot mass = ↓ trailing toe clearance and ↑ heel contact velocity ↑ sole flexibility = ↑ oxygen consumption	Firefighter

	negotiating obstacles	166.6 ± 5.0 cm)				
		firefighters				
Cikajlo and Matjacic (2007)	Investigate the influence of boot-shaft stiffness on kinematics and kinetics during walking of participants with and without carrying a 20 kg backpack	9 men (24.7 ± 2.1 yr; 73.9 ± 4.1 kg; 178.6 ± 5.7 cm)	Cross-over, randomised, controlled comparison	Walking (self-selected) on a 7 m long runway in two different military boots with apparently different boot shaft stiffness	More flexible shaft = ↑ peak power during push-off, ↑ dorsiflexion during midstance and terminal stance and overall ↑ ankle range of motion	Military
Dobson et al. (2015)	Investigate the effects of wearing two standard underground coal mining work boots (a gumboot and a leather lace-up boot) on lower limb muscle activity when participants walked across simulated underground coal mining surfaces	20 men (33 ± 12 yr) who matched the demographics of underground coal mine workers	Cross-over, randomised, controlled comparison	Walking (self-selected) around a circuit (level, inclined and declined surfaces composed of rocky gravel and hard dirt) in two different underground coal mining work boots (gumboot and leather lace-up boot)	Leather lace-up boot = ↑ vastus lateralis muscle activity at initial contact on decline and ↑ biceps femoris muscle activity during pre-swing on incline and decline	Underground coal mining
Garner et al. (2013)	Examine the differences in balance and gait in professional firefighters wearing rubber and leather boots participating in a fire simulation activity	12 professional male firefighters (33.4 ± 6.8 yr)	Cross-over, randomised, controlled comparison	2 x 3 min simulated firefighter stair climb (60 steps/min) wearing 50 lb weighted vest (simulate typical PPE) and 25.7 kg weights on shoulders (simulate weight of hose bundle) in two different firefighting boots (leather and rubber)	Rubber boot = ↑ sway and ↑ decrement in peak torque (indicates fatigue)	Firefighter
Hamill and Benseal (1996)	Develop a series of recommendations for future military footwear with regard to	Reserve Officer Training Corps and university students: 15 men (25.5 ± 5.6	Cross-over, randomised, controlled comparison	Walking (controlled), marching, running, jumping from heights and running an agility course in a variety of boots (combat boot, jungle boot,	Combat boot, jungle boot and work boot = ↑ metatarsal flexion and limited dorsiflexion during walking, marching and running	Military, work, hiking and athletic

	materials, design, construction, fabrication techniques and any other features that would benefit the performance and the lower extremity health of military personnel, particularly ground troops	yr; 77.8 ± 13.7 kg; 178 ± 6 cm) and 15 women (22.5 ± 1.6 yr; 64.4 ± 4.1 kg; 163 ± 8 cm)		Reebok pump, Nike cross-trainer, Rockport hiking boot, Red Wing work boot)	Reebok pump and Nike cross-trainer = ↑ centre of pressure excursion when marching and running	
Kim et al. (2015)	Analyse the effects of muscle activity on walking according to various shoes frequently worn by young women	15 female university students (20.5 ± 0.5 yr; 51.4 ± 7.2 kg; 159 ± 4.9 cm)	Cross-over, controlled comparison	Walking (4 km/h) on a treadmill for 30 min in 3 different types of footwear (Converse sneaker, rain boot and combat boot)	Rain boot vs. Converse sneaker = ↑ vastus medialis muscle activity Combat boot vs. rain boot = ↑ vastus medialis muscle activity	Rain and military
Lin et al. (2007)	Evaluate the significance of boot sole properties for reducing fatigue, to evaluate the effect of load carrying and walking on biomechanical, physiological and psychophysical responses	12 healthy female students (24.2 ± 1.9 yr; 52.0 ± 5.8 kg; 160 ± 5.8 cm)	Cross-over, randomised, controlled comparison	Walking (3.1 km/h) on a 6 m walkway for 5 mins (repeated for an hour) in 3 boots with different outsole cushioning	Boot C (with less elasticity and shock absorption) = ↑ GRF and higher discomfort ratings than boot A (greater elasticity and shock absorption)	Clean room
Majumdar et al. (2006)	Observe the temporal spatial parameters of gait while walking barefoot, with bathroom slippers	8 healthy infantry soldiers (26.7 ± 2.7 yr; 59.3 ± 5.1 kg; 164.8 ± 4.4 cm)	Cross-over, consecutive, controlled comparison	Walking (self-selected) on a 10 m platform barefoot and 2 different types of footwear (military boots and bathroom slippers)	Military boot vs. barefoot = ↓ step length and stride length, ↑ cadence, ↓ swing phase and single support time and ↓ total support time and initial double	Military

	and military boots on, respectively and to look into the possible existence of any differences in gait pattern in these three conditions				support time	
Nunns et al. (2012)	Investigate the effects of standard issue CAB (combat assault boot) and GT (gym trainer) on factors proposed to be associated with MT3 (third metatarsal) stress fracture risk	7 injury-free physically active male university volunteers familiar with wearing and running in combat boots (18.3 ± 0.4 yr; 81.1 ± 8.2 kg)	Cross-over, controlled comparison	Running (3.6 m/s) across a force plate in 2 different types of standard military footwear (combat assault boot and gym trainer)	Combat assault boot = ↑ peak plantar pressure, impulse and loading rate under MT3, smaller and earlier peak ankle dorsiflexion, later heel-off, greater magnitudes of peak plantarflexion moment and ankle joint stiffness and more lateral resultant horizontal force vector at the instant of peak horizontal breaking force	Military
Park et al. (2015)	Assess the incremental impact of each item of personal protective equipment on the gait performance of male and female firefighters	8 male firefighters (28.6 ± 8.3 yr, 183.5 ± 3.8 cm, weight: 85.5 ± 15.7 kg) and 4 female firefighters (31.5 ± 13.5 yr, 170.8 ± 7.6 cm, 68.3 ± 14.3 kg)	Cross-over, counter-balanced, controlled comparison	Walked 10 m (self-selected) wearing a turnout coat and pants (5.74 ± 0.79 kg), SCBA air tank (8.1 kg) on their back and either running shoes or rubber pull-up bunker boots	Rubber boot = Sagittal plane: ↓ ankle plantarflexion- dorsiflexion and ball of foot flexion-extension range of motion Frontal plane: ↑ ankle inversion-eversion and ball of foot abduction-adduction range of motion Transverse plane: ↓ ankle intra-extra rotation and ↑ ball of foot intra-extra rotation range of motion	Firefighting

Schulze et al. (2011)	Identify the influence of footwear shape and material on the muscles of the lower extremities. Also analyse if there is a link between strained muscles and the occurrence of musculoskeletal complaints such as shin splints, sprains and strain-related knee pain	37 soldiers (36 men; 29 yr; 81.5 kg; 177.8 cm). Five did not complete analysis	Cross-over, consecutive, controlled comparison	Walked (3.2 km /h) on a treadmill in 5 different types of shoes (leather dress, combat boot, outdoor old, outdoor new, indoor)	Combat boot = ↑ muscle activity of tibialis anterior and rectus femoris	Military
Simeonov et al. (2008)	Investigate footwear style effects on worker's walking balance in a challenging construction environment	24 male construction workers (39 yr; 86.4 ± 12.6 kg; 178.3 ± 6.9 cm)	Cross-over, counter-balanced, controlled comparison	Walking (self-selected) on 3 m roof planks in a surround-screen virtual reality system, simulating a residential roof environment. 3 common athletic shoes (running, basketball and tennis) and 3 work styles (low-cut shoe, work boot and safety boot) tested on wide (25 cm), narrow (15 cm) and tilted (14°) planks	On roof planks, high cut footwear = ↓ trunk and rearfoot angular velocity when compared to low-cut. On tilted plank, high cut footwear = ↑ rearfoot angular velocity when compared to lowcut. Overall high cut footwear = ↑ stability perception	Work
Sinclair and Taylor (2014)	Examine the kinetics and 3D kinematics of the PT-03 and PT100 footwear in relation to conventional army boots	13 male runners, completing a minimum of 35 km per week (26.7 ± 5.2 yr; 69.5 ± 14.6 kg; 175.8 ± 4.9 cm)	Cross-over, counter-balanced, controlled comparison	Ran (4 m/s) on a 22 m laboratory floor in 3 types standard military footwear (army boot, PT-03 and PT1000 athletic shoes)	Army boot = ↑ impact loading and ankle eversion/tibial internal rotation	Military
Sinclair et al. (2015)	Examine patellofemoral joint loading when running in military boots, when compared	12 male recreational runners who at least 3 times per week and had a	Cross-over, counter-balanced, controlled	Ran across a 22 m laboratory floor (4.0 m/s ± 5%) in 3 types standard military footwear (army boot, PT-03 and PT1000 athletic shoes)	Army boot = ↑ knee extensor moment, patellofemoral contact pressure and patellofemoral contact force PT100 = ↑ peak abduction moment)	Military

	to cross-trainer and running shoe conditions using a biomechanical modelling approach.	minimum of 3 years running experience (26.3 ± 5.9 yr; 73.9 ± 5.2 kg; 175.6 ± 6.1 cm)	comparison			
Yang et al. (2015)	Investigate the effects of lower limb muscle fatigue generated while walking in rain boots of different shaft lengths, on balance abilities according to visual feedback	12 healthy female students (20.5 ± 0.5 yr; 51.4 ± 7.3 kg; 159.1 ± 5.0 cm)	Cross-over controlled comparison	Treadmill walking (4 km/h) 30min to induce muscle fatigue. Romberg's test of stability limits pre and post walking in rain boots with 3 different shaft heights (40 cm, 29 cm and 17 cm)	No significant main effect of shaft height	Rain