Final Report

Improving Footwear for Underground Coal Miners

Coal Services Health and Safety Trust (HST Project No. 20620)

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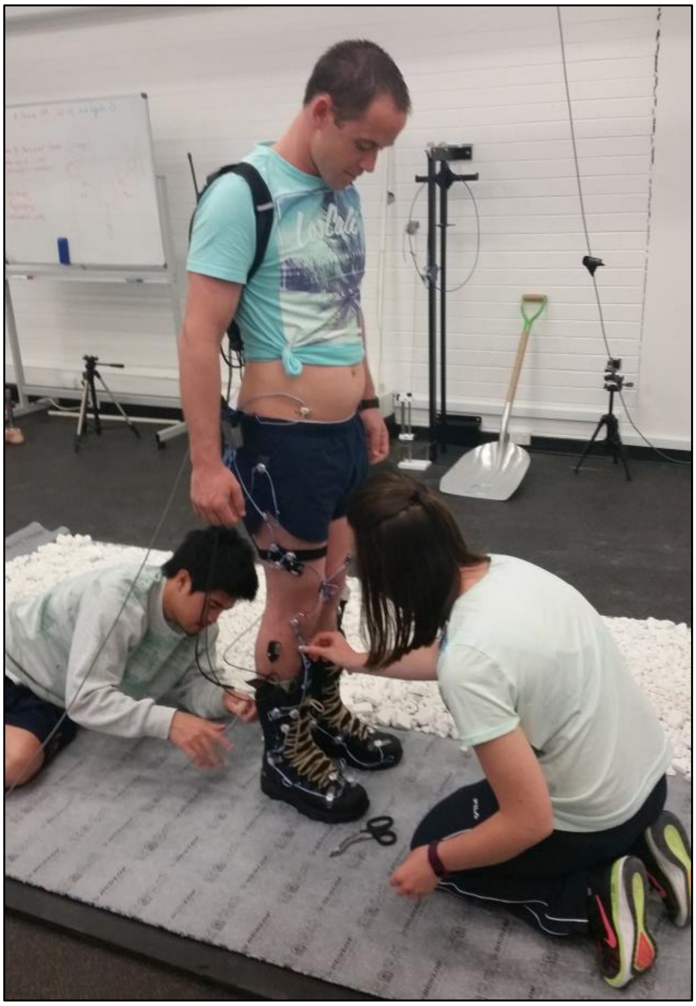
Contents



Figures

Tables

Executive Summary

Underground coal miners are required to remain on their feet for extended periods of time throughout their working shifts. It is therefore imperative they have access to comfortable and safe footwear during these long shifts. Unfortunately, the work boots underground coal miners currently wear are not only uncomfortable but are potentially contributing to the high incidence of lower limb injuries sustained in this occupational group.

This project aimed to identify design features that influence the fit and comfort of mining work boots in order to develop evidence-based recommendations to improve the fit and comfort of work boots for underground coal miners. To achieve this aim, we conducted four studies, which are described below.

Underground coal miners (n = 355 men and 3 women; age = 39.1 ± 10.7 years; height =1.78 ± 0.31 m; mass = 92.1 ± 13.7 kg) employed by Illawarra Coal, at Dendrobium and West Cliff sites (NSW, Australia), completed a comprehensive survey about their work boots. We found that current work boots do not meet the requirements of these underground coal miners. This is evident in the high incidence of reported foot problems and lower limb and lower back pain among the underground coal miners surveyed, regardless of boot type.

The feet of 270 underground coal miners from the Dendrobium and West Cliff mine sites were scanned to provide a model of their foot shape. From these data, the shape of the feet of 208 miners (males; age 38.3 ± 9.8 years; height 178.9 ± 5.7 cm, body mass 93.2 ± 12.5 kg) who wore a US size 9, 10, 11 or 12 work boot were compared to the shape of the internal dimensions of their work boots. We found that underground coal miners wore boots that were substantially longer than their feet but the width of the forefoot and heel areas of the boots were not wide enough for the miners' feet. Based on the results it appears that the instep (height) and forefoot (foot breadth and ball girth circumference) are more important measures to consider when fitting underground coal mining work boots that just foot length.

Twenty men (age 33.4 ± 12 years; body mass 84.8 ± 10 kg; height 179.5 ± 7 cm) who matched the demographics of underground coal mine workers walked over a variety of surfaces in two types of underground coal mining work boot (gumboot and leather lace-up boots). Perceived comfort, muscle activity, joint angles and in-shoe pressure data were collected while they walked. We found that the structure of an underground coal mining work boot can significantly influence walking and perceptions of comfort when participants walk on uneven surfaces typically encountered by underground coal mine workers.

Twenty male underground coal miners (age 36 ± 13.8 years; height 174.8 ± 6.3 cm, body mass 76.9 ± 9.2 kg) performed walking trials in four custom designed underground coal mining work boots while perceived comfort, muscle activity, three-dimensional motion and in-shoe pressure data were collected. Preliminary results show that underground coal miners prefer a work boot with a flexible shaft and a stiff sole. This differs to current work boots used in the industry, which feature either a stiff shaft and stiff sole (leather lace-up boot) or a flexible shaft and flexible sole (gumboot).

Underground coal mining work boots need to be redesigned to better fit the feet of miners and the miners themselves need to be better educated on how to select a boot that fits properly. A wider boot with a flexible shaft and a stiff sole warrants further investigation as an evidence-based boot for walking efficiently and comfortably in underground coal mines.

1. Introduction

Steel-cap work boots are a mandatory part of personal protective equipment for workers in all occupations where the risks of sustaining cutting and crushing injuries to the feet are high (Marr & Quine, 1993). One such occupation in which steel-cap work boots are imperative is underground coal mining. In underground coal mining two main styles of mining work boots are typically provided to the workers: (i) a slip-on rubber gumboot, and (ii) a leather lace-up boot (see Figure 1). Combinations of these boot styles and materials result in structurally different work boots, particularly in regards to overall boot mass, shaft stiffness and height, ankle support and sole flexibility. These different features will ultimately affect the fit and comfort of a work boot, as well as how the footwear affects a coal miner's ability to perform activities such as walking.

Figure 1: Two typical underground coal mining steel-capped work boots. A: Gumboot (Style 015; Blundstone®, Australia) and B: Leather lace-up boot (Style 65-691; Oliver, Australia).

In underground coal mining, miners spend a large proportion of their day-to-day activity continuously walking, with 82.5% of workers required to remain on their feet all day (Marr, 1999). As a result lower limb injuries, specifically overuse and sprains/strains, are prevalent. These lower limb injuries contribute to approximately 18,863 days off work annually (Australia, 2011) and, in a five year period, incurred a cost of $140 million in compensation claims (Armour, 2003). It is therefore imperative that evidence-based strategies to reduce the prevalence of these lower limb injuries are developed.

In order to limit the risk of lower limb injuries during walking, it is vital that the work boots worn by miners fit their feet properly, and provide sufficient support while permitting adequate motion of the foot and ankle to absorb the ground reaction forces generated with each step (Neely, 1998). Despite the importance of good footwear in occupations such as underground coal mining, previous researchers have reported that 52.1% of miners claimed their boots did not fit properly (Smith et al., 1999, Marr, 1999). Furthermore, 63.5% of miners reported that their work boots provided inadequate ankle support and 41.3% reported that their feet slid inside their boots (Smith et al., 1999, Marr, 1999). Because the foot is the end segment of the lower limb, any foot problems caused by poor footwear can influence the ankle joint, as well as joints further up the lower limb such as the knee (Neely, 1998, Liu et al., 2012). This perhaps explains why, in underground coal mines, 49.2% of lower limb related injuries occur at the knee and 36.5% at the ankle (Smith et al., 1999). Alarmingly, 37.4% of miners who sustained lower limb injuries believed their work boots were the main contributing factor (Smith et al., 1999).

Underground coalmines pose additional challenges to walking because the supporting surfaces typically include loose rocks and gravel, which are uneven and moveable (Gates et al., 2012). This creates an unpredictable environment where the demand placed on the lower limb to maintain balance while walking is already magnified (Menz et al., 2003). Although there has been previous research investigating how work boots affect walking on unpredictable surfaces (Harman et al., 1999, Hamill & Bensel, 1996, Williams et al., 1997, House et al., 2013), the researchers often compared completely different types of boots, which had numerous features that varied, making conclusions difficult. Systematically altering critical design features in a standard boot, as opposed to comparing boots with multiple design features, is likely to provide more meaningful information upon which to develop guidelines about specific design features that should be included in comfortable work boots (Menant et al., 2008).

Evidence-based recommendations need to be developed in order to identify specific design features that can improve the fit and comfort of work boots for underground coal miners. Although we know that altering boot design can influence boot fit and walking ability, we do understand how specific mining work boot design features (e.g. overall boot mass, shaft stiffness, shaft height, ankle support or sole flexibility) interact to affect work boot fit and comfort when underground coal miners walk on surfaces that simulate underground coal mining conditions.

2. Project Description

2.1 Goals and Objectives

The overall aim of this project was to identify design features that influence the fit and comfort of mining work boots in order to develop evidence-based guidelines to improve the design of footwear for underground coal miners. To achieve this overall aim, four studies were conducted. These studies and how they contribute to the overall aim of the project are depicted in Figure 2.

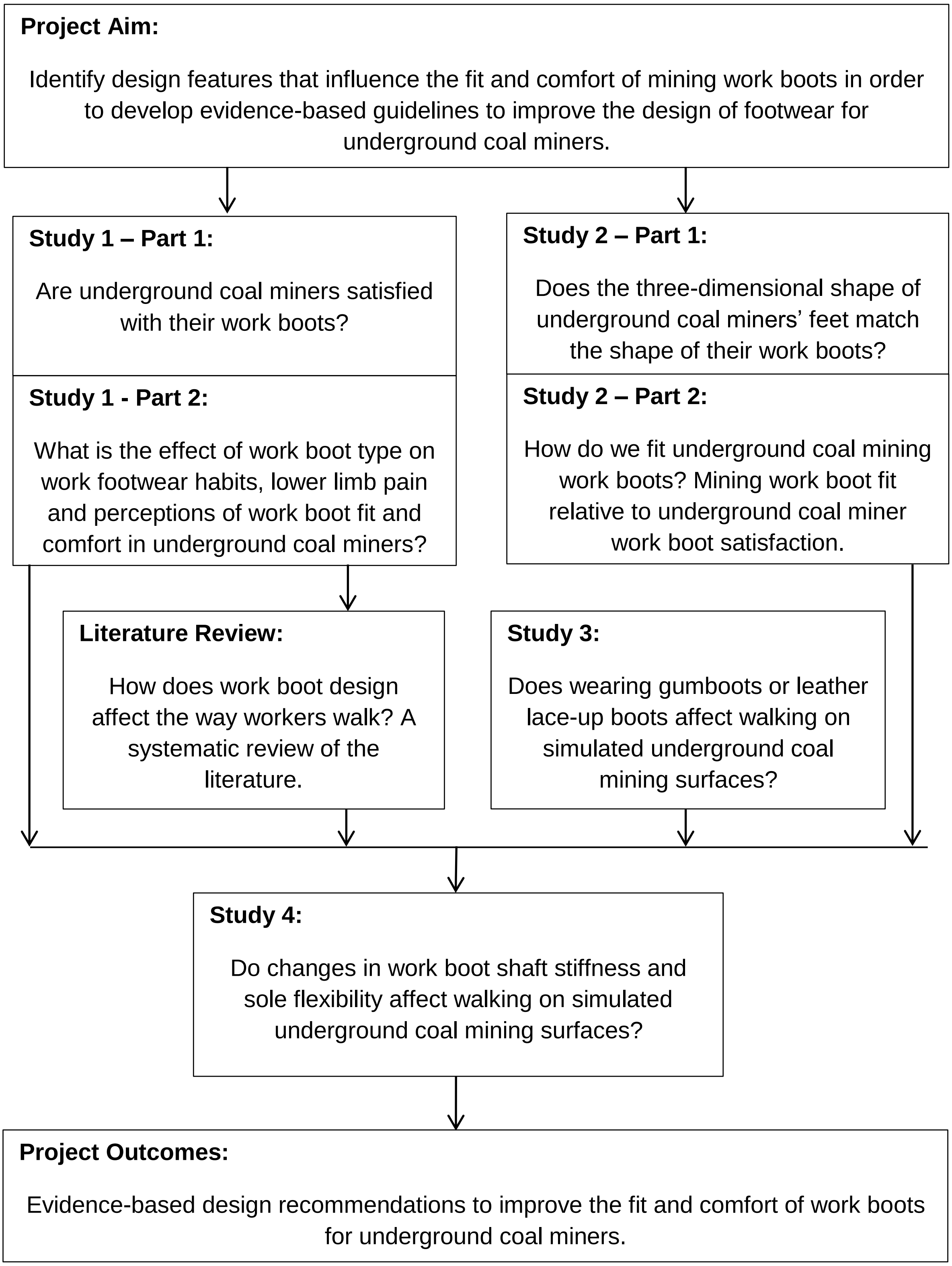


Figure 2: Schematic representation of the aim of the project and how each of the studies systematically contributed to developing evidence-based recommendations to improve the fit and comfort of work boots for underground coal miners.

2.2 Changes to the Initial Grant Proposal

The initial project was structured to include four studies, with the following objectives:

- To evaluate the morphology of the feet of underground coal mine workers ***(Study 1)***;
- To determine the effects of safety footwear on foot function in underground coal mine workers ***(Study 2)***; and
- To investigate whether semi-customised safety footwear, which cater for the unique structural and functional characteristics of the feet of underground coal mine workers, improve shoe fit and are perceived as comfortable ***(Study 3 & 4)***.

As highlighted in a previous interim report (see Interim Report May 2014), the grant team had to be restructured, primarily when the Chief Investigator, Dr Bridget Munro, left the University of Wollongong and Australia, and was no longer involved in the study. Professor Julie Steele took over the role as Chief Investigator, and conducted an internal review of the study, in conjunction with Dr Diane Harland, Dr Alison Bell, Ms Jessica Dobson and Mr Mark Collier. The review identified that, although the overall aim of the project would remain unchanged, some of the initial strategies proposed to achieve this aim were unfeasible. For example, it was initially proposed to use a clustering approach to identify shapes that represented the feet of underground coal miners. However, such an approach was not feasible because at least 1,000 scans was required for this type of analysis, which was beyond the scope of the current study (see Interim Report May 2014). Also, this approach would not help identify which foot dimensions were causing miners to experience discomfort while wearing their work boots. Consequently, after discussion with our industry partner, the study was restructured (as shown in Figure 2). This approach allowed us to firstly analyse the survey data to identify what boots the miners wear and what they like and do not like about those boots. We then compared the three-dimensional shape of the miners' feet, using the foot scans, to a three-dimensional model of their current work boots (see Interim Report May 2015). This, in turn, allowed us to formulate specific recommendations in regards to the fit of underground coal mining work boots. All changes to the study were documented in previous interim reports and approved by the Coal Services Health and Safety Trust Board.

3. Study 1

- Are underground coal miners satisfied with their work boots? (Part 1)
- What is the effect of work boot type on work footwear habits, lower limb pain and perceptions of work boot fit and comfort in underground coal miners? (Part 2)

3.1 Methodology

3.1.1 Participants and Survey Implementation

Underground coal miners (n = 355 men and 3 women; age = 39.1 ± 10.7 years; height =1.78 ± 0.31 m; mass = 92.1 ± 13.7 kg) employed by Illawarra Coal, at Dendrobium and West Cliff sites (NSW, Australia), volunteered to complete a survey about their work boots. Over half of the participants had worked underground (54.8%), and performed their current working role (52.6%), between 3 and 10 years. Nearly a fifth had worked underground for over 16 years (18.8%). The most common mining work boot sizes worn were sizes 8-12 with 90% of participants falling within this range. Surveys were handed out to the participants at scheduled work health and safety meetings, at training days or immediately prior to commencing a shift at the mines. The participants completed the survey under the guidance of the research team, who clarified any questions the participants had and ensured all questions were completed. All 358 participants who volunteered to fill out the survey completed it.

3.1.2 Survey Design and Development

The design of the survey was based on previously validated surveys that had investigated underground coal mining work boots (Marr & Quine, 1993, Marr, 1999, Smith et al., 1999), and modified after discussions with coal mining industry representatives. The survey was trialled by 15 participants (age = 18 - 40 years) to ensure questions were readily understood. The final survey instrument included 54 items (15 closed-ended and 39 open-ended items), divided into six sections that sought information pertaining to the underground coal miners' job details, work footwear habits, foot problems and lower limb pain history, orthotic use, work footwear fit and comfort, and foot and footwear knowledge. The University of Wollongong Human Research Ethics Committee (HE11/198) approved the survey content and administration procedures.

3.1.3 Survey Analysis

Responses to the closed-ended items were coded and counted to determine the frequency of responses for each item, before calculating descriptive statistics. A thematic analysis was conducted on the answers to the open-ended questions to determine response frequencies. The number of responses for each question varied due to non-responses, multiple answer selection or when questions did not require an answer from all participants. Data were analysed only on the miners who provided a response to that question.

Part 1: To assess current mining work boot design in relation to the work-related requirements and miner satisfaction with their current mining work boots, Chi-squared tests were applied to the data pertaining to work footwear habits, foot problems and lower limb pain history. This determined whether the frequency of responses differed significantly ($p < 0.05$) based on job details or work footwear fit and comfort (SPSS Version 21, USA).

Part 2: Chi-squared tests were applied to data related to work footwear habits, foot problems, lower limb and lower back pain history and work footwear fit and comfort. The purpose of this statistical design was to determine whether the participants' lower limb pain and perceptions of fit and comfort differed significantly ($p < 0.05$) based on boot type worn (gumboot, leather lace-up boot; SPSS Version 21, USA).

3.2 Results: Part 1[1]

3.2.1 Job Details

The main working roles reported by the participants were machine operation and heavy lifting (see Figure 3). Some participants described their job title (e.g. electrician), whereas others described the activity they most commonly performed (e.g. walking). Muddy (86.1%), uneven (88.3%), and slippery/wet (72.4%) surfaces were the most common ground-surface conditions worked on.

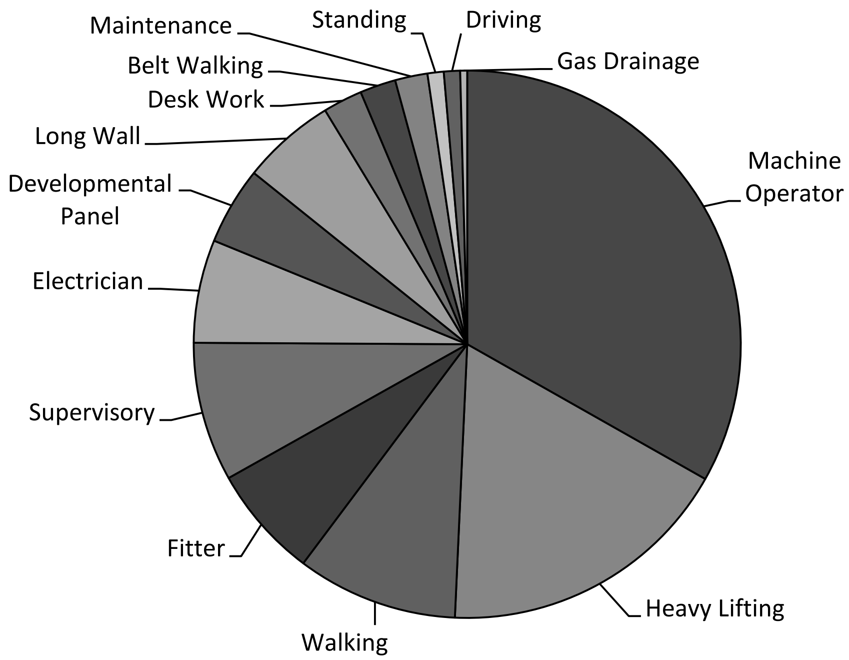


Figure 3: Current main working roles or tasks reported to be undertaken by the participants (n = 349).

[1] For ease of reading this document, the detailed statistical results are presented in the attached publications.

During a typical 8-12 hour shift, the participants spent the most time walking and the least time sitting (see Figure 4).

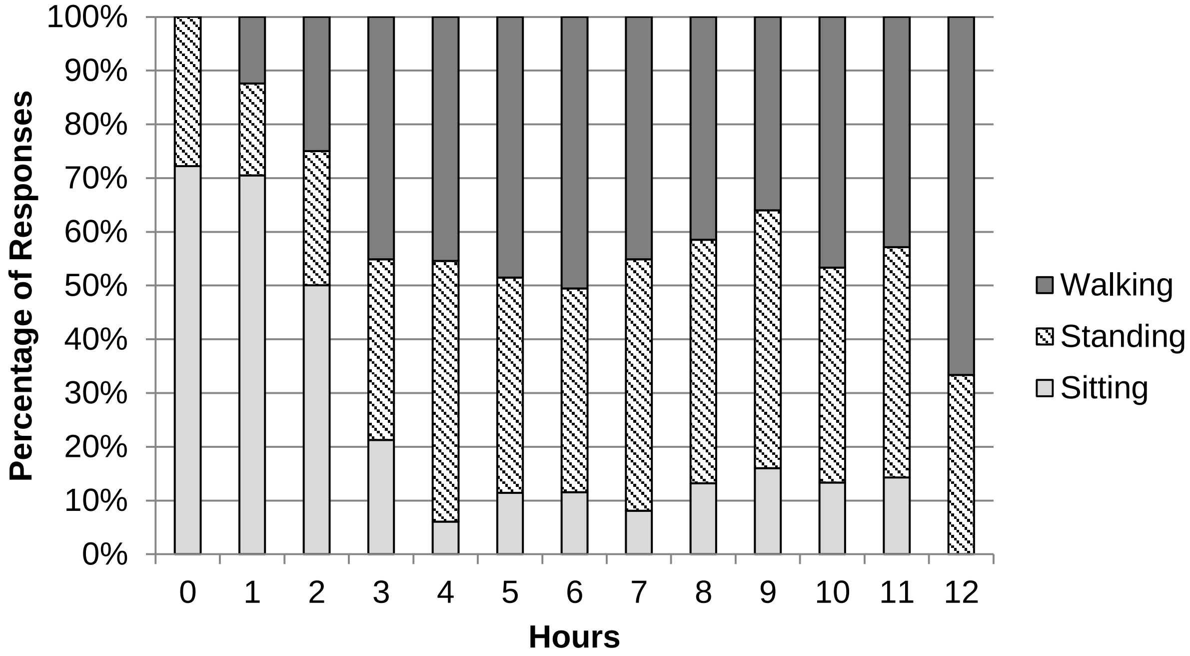


Figure 4: Amount of hours participants spend walking, standing and sitting during a typical 8-12 hour shift (n = 288).

3.2.2 Foot Problems, Lower Limb Pain History and Orthotic Use

Foot problems were reported by 55.3% of the participants, with calluses (33.1%), dry skin (30.2%) and tinea (12.8%) being the most common complaints. Most miners reported similar levels of foot pain and lower back pain (see Figure 5). Almost half of the miners who answered this question had lower back pain (44.5%) and foot pain (42.3%), and almost a quarter had knee pain (21.5%) and ankle pain (24.9%). Of the miners who reported having foot pain, over half said the foot pain occurred 'occasionally' to 'often' (68.8%). This was similar to ankle pain where 57.9% of miners who had ankle pain said it occurred 'occasionally' to 'often'. Of those who listed foot and/or ankle pain, over half (62.3%) believed the pain was related to their mining work boots. The most common locations on the foot indicated as causing pain are presented in Figure 6. Although 17.3% of participants had previously been prescribed orthotics by a health professional, only 6.7% currently wore orthotic devices.

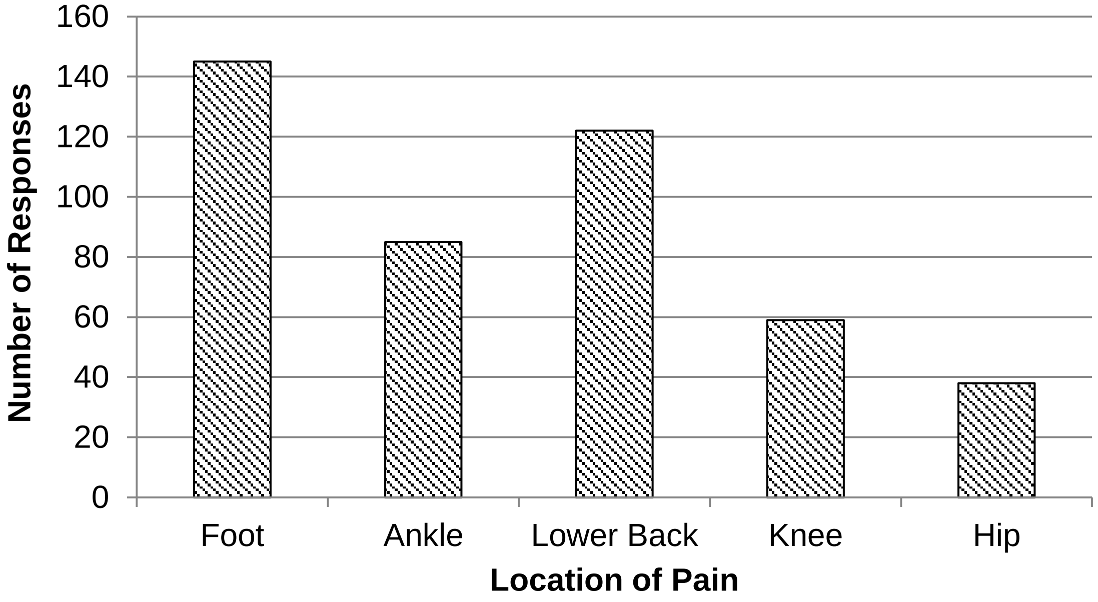


Figure 5: Number of participants who reported having lower limb or back pain (n = 343 for foot and ankle, n = 274 for lower back, knee and hip).

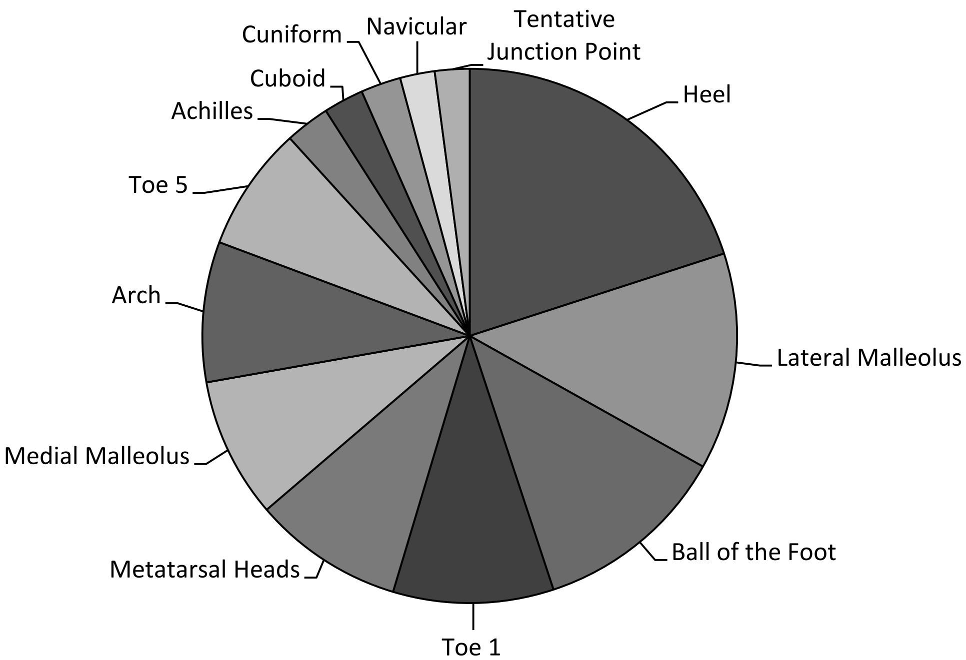


Figure 6: Specific locations of pain marked by the participants on a picture of the foot. Only participants who reported having foot pain (n = 182) were included.

3.2.3 Foot Problems and Lower Limb Pain Related to Job Details, Comfort and Fit

Foot problems were significantly more likely if a participant was a belt walker but less likely if they worked at a desk or on flat ground. Of the participants who reported having foot problems, miners who listed walking as a main working role were significantly more likely to have calluses, hammer toes and Achilles pain, whereas miners who listed standing as a main working role were significantly more likely to have pain where the foot meets the leg. Supervisors were significantly more likely to have rashes and spurs, whereas electricians were significantly more likely to have blisters and arch pain. Gas drainers were significantly more likely to have cuboid and navicular pain. Dry skin and heel pain were significantly more likely to be reported if participants worked on hard ground and ball of foot pain was significantly more likely when the participants worked on wet/slippery ground.

Foot pain was significantly more likely to be reported by participants who performed heavy lifting and worked on muddy and dirt surfaces. Supervisors were significantly more likely to have knee pain but working on dry and flat ground made knee pain less likely. Miners working on dirt surfaces were significantly more likely to have hip pain.

3.2.4 Work Footwear Habits and Work Footwear Fit and Comfort

The gumboot was the most popular boot worn by the participants (66.3%), followed by the leather lace-up boot (32.5%). Some participants purchased their own work boots but the employer provided most (83.8%) work boots. More than three-quarters of participants (82.4%) rated their mining work boot fit as 'reasonable' to 'good'. The ratings of comfort, however, were not as clustered with 18.1% of the participants rating their mining work boots as 'uncomfortable', 38.5% as 'indifferent' and 37.7% as 'comfortable'. The main features participants did not like about their current mining work boots are displayed in Figure 7. The preferred fastening method of an ideal underground coal mining work boot was non-fastening (i.e. slip-on; 62.9%) or zipper (31.1%) and the boot features that the participants reported would make an ideal work boot more comfortable are displayed in Figure 8.

3.2.5 Work Footwear Habits and Work Footwear Fit and Comfort Related to Foot Problems, Lower Limb Pain History and Job Details

Participants who had hip pain were significantly more likely to rate their work boot fit as 'very poor', 'poor' and 'reasonable', whereas those with foot pain were significantly more likely to rate comfort as 'uncomfortable' to 'indifferent'. The presence of calluses made fit ratings of 'poor' to 'reasonable' significantly more likely and ratings of comfort significantly more likely to be 'uncomfortable' to 'indifferent'. Participants with swollen feet were significantly more likely to rate their boot fit as 'poor' and their boot comfort as 'uncomfortable'.

Irrespective of mine site (Dendrobium or West Cliff) the top listed mining work boot features required for an ideal boot remained the same; waterproof (40%, 33.8%, respectively) and provide ankle support (18.9%, 16.9%, respectively). This finding was despite environmental differences between the two mines, with Dendrobium workers significantly more likely to list working on muddy and uneven surfaces and West Cliff miners significantly more likely to work on dry, hard and flat surfaces.

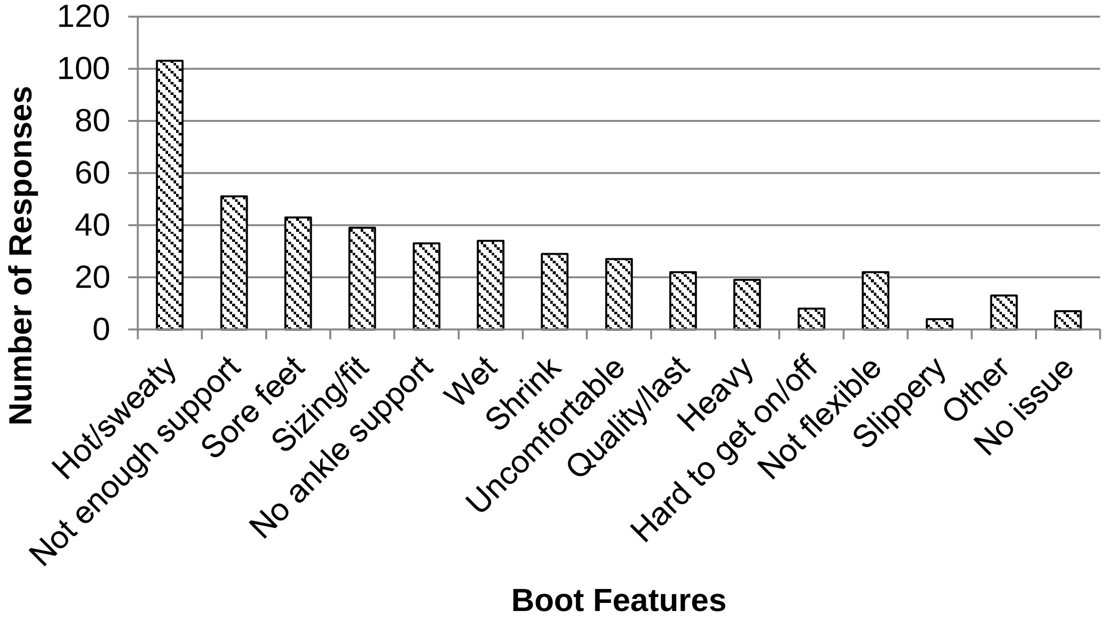


Figure 7: Features participants did not like about their current mining work boots (n = 380).

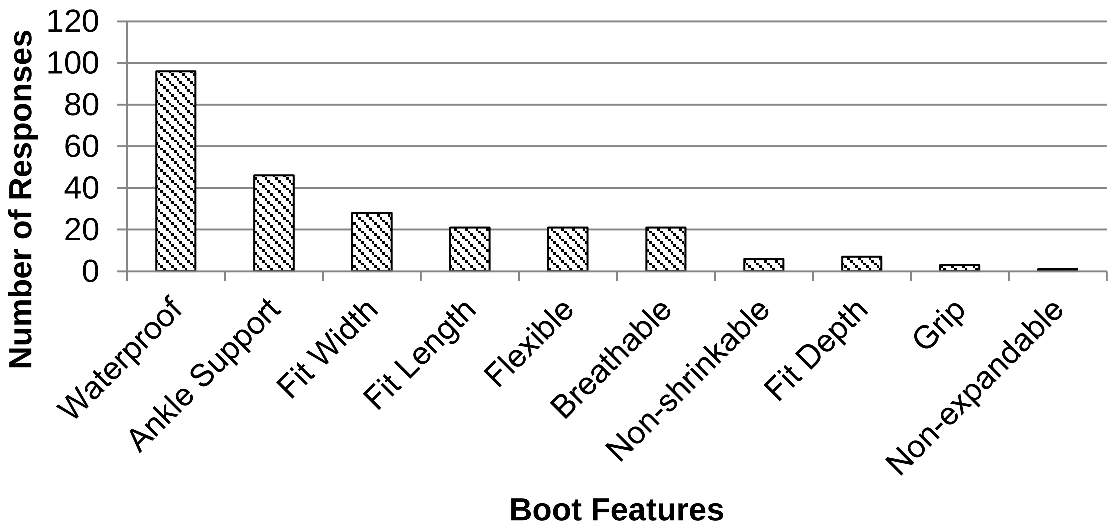


Figure 8: Design features participants preferred to make an ideal boot more comfortable (n = 359).

3.3 Results: Part 2

3.3.1 Work Footwear Habits

Leather lace-up boot wearers were significantly more likely to select fit-length, fit-width, ankle support, comfortable, flexible, fastening method, grip and breathable as preferred features of their current work boot (see Figure 9). Conversely, gumboot wearers were significantly more likely to select waterproof and only option available as why they preferred their current work boot (see Figure 9).

In regards to what underground coal miners did not like about their current work boots, those who wore a leather lace-up boot were significantly more likely to select boot gets wet, shrinks and hard to get on/off (see Figure 10). In contrast, gumboot wearers were significantly more likely to select hot/sweaty and no support as what they did not like about their current work boot (see Figure 10).

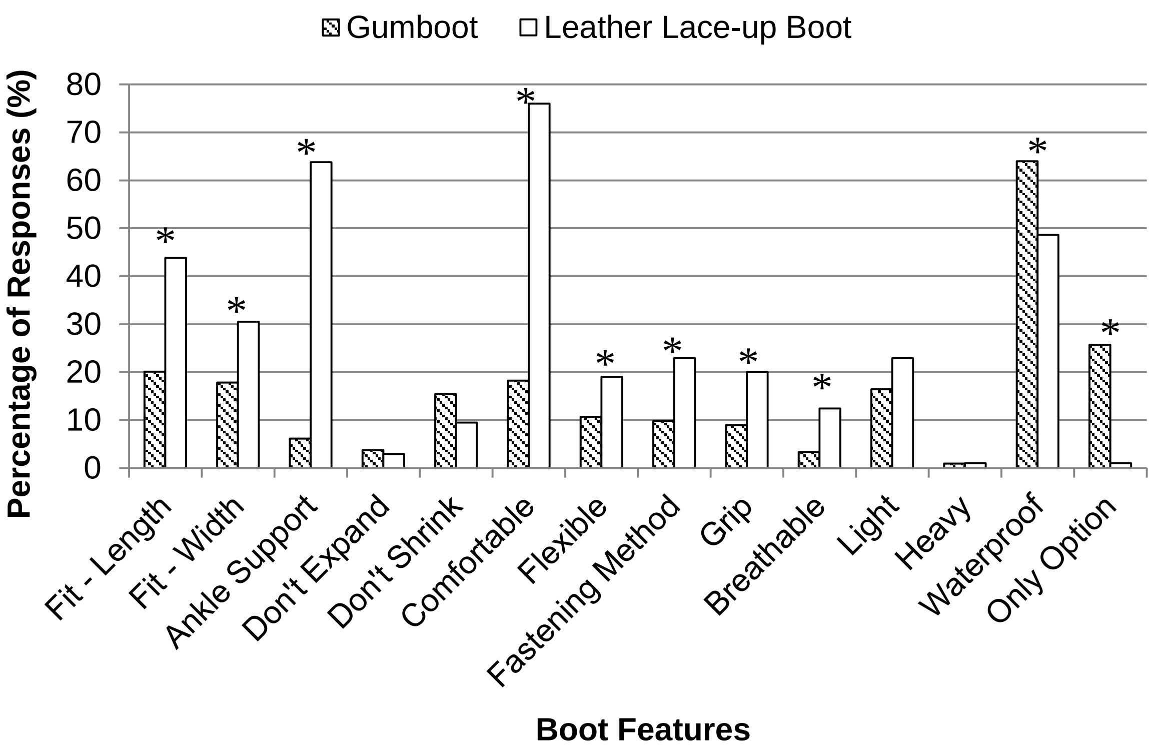


Figure 9: Features participants preferred about their current mining work boots based on work boot worn (gumboot or leather lace-up boot; n = 323). * indicates a significant difference between boots ($p < 0.05$).

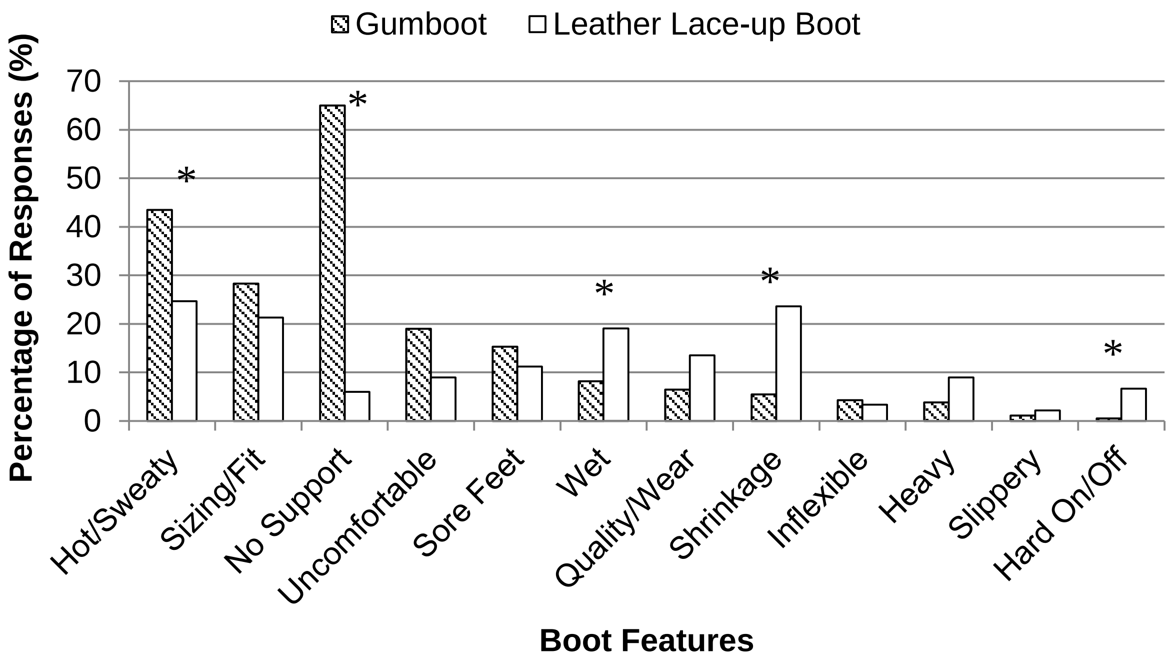


Figure 10: Features participants did not like about their current mining work boots based on work boot worn (gumboot or leather lace-up boot; n = 276). * indicates a significant difference between boots ($p < 0.05$).

3.3.2 Foot Problems, Lower Limb and Lower Back Pain History

There was no significant difference between the gumboot wearers compared to the leather lace-up boot wearers in regards to the reported presence of lower back pain, hip pain, knee pain, ankle pain or foot pain (see Figure 11). The existence of foot problems also did not differ significantly between wearers of the two boot types. However, of those who reported having a foot problem and/or foot pain, there were significant differences between the gumboot and leather lace-up boot wearers in regards to the type and location of the foot problems and pain (see Figure 12). Furthermore, of those participants who reported having ankle pain, leather lace-up boot wearers were significantly more likely to report it occurred 'rarely' (55.3% versus 24.7%) compared to gumboot wearers who were significantly more likely to report their ankle pain as occurring occasionally (50.6% versus 21.3%).

There was no significant difference between gumboot wearers and leather lace-up boot wearers in whether they experienced calluses or blisters. Furthermore, there was no significant difference between gumboot wearers and leather lace-up boot wearers in whether they thought their work boots contributed to their foot pain.

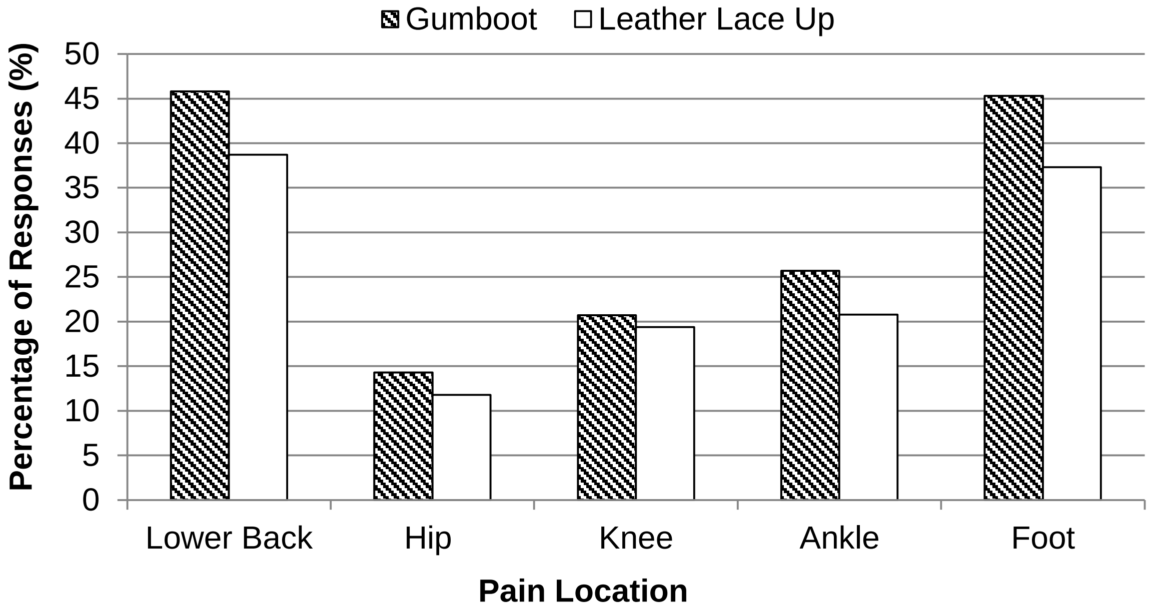


Figure 11: Reported pain incidence based on work boot worn (gumboot or leather lace-up boot; n = 319 foot and ankle pain, n = 263 lower back, hip and knee pain).

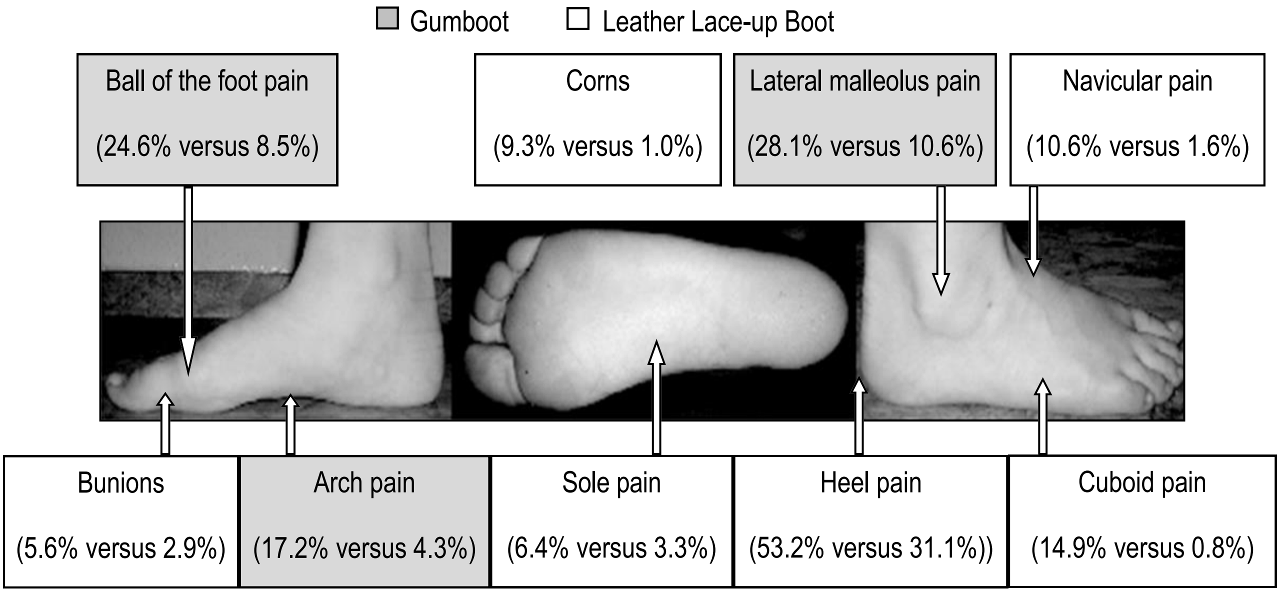


Figure 12: Specific pain locations and foot problems based on the work boots participants reported they were more likely to occur in (percentage of responses; n = 159 foot problems and n = 136 foot pain location).

3.3.3 Work Footwear Fit and Comfort

Comparing responses from participants who wore gumboots versus leather lace-up boots revealed significant differences in regards to ratings of mining work boot fit (see Figure 13) and comfort (see Figure 14). Participants who wore gumboots, compared to leather lace-up boots, stated the fit of their mining work boots was 'poor' (14.5 versus 3.6%; see Figure 13) and their mining work boot comfort was either 'uncomfortable' (24.9% versus 4.6%) or 'indifferent' (45.0% versus 25.7%; see Figure 14). Conversely, leather lace-up boot wearers were significantly more likely to rate their mining work boot comfort as 'comfortable' when compared to gumboot wearers (59.6% versus 27.1%; see Figure 14).

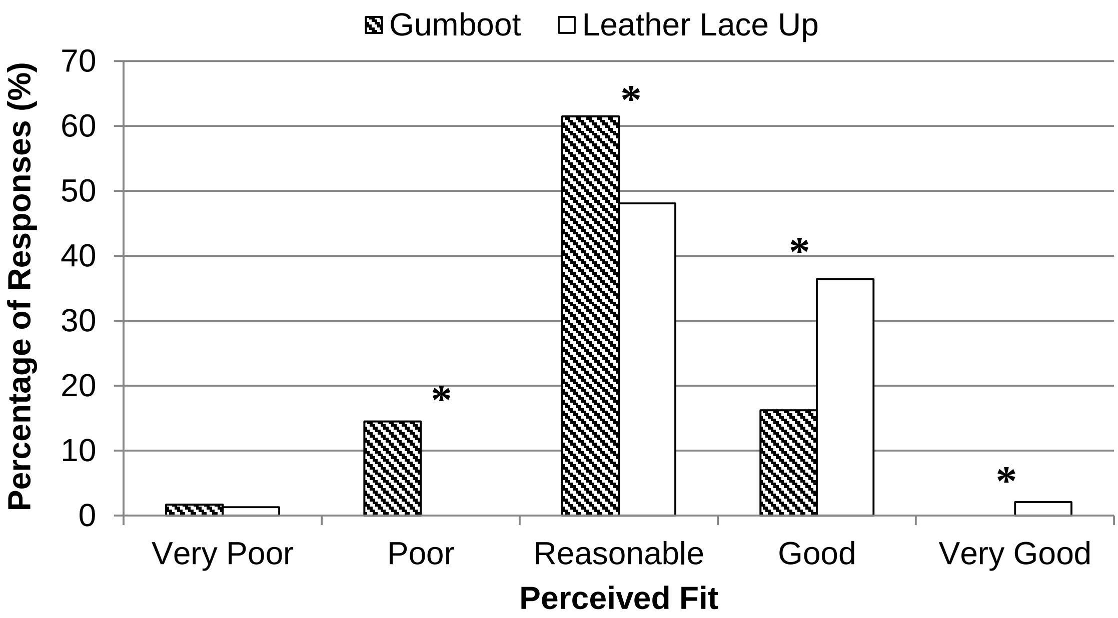


Figure 13: Mining work boot fit ratings based on work boot worn (gumboot or leather lace-up boot; n = 329). * indicates a significant difference between boots ($p < 0.001$).

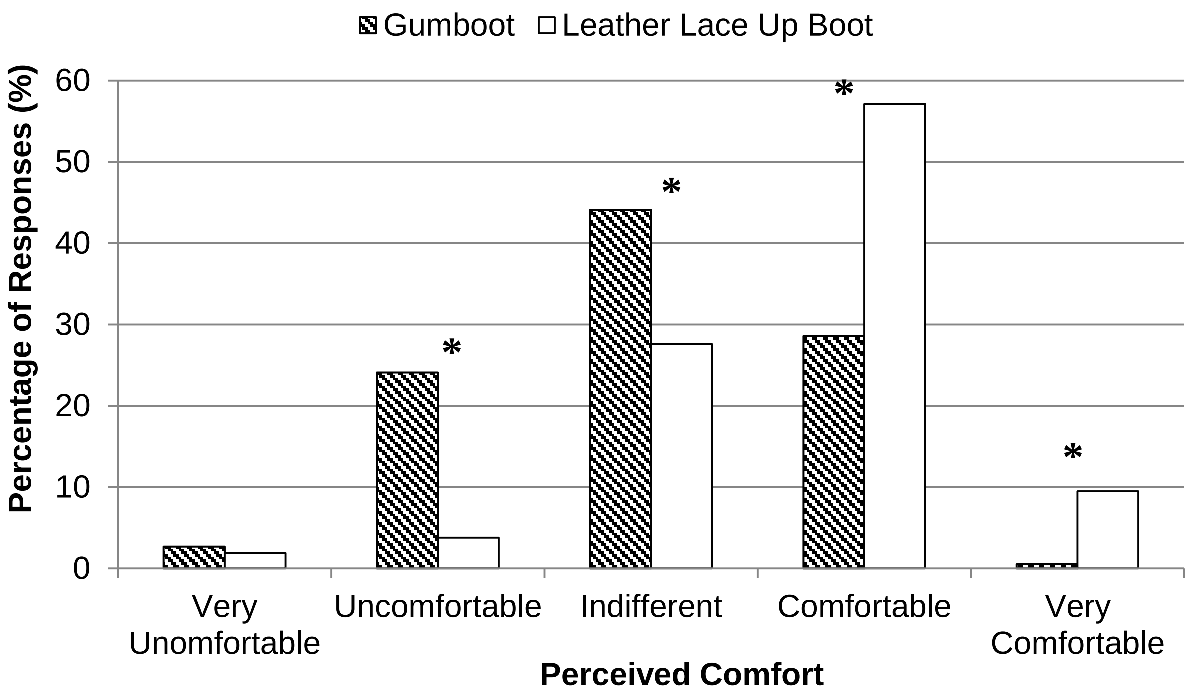


Figure 14: Mining work boot comfort ratings based on work boot worn (gumboot or leather lace-up boot; n = 329). * indicates a significant difference between boots ($p < 0.001$).

Leather lace-up boot wearers were significantly more likely to select a work boot that was larger than their everyday shoe size (40.0% versus 27.1%) compared to gumboot wearers, who were significantly more likely to select a smaller sized work boot (29.4% versus 10.0%). There was no significant difference between what gumboot wearers and leather lace-up boot wearers selected as their first or second choices in regards to what design features would make an ideal work boot more comfortable. Waterproofing was the most common first choice and ankle support the most common second choice across the responses from wearers of both boots type.

3.4 The "Take-Home Message"

Underground coal miners are required to remain on their feet for long periods of time, perform tasks of a physical nature and walk on challenging surfaces that are muddy, uneven and slippery/wet. Current mining work boots do not appear to be meeting the requirements of the underground coal miners who work in this challenging environment. This is evident in the high incidence of foot problems and lower limb and lower back pain reported by the underground coal miners surveyed in this study. More importantly, the miners believe their work boots are contributing to the pain they experience. The introduction a decade ago of a more structured leather lace-up boot as a work boot option has positively influenced perceptions of ankle support, fit and comfort reported by underground coal miners. However, the frequency of foot problems, lower limb pain and lower back pain reported by these miners are still high, irrespective of the work boot type their wear. Although boot type did not alter the incidence of foot pain, underground coal miners reported different locations of foot pain depending on boot type, indicating differences in work boot design have the potential to influence foot pain.

Based on the results of Study 1, we recommended further investigation to identify which specific boot design features caused these observed differences in work boot fit, comfort and locations of foot pain. We also recommended investigating how these boot design features could be manipulated to create an underground coal mining work boot that is comfortable and reduces the high incidence of foot problems and lower limb pain suffered by underground coal miners. The research based on these recommendations is described in the following sections of this report.

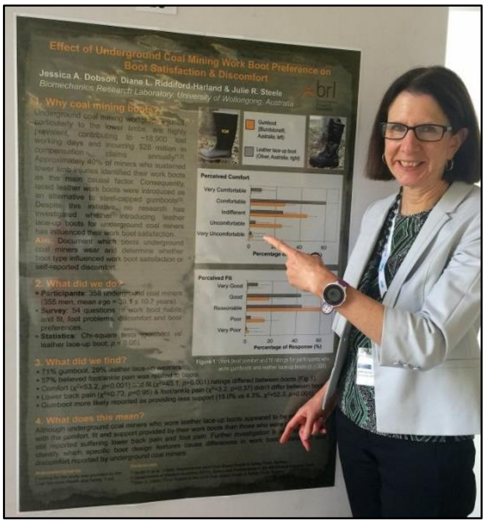
3.5 Outputs[2]

3.5.1 Publications

- Dobson J, Riddiford-Harland DL, Bell A & Steele JR. Underground coal mining work boots do not meet the requirements of underground coal miners. Submitted to *Applied Ergonomics* (waiting for review outcome), 2017.
- Dobson J, Riddiford-Harland DL, Bell A & Steele JR. Effect of work boot type on work footwear habits, lower limb pain and perceptions of work boot fit and comfort in underground coal miners. *Applied Ergonomics* **60**: 146-153, 2017.

3.5.2 Conferences

- Dobson JA, Riddiford-Harland DL & Steele JR. Effect of underground coal mining work boot preference on boot satisfaction and discomfort. *Twelfth Footwear Biomechanics Symposium*, Liverpool, UK, July, 2015.



[2] The publications and conference abstracts listed here are included in the appendices. Publications accepted after this report has been submitted will be sent to the Coal Services Health and Safety Trust Board.

4. Study 2

- Does the three-dimensional shape of underground coal miners' feet match the shape of their work boots? (Part 1)
- How do we fit underground coal mining work boots? Mining work boot fit relative to underground coal miner work boot satisfaction. (Part 2)

4.1 Methodology

4.1.2 Participants

The feet of 270 underground coal miners from Dendrobium and West Cliff mine sites (Illawarra Coal, Australia) were initially scanned. From these data, 208 scans of the feet of all miners (males; age 38.3 ± 9.8 years; height 178.9 ± 5.7 cm, body mass 93.2 ± 12.5 kg) who wore a US size 9, 10, 11 or 12 work boot were selected for analysis. These sizes represented the four most common work boot sizes worn by underground coal miners at Illawarra Coal. The University of Wollongong Human Research Ethics Committee approved all testing procedures (HE11/198) and written informed consent was obtained from all participants before commencing data collection.

4.1.3 Foot Scans

Three-dimensional foot scans (INFOOT three-dimensional foot scanner; I-Ware, Japan) of all the participants' left and right feet were collected. In brief, prior to scanning, 15 felt dots (5 mm diameter and 2 mm thickness) were placed on specific bony landmarks on the left and right foot of the participants following the manufacturer's instructions (Figure 15; I-Ware, Japan). The participants then stood with their bodyweight evenly distributed across their two feet, with one foot placed in the foot scanner. Each foot was scanned three times.

Figure 15: Markers placed on the participants' feet to highlight data points used by the INFOOT three-dimensional foot scanner (I-Ware, Japan) to calculate foot dimensions.

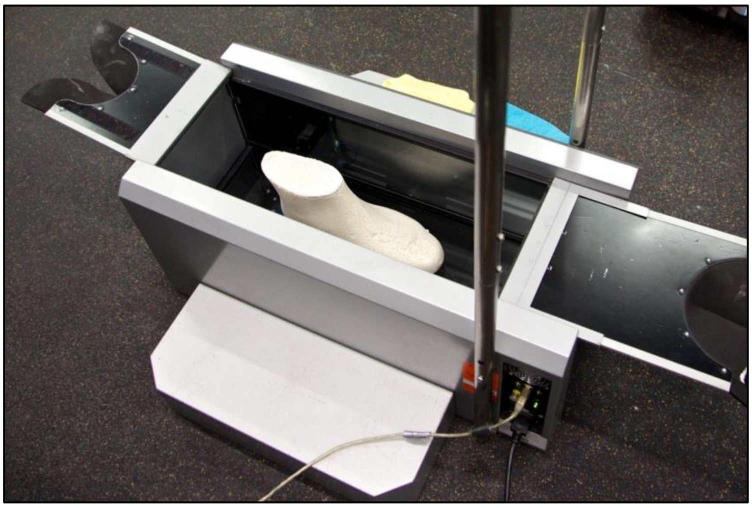
4.1.4 Boot Moulds

The two mandatory safety work boot types provided to underground coal miners at Illawarra Coal were selected as the experimental footwear. These work boots were: (i) a gumboot (Style 015; 2.7 kg; 37.5 cm shaft height; rubber; Blundstone®, Australia), and (ii) a leather lace-up boot (Style 65-691; 3.1 kg; 35 cm shaft height; full grain leather; Oliver, Australia) in sizes 9, 10, 11 and 12. All of the miners who participated in the current study wore one of these boot types, with 60% wearing the gumboot and 40% wearing the leather lace-up boot.

To characterise the internal shape and dimensions of the two work boots, Plaster of Paris moulds of each boot were made (see Figure 16). Plaster of Paris (Uni-PRO, Australia), at a ratio of 1.5 parts plaster to 1 part water, was poured inside each boot and left to dry for a minimum of 72 hours in a climate controlled environment (24.3 degrees C; 64.5% humidity; The Sounding Stone, 2010). Once dry, the hardened Plaster of Paris moulds were manually cut out of the boots and scanned immediately. Three moulds per boot condition (gumboot and leather lace-up) per boot size (9, 10, 11, and 12) for the left and right side were created (i.e. three pairs of boots in total per size per boot condition).

4.1.5 Boot Mould Scanning

To quantify the internal shape and dimensions of each boot size, each boot mould was scanned using the same device that scanned the feet of the underground coal miners. To achieve this, each boot mould was placed one at a time into the scanner, and scanned for 15 seconds whereby the scanner projected two laser beams across the mould and eight cameras recorded the resulting image. The scanning process was repeated four times per mould. A single scan of a mould provided a three-dimensional shape with a resolution of 1 mm. The scanner was calibrated before testing and daily checks were performed before each scanning session, following the manufacturer's instructions (I-Ware, Japan).



Due to the nature of Plaster of Paris, the felt dots used to highlight specific bony landmarks on the miners' feet would not adhere to the boot moulds. Therefore, to allow the same variables to be calculated for the boot moulds and the feet during analysis, the marker positions were manually created after each scan for the most medial and lateral points of the forefoot (see Figure 16). The location of toes 1 and 5 were then approximated, based on the definition that the forefoot was 60-80% of the full length of the mould (Cavanagh & Ulbrecht, 1994; see Figure 16).

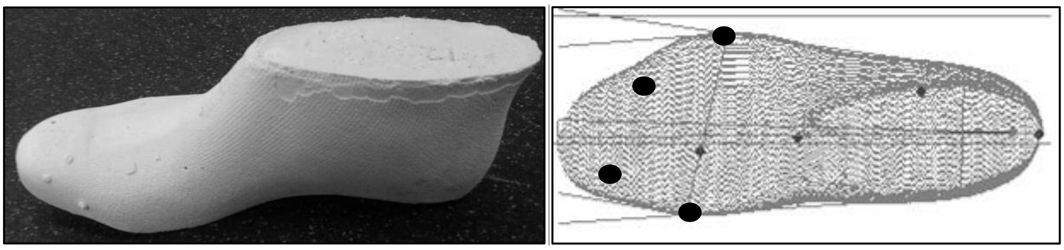


Figure 16: An example mould representing the internal shape of the gumboot and the associated three-dimensional scanned image, showing the four marker locations.

4.1.6 Analysis of the Scanned Images

The scanned images of the participants' feet and the boot moulds were analysed using Diplus software (Di+ 1.0; I-Ware, Japan). Based on the marker positions highlighted in each scan, the following variables were automatically calculated: length (foot length), width (foot breadth, heel breadth, toe 1 angle, toe 5 angle), circumference (ball girth circumference, instep circumference, heel girth circumference) and height (ball girth height, instep height, toe 1 height, toe 5 height; see Figure 17 and Figure 18). These variables were selected for analysis because similar variables have been shown to influence shoe fit based on anthropometric and subjective comfort measures (Miller et al., 2000, Nácher et al., 2006).

The variables derived from the scanning process described above were shown to have high reliability. That is, intraclass correlation coefficients of $R > 0.90$ were achieved when comparing the dimensions calculated for the three foot scans taken for the miners across all boot sizes and for the three boot moulds taken for all sizes in both boot conditions (Portney & Watkins, 1993).

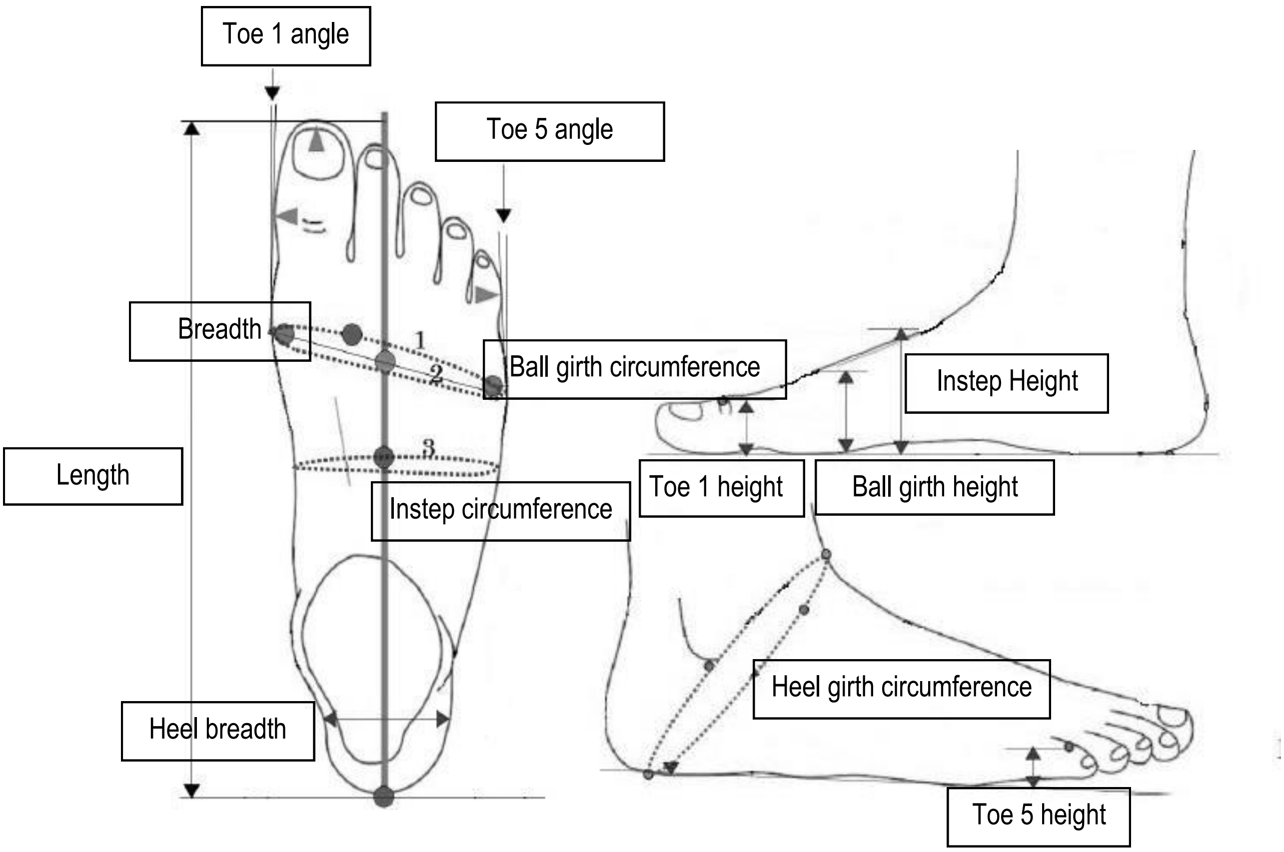


Figure 17: The 12 variables calculated from the participants' feet and the boot moulds based on the marker positions.

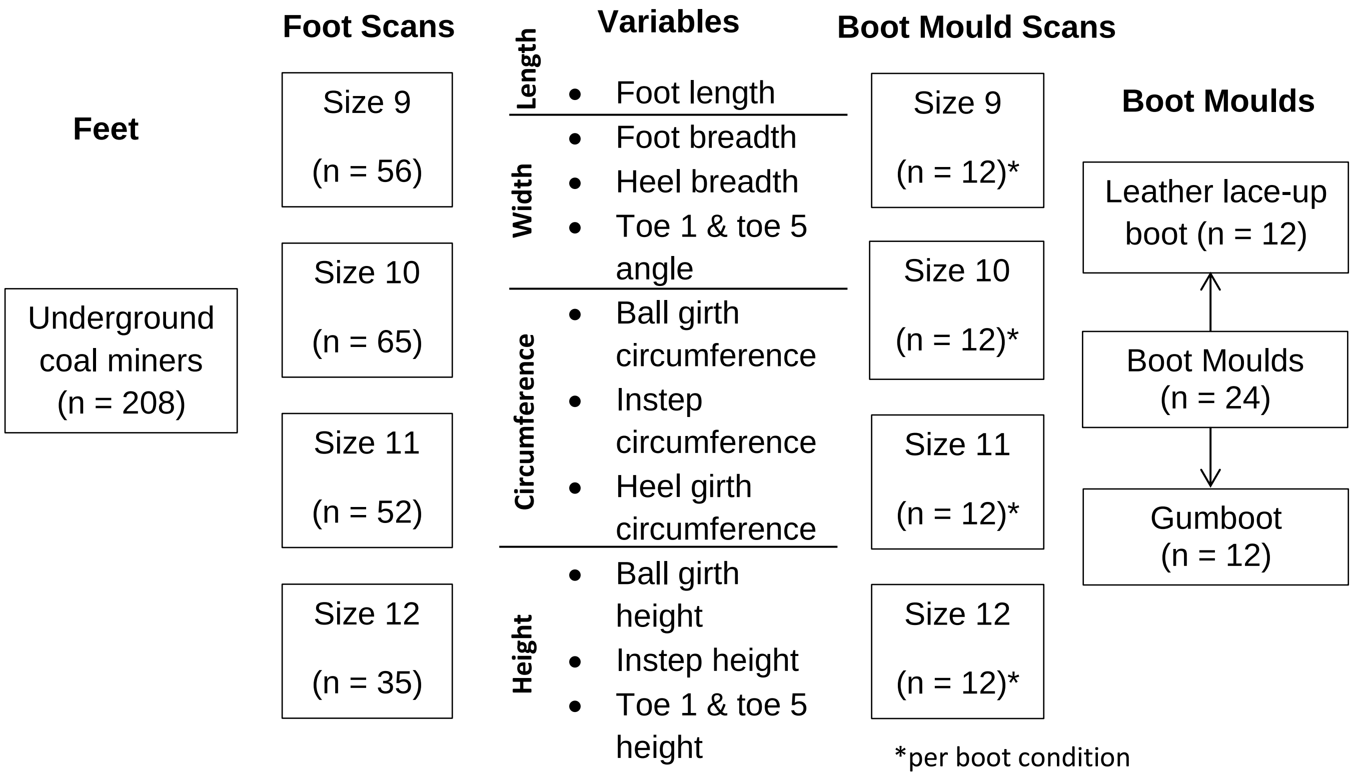


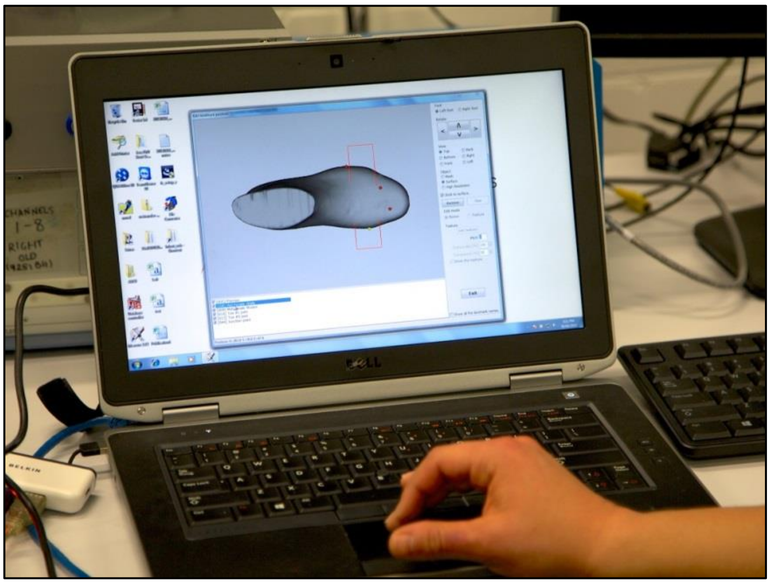
Figure 18: Summary of the experimental protocol: The right feet of 208 underground coal miners were grouped into four sizes while three moulds per boot condition per boot size (9, 10, 11, and 12) were created and scanned four times. The length, width, circumference and height variables were calculated for both the foot scans and boot mould scans.

4.1.7 Statistical Analysis

Descriptive statistics (means and standard deviations) were calculated for the 12 variables for both the right and left feet of the miners and the right and left boot moulds. Paired *t*-tests were then used to determine whether there were any significant differences between the left and right feet of the miners or the left and right boot moulds. As there were no significant differences between left and right (p = 0.27 - 0.98) only data representing the right feet of the miners and the right boot moulds were used in further analyses.

Part 1: A series of independent samples *t*-tests were used to compare the variables derived from the foot scans to the same variables derived from the boot mould scans. These tests determined whether there were any significant differences in the length, width, circumference and height dimensions between the miners' feet and the internal structure of their work boots. The difference between the foot scans and boot moulds for each of the variables were also calculated to represent the "gap" between a miner's foot and the internal edge of their work boot. Positive values indicated a miner's foot was larger than their work boot and a negative value indicated a miner's foot was smaller than their work boot at a given location. A repeated measures ANOVA design with one between factor of boot type (gumboot, leather lace-up boot) and one within factor of boot size (9, 10, 11, 12) was then used to determine whether the gap between the foot scans and boot moulds for each of the variables was consistent across boot type and sizes. Wilks' Lambda multivariate test was used to determine significant main effects and interactions. Where a significant interaction was evident, independent samples *t*-tests were used to determine where the significant differences lay. An alpha level of $p < 0.05$ was used and all statistical procedures were conducted using SPSS statistical software (Version 21, SPSS, USA). Although multiple *t*-tests were conducted, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring an error.

Part 2: Chi-squared tests were applied to the survey data (foot problems, lower limb and lower back pain history and work footwear fit and comfort) and the gap data (the difference between the foot scans representing the participants' feet and the boot moulds representing the internal work boot structure; SPSS Version 21, USA). This analysis identified the relationship between objective measures of mining work boot fit and the underground coal miners' subjective ratings of work boot fit and comfort and reported foot problems, and lower limb and lower back pain history. This design allowed more specific work boot fit recommendations to be determined by identifying what numerical gaps between a miner's feet and their work boot structure were significantly associated ($p < 0.05$) with positive and negative work boot fit and comfort and increased or decreased likelihood of having foot problems, and lower limb and/or lower back pain. A multivariate backward stepwise elimination logistic regression design (SPSS Version 21, USA) was also used to determine which objective measures of mining work boot fit were the strongest predictors of the self-reported lower limb pain, lower back pain and foot problems.



4.2 Results: Part 1[3]

4.2.1 Comparing the Miners' Feet and their Internal Boot Dimensions

Means (± standard deviations) of the 12 variables derived from the scans of the miners' feet and the scans of the gumboot and leather lace-up boot moulds are presented in Table 1. All variables derived from the scans of the miners' feet were significantly different to the variables derived from the scans of the mining work boots, with the exception of toe 5 angle in the gumboot and foot breadth in the leather lace-up boot.

Visual representations of the gap between the foot scans and boot moulds for each of the variables, including all outliers, are displayed in box plots (see Figure 19 (A) to (D)). Outliers in the data were not excluded because, after visual inspection of the data, each one could be explained by the presence of factors such as foot deformities (e.g. hammertoe). These outliers highlight the broad range of feet displayed by underground coal miners. Foot breadth, heel breadth and toe 5 angle were regions where the miners' feet were larger than their work boots.

4.2.2 Boot Type and Boot Size Effect

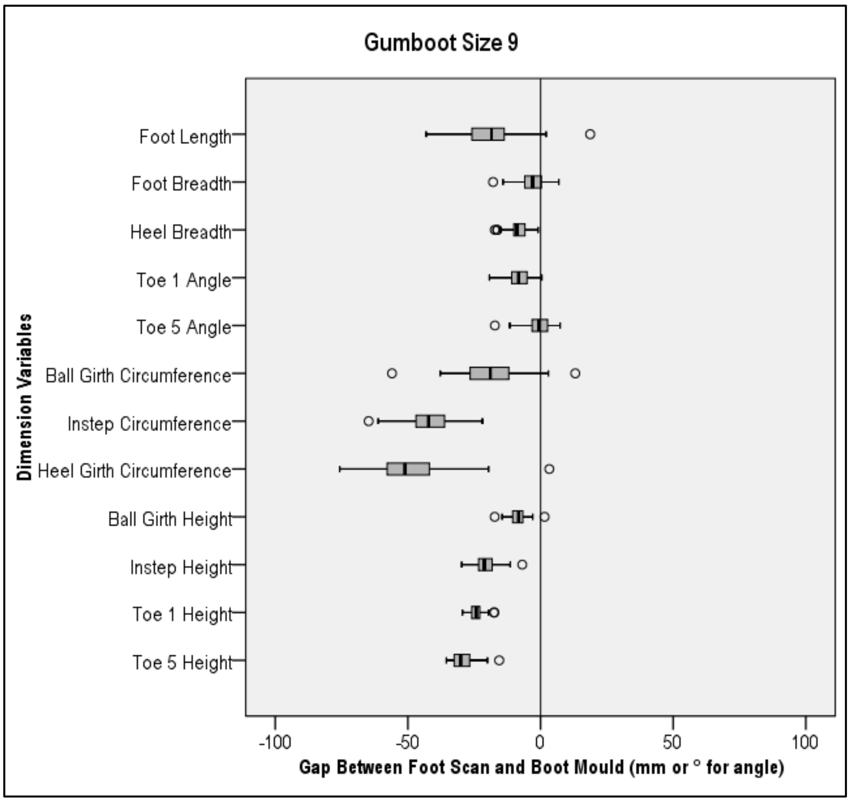
There was a significant main effect of boot type and boot size and a significant interaction of boot type x boot size on the gap data (i.e. the difference between the foot scans representing the miners' feet and the boot moulds representing the internal work boot structure). Upon further investigation, a main effect of boot type was evident for the variables of foot breadth and ball girth circumference, whereby the leather lace-up boot was narrower compared to the gumboot (see Figure 20). There was also a main effect of boot size for the variables of foot length and toe 1 height, whereby the miners' feet were closer to the internal edge of their work boots in the larger boot sizes compared to the smaller boot sizes (see Figure 20). The main effects of boot type were moderated by boot size in the variables of heel breadth, toe 1 angle, toe 5 angle, instep circumference, heel girth circumference, ball girth height, instep height and toe 5 height (see Figure 20). Post hoc analysis revealed that the leather lace-up boot heel girth circumference, instep circumference and instep height were narrower compared to the gumboot, with boot sizes 11 and 12 having less of a gap than the smaller boot sizes. The gumboot heel girth circumference, instep circumference and instep height had a consistent gap across boot sizes, whereas the heel breadth size 12 gap was significantly smaller than sizes 9, 10 and 11. In the leather lace-up boot, the heel breadth gap was significantly smaller in sizes 10 and 11 when compared to size 9. Ball girth height was one of few variables where the gumboot had a smaller gap than the leather lace-up boot and, despite the gap data fluctuating in different directions for the different boots at sizes 10 and 11, size 12 had a similar gap to size 9 in both boot types.

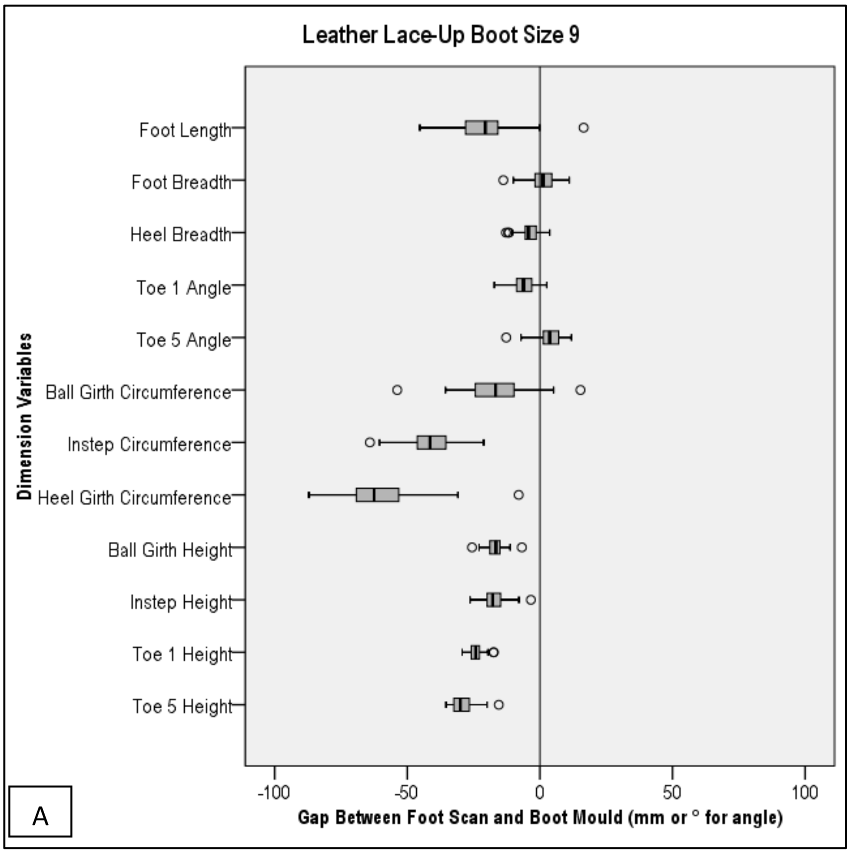
[3] For ease of reading this document, the detailed statistical results are presented in the attached publications.

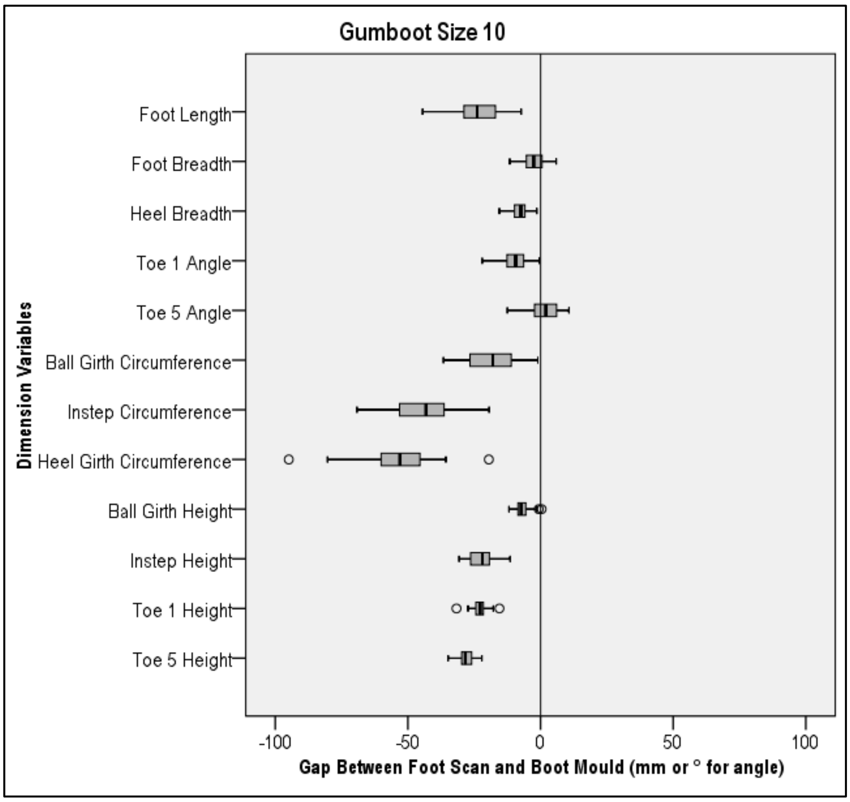
Table 1: Means (± standard deviations) of the gumboot and leather lace-up boot moulds and the miners' foot scans for each of the 12 variables (mm or degrees for angle). Independent samples *t*-test results comparing the gumboot and leather lace-up boot mould scans to the miners' feet are also presented.

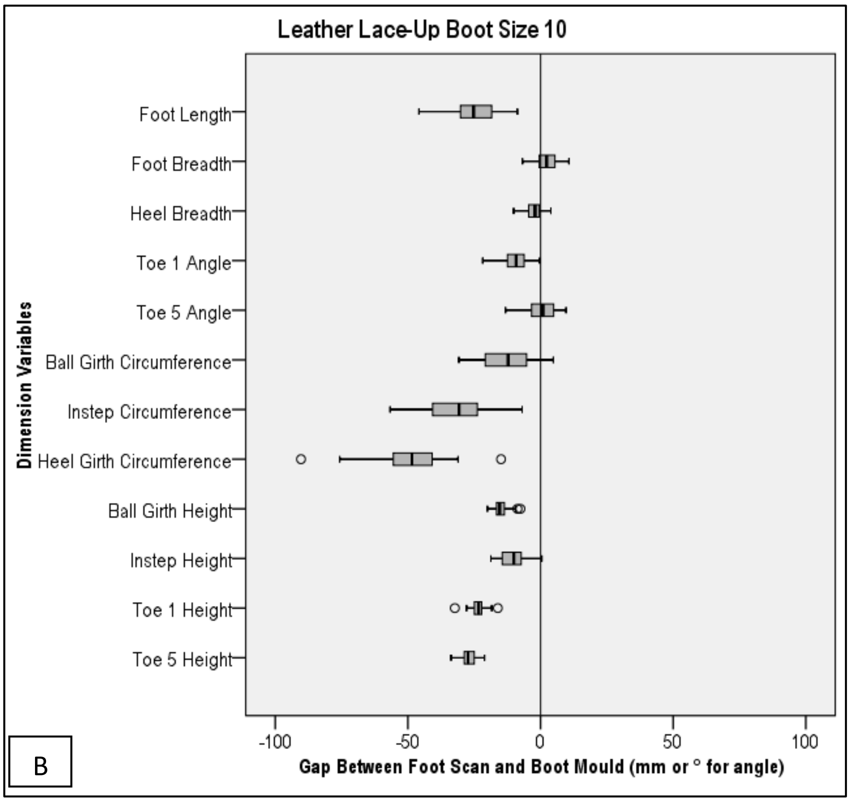
	Variable	*p*-value Gumboot/Feet	Gumboot Mould	Miners' Feet	Lace-Up Boot Mould	*p*-value Lace-Up Boot/Feet
Length	Foot Length (mm)	< 0.001 [a]	298.5 ± 10.6	273.3 ± 11.2	300.7 ± 11	< 0.001 [b]
Width	Foot Breadth (mm)	0.002 [a]	111.9 ± 2.4	109.3 ± 5.5	107.7 ± 2.8	.065
	Heel Breadth (mm)	< 0.001 [a]	77.9 ± 2.8	70.1 ± 4.1	72.8 ± 1.9	< 0.001 [b]
	Toe 1 Angle (°)	< 0.001 [a]	14.9 ± 1.6	5.8 ± 5.3	13.7 ± 2.9	< 0.001 [b]
	Toe 5 Angle (°)	.859	14.3 ± 1.8	13.9 ± 5.2	11.4 ± 2.4	< 0.001
Circumference	Ball Girth Circumference (mm)	< 0.001 [a]	283.2 ± 6.1	265.9 ± 14.7	282.3 ± 8.1	< 0.001 [b]
	Instep Circumference (mm)	< 0.001 [a]	309.1 ± 9.9	266.1 ± 12.5	299.5 ± 5.2	< 0.001 [b]
	Heel Girth Circumference (mm)	< 0.001 [a]	409.4 ± 12.8	356.1 ± 18.4	398.6 ± 11.8	< 0.001 [b]
Height	Ball Girth Height (mm)	< 0.001 [a]	53.6 ± 1.8	45.8 ± 3.7	63.4 ± 3.6	< 0.001 [b]
	Instep Height (mm)	< 0.001 [a]	95.5 ± 4.8	73.9 ± 5.0	85.3 ± 3.8	< 0.001 [b]
	Toe 1 Height (mm)	< 0.001 [a]	49.6 ± 2.2	26.1 ± 3.6	50.1 ± 3.2	< 0.001 [b]
	Toe 5 Height (mm)	< 0.001 [a]	48.6 ± 2.1	19.2 ± 3.6	47.5 ± 2.0	< 0.001 [b]

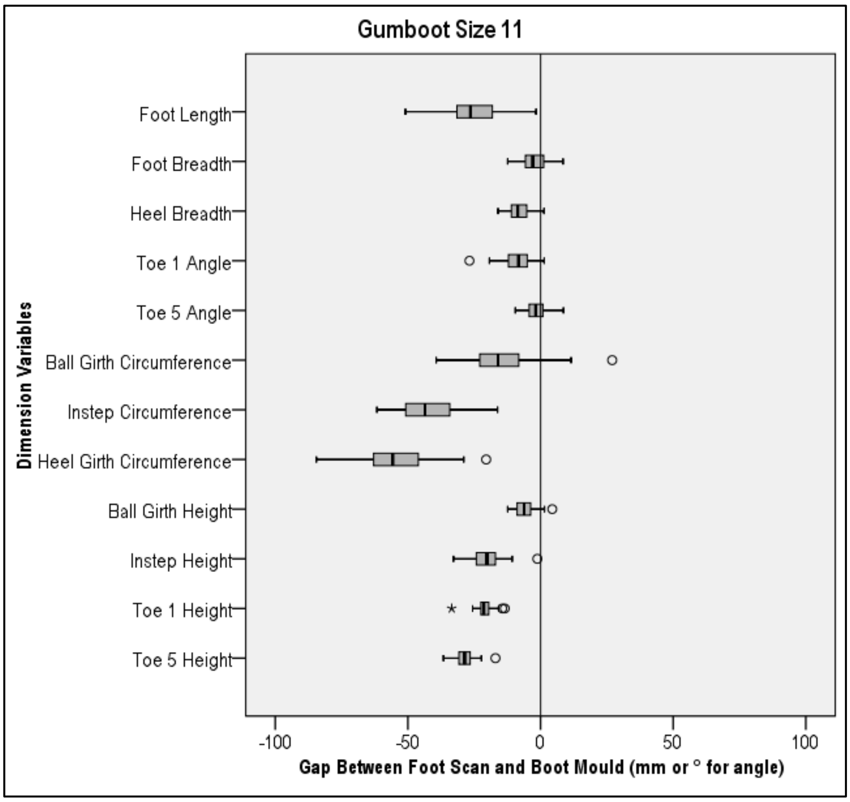
[a] indicates a significant difference between the gumboot and miners' feet ($p \leq 0.05$)
[b] indicates a significant difference between the leather lace-up boot and miners' feet ($p \leq 0.05$)

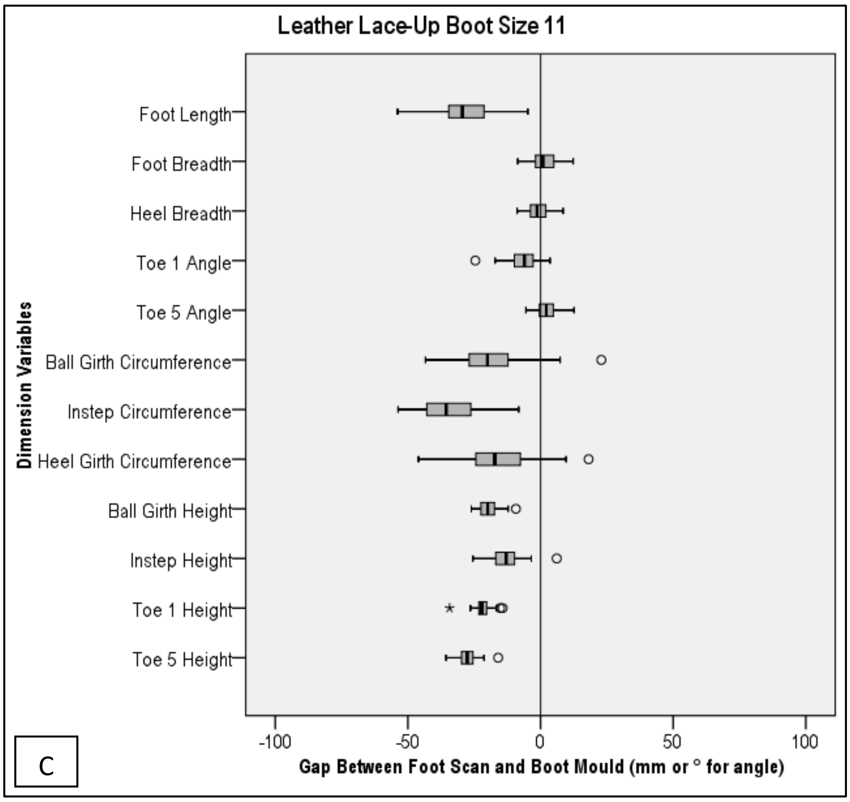

Gumboot Size 9
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)

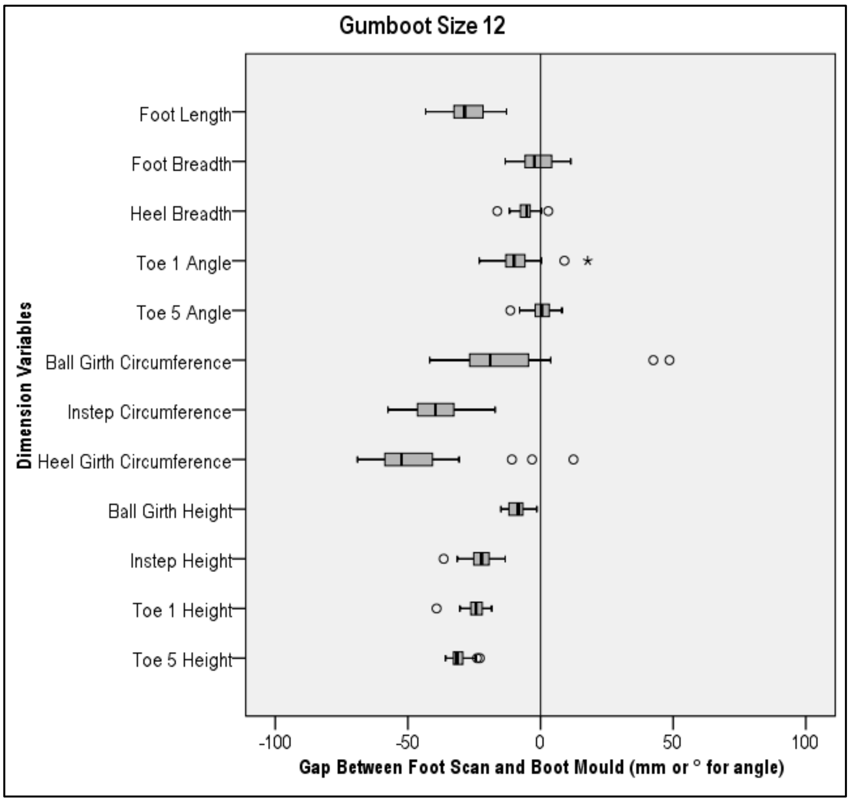

Leather Lace-Up Boot Size 9
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
A
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)


Gumboot Size 10
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)


Leather Lace-Up Boot Size 10
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)
B


Gumboot Size 11
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)


Leather Lace-Up Boot Size 11
Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Instep Circumference
Heel Girth Circumference
Ball Girth Height
Instep Height
Toe 1 Height
Toe 5 Height
Dimension Variables
-100
-50
0
50
100
Gap Between Foot Scan and Boot Mould (mm or ° for angle)
C



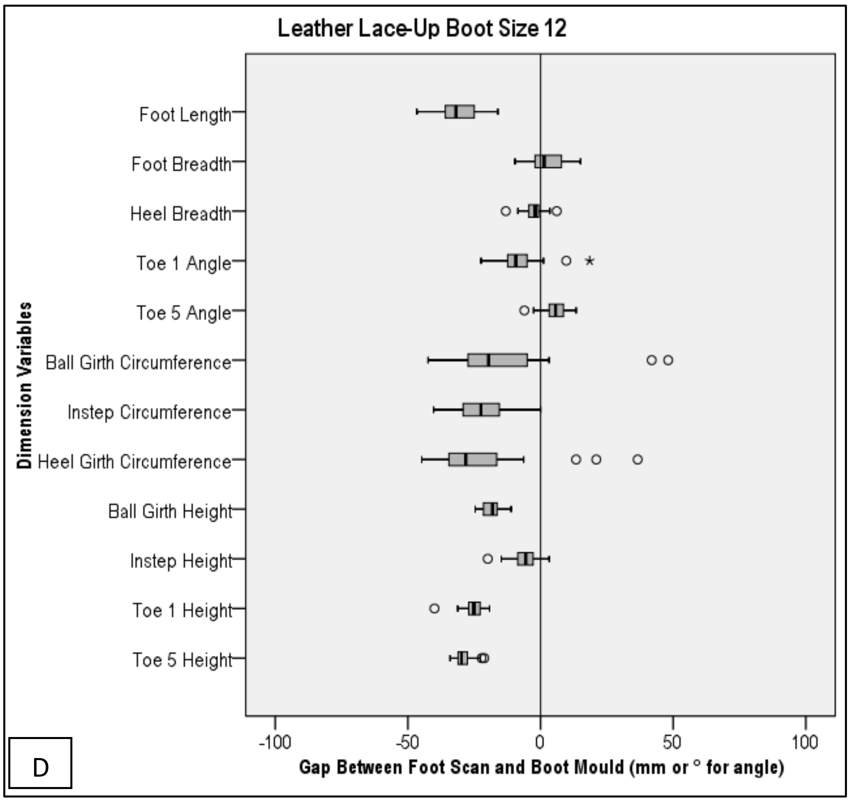
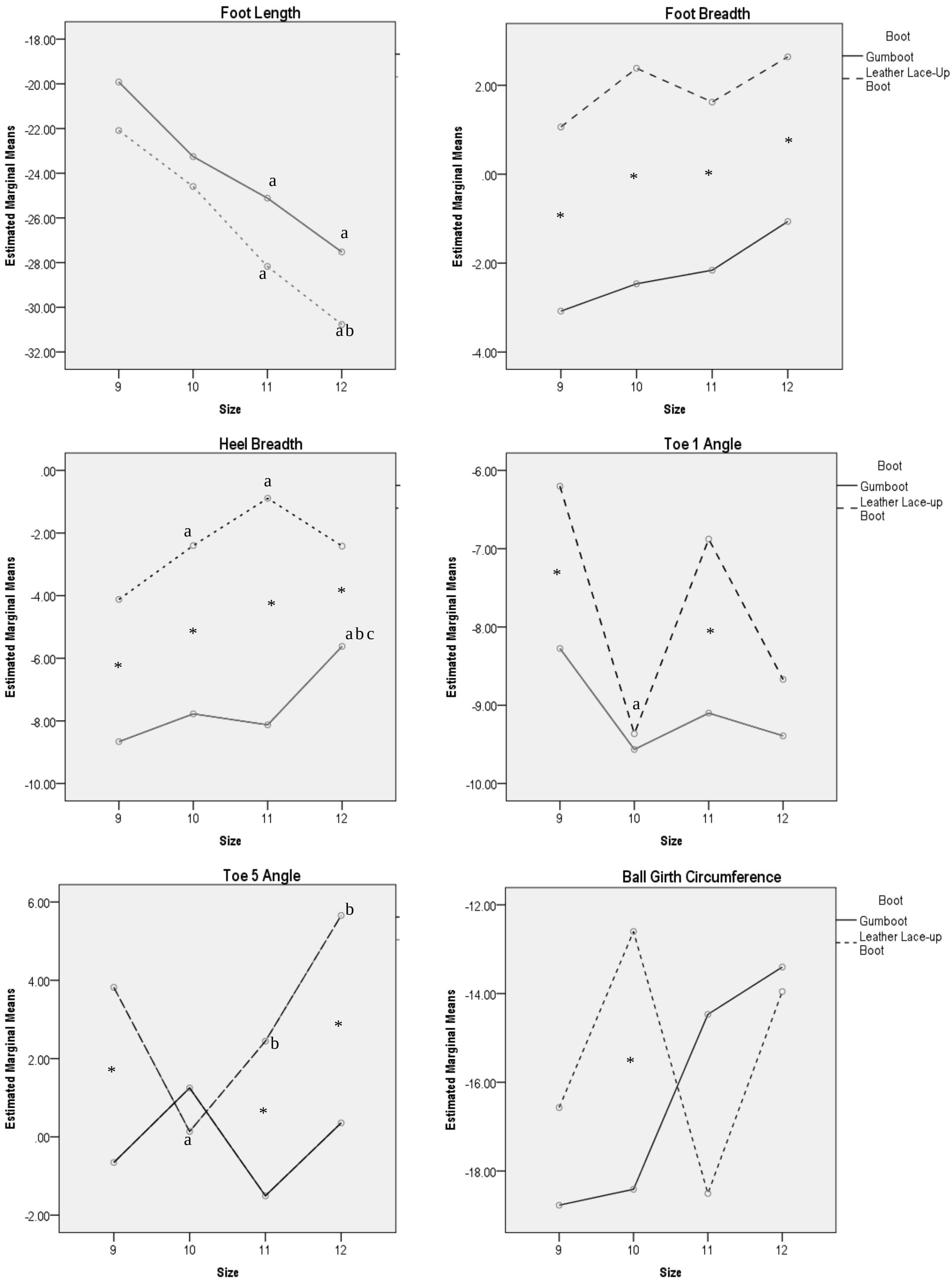
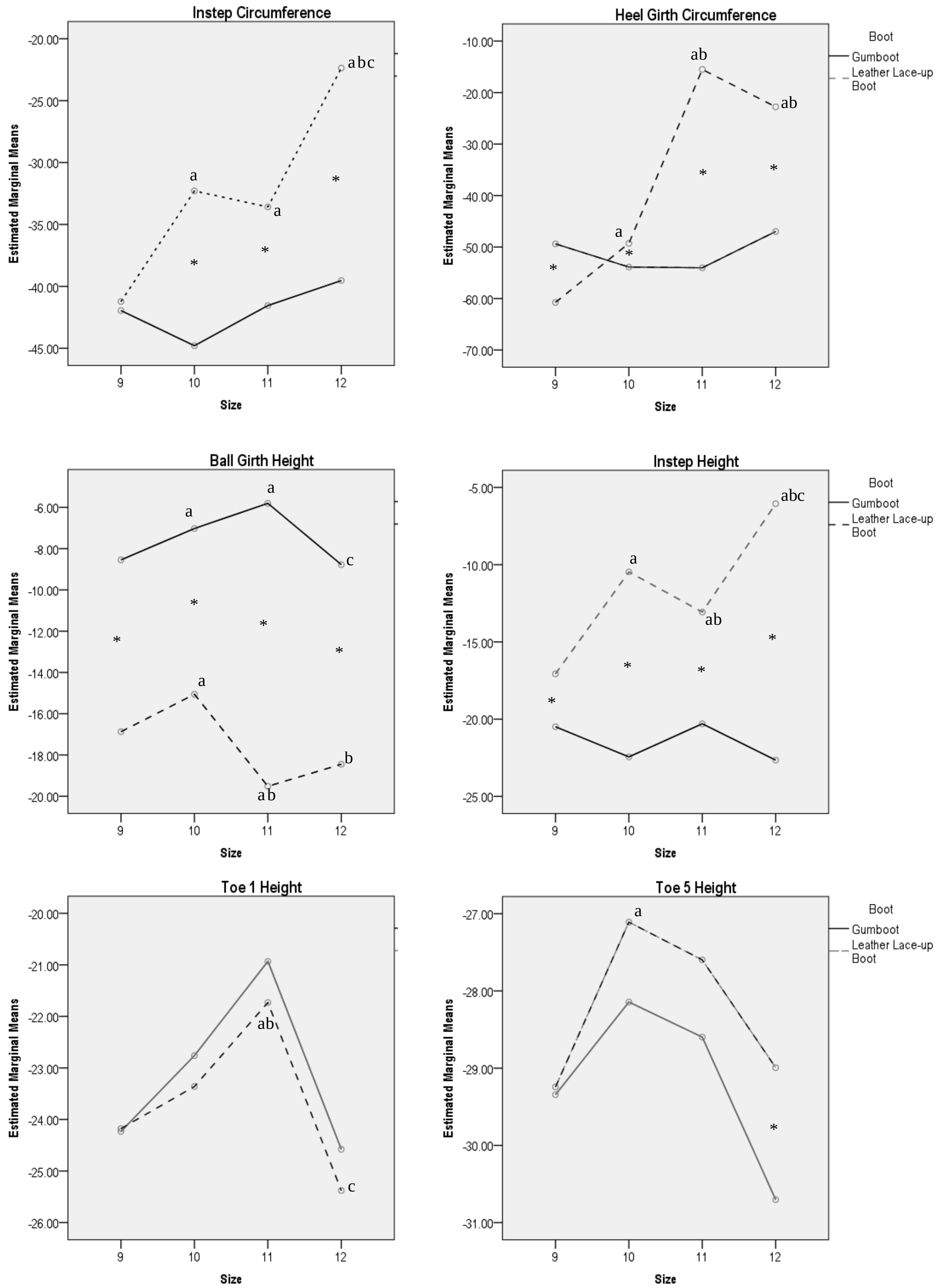


Figure 19: The gap between a miner's feet and their internal boot dimensions for boot sizes: (A) 9, (B) 10, (C) 11 and (D) 12. Values to the left of the 0 line indicate the miners' feet are smaller than their boots and values to the right of the 0 line indicate their feet are larger than their boots.


Foot Length
Foot Breadth
Heel Breadth
Toe 1 Angle
Toe 5 Angle
Ball Girth Circumference
Estimated Marginal Means
Size
9
10
11
12
Boot
Gumboot
Leather Lace-Up Boot
Leather Lace-up Boot
a
ab
abc
b
*



[a] indicates a significant difference to size 9 ($p \leq 0.05$)

[b] indicates a significant difference to size 10 ($p \leq 0.05$)

[c] indicates a significant difference to size 11 ($p \leq 0.05$)

* indicates significant difference between the gumboot (solid line) and leather lace-up boot (dotted line; $p \leq 0.05$)

Figure 20: Boot type x boot size interactions for the 12 variables on the gap data (i.e. the difference between the foot scans representing the miners' feet and the edge of the boot moulds representing their internal work boot structure). Negative values indicate the miners' feet are smaller than their boots and positive values indicate their feet are larger than their boots.

4.3 Results: Part 2

4.3.1 Work Boot Fit and Comfort and Reported Foot Problems, Lower Limb Pain and Lower Back Pain History

Lower back pain incidence reported by the coal miners was significantly related to heel breadth and heel girth circumference difference values. That is, a gap of 40-50 mm at the heel girth circumference and 10-20 mm at the heel breadth led to an increased incidence of lower back pain. Of the miners who reported having foot pain, heel girth circumference gaps significantly affected this occurrence whereby gaps of -30-50 mm led to foot pain occurring more often. Comfort ratings were significantly affected by heel girth circumference and ball girth height with gaps of -20-30 mm appearing to be ideal (see Table 2). Fit ratings were significantly affected by instep height (see Table 2) and ball girth height (see Table 2) gaps with -10-20 mm and -20-30 mm leading to better-fit ratings, respectively. Finally instep height gaps of -30-40 mm significantly affected hip pain incidence such that it was more likely to occur. Of those miners who reported ankle pain, toe 5 angle had a significant effect on how frequent this pain occurred. Gaps of +10-15 degrees (foot wider than the boot internal dimensions) were associated with this pain occurring ‘always’, whereas, gaps of -10-15 degrees resulted in ‘very often’ for ankle pain occurrence. No significant relationships were found in regards to length or foot breadth.

4.3.2 Predictors of Foot Problems, Lower Limb and Lower Back Pain History

Instep circumference and instep height were significant predictors of whether a miner reported having foot pain with an overall prediction success of 57.3%. Toe 1 angle predicted 72.8% of results of whether a miner selected having ankle pain. These results, however, had low Nagaelkerke R Square values (0.044 and 0.30, respectively) and, on further investigation, the relationship between instep circumference and foot pain, and toe 1 angle and ankle pain were only found to be trends (see Table 3).

Instep height significantly predicted (66.7% power) whether a miner had lower back pain whereas instep height, foot breadth and ball girth circumference were significant predictors (88.4% power) of hip pain. Foot breadth and instep height were also significant predictors (61.1% power) of whether a miner reported foot problems. After further investigation, each dimension variable in the equation was significant (see Table 3), although the Nagaelkerke R Square values were low (0.062 lower back pain, 0.157 hip pain, 0.066 foot problems).

There were no significant predictors of whether a miner reported knee pain.

.

Table 2: Significant ($p \leq 0.05$) boot satisfaction relationships for the dimension variables of heel girth circumference, heel breadth, ball girth circumference, instep height, top of ball girth height and instep circumference (based on the gap between the underground coal miners' feet and their internal work boot dimensions where positive values indicate the miners' feet were larger than their work boots and negative values indicate their feet were smaller than their boots).

	Difference	Instep Height	Ball Girth Height	Heel Girth Circumference	Heel Breadth	Ball Girth Circumference
Boot Bigger than Feet	>-50mm			Less likely comfortable		
	-40-50mm			More likely lower back pain 'Often' foot pain		More likely bunions
	-30-40mm	More likely hip pain Very poor fit		'Occasionally' foot pain		
	-20-30mm	Poor fit	Very comfortable Very good fit Less likely uncomfortable	Very comfortable'		
	-10-20mm	Less likely calluses Less likely poor fit	Good fit Less likely indifferent comfort Less likely reasonable fit	Indifferent comfort	More likely lower back pain	
	-0-10mm		Uncomfortable- Indifferent Poor - Reasonable fit Less likely comfortable- very comfortable Less likely good fit - very good fit	Very uncomfortable		
Boot Smaller	+0-10mm		Uncomfortable Poor fit			

Table 3: Dimension variables that significantly ($p < 0.05$) predicted whether a miner had a history of foot pain, ankle pain, lower back pain and foot problems.

History	Dimension Variable	B	S.E.	Wald	df	Sig.	Exp(B)
Foot Pain	Instep Circumference	0.027	0.016	2.813	1	0.094	1.028
	Instep Height	-0.067	0.28	5.874	1	0.015	0.935
Ankle Pain	Toe 1 Angle	0.06	0.031	3.632	1	0.057	1.062
Lower Back Pain	Instep Height	-0.68	0.024	7.9	1	0.005	0.934
Hip Pain	Ball Girth Circumference	-0.103	0.047	4.82	1	0.028	1.257
	Foot Breadth	0.229	0.102	4.974	1	0.026	0.871
	Instep Height	-0.139	0.045	9.609	1	0.002	0.002
Foot Problems	Foot Breadth	0.078	0.003	5.459	1	0.019	1.081
	Instep Height	-0.069	0.033	4.446	1	0.035	0.933

4.4 The "Take-Home Message"

Underground coal miners have previously indicated that although the fit of their mining work boots is reasonable to good, their mining work boots are uncomfortable to wear. When comparing the shape of underground coal miners' feet to the internal dimensions of their work boots, we found underground coal miners wore boots that were substantially longer than their feet, whereas the width of the forefoot and heel areas of the boots were not wide enough for the wearer. It is therefore recommended that boot manufacturers reassess the algorithms used to create boot lasts and make them wider, particularly focusing on adjusting boot circumference at the instep and heel relative to increases in foot length.

Unfortunately, acceptable fit is subjective and vaguely quantified in the literature, making specific design recommendations difficult. We therefore conducted Part 2 to establish the association between objective measures of mining work boot fit and underground coal miners' subjective ratings of work boot fit and comfort and reported foot problems, lower limb pain and lower back pain history. A secondary aim was to establish which objective measures of mining work boot fit were the main predictors of foot problems, lower limb pain and lower back pain.

We found that the gap between a miner's longest toe and the end of their work boot did not influence how the miners rated their work boot fit and comfort, or their reported foot problems, lower limb pain or lower back pain history. Despite recommendations in the literature that a 0-10 mm gap between a miner's foot and the edge of the inside of their work boot (in terms of width) are sufficient, we found this gap was not enough. Gaps of 10-20 mm appeared to be minimum at the instep and ball girth, whereas the gap at the heel was 20-30 mm. The instep (height) and forefoot (foot breadth and ball girth circumference) appear to be important measures to consider when fitting underground coal mining work boots to ensure the work boots are comfortable.

4.5 Outputs[4]

4.5.1 Publications

- Dobson JA, Riddiford-Harland DL, Bell AF & Steele JR. The three-dimensional shape of underground coal miners' feet does not match their internal boot dimensions. Submitted to *Ergonomics* (waiting for review outcome), 2017.
- Dobson JA, Riddiford-Harland DL, Bell AF & Steele JR. Quantifying work boot fit. To be submitted to *Ergonomics*, August 2017.

4.5.2 Conferences

- Dobson JA. Riddiford-Harland DL, Bell AF & Steele JR. Does the 3D shape of underground coal miners' feet match their internal boot dimensions? *7th International Conference on Applied Human Factors and Ergonomics* (AHFE), Orlando, Florida, USA, July 27-31, 2016
- Dobson JA, Riddiford-Harland DL, Bell AF & Steele JR. How do we fit underground coal mining work boots? *Thirteenth Footwear Biomechanics Symposium*, Surfers Paradise, AUS, July 20-22, 2017.
- Dobson JA, Riddiford-Harland DL, Bell AF & Steele JR. Improving work boot fit for underground coal miners. *Human Factors and Ergonomics Society of Australia*, Wollongong, AUS, November 26-29, 2017.

[4] The publications and conference abstracts listed here are included in the appendices. Publications accepted after this report has been submitted will be sent to the Coal Services Health and Safety Trust Board.

5. Study 3

- Does wearing gumboots or leather lace-up boots affect walking on simulated underground coal mining surfaces?

5.1 Methodology

5.1.1 Participants

Twenty male participants (age 33.4 ± 12 years; body mass 84.8 ± 10 kg; height 179.5 ± 7 cm) who matched the demographics of Illawarra Coal (NSW, Australia) underground coal mine workers volunteered to participate in this study. Exclusion criteria included lower limb injuries or foot pain/discomfort that impaired their ability to perform the experimental procedures, or habitual wearing of corrective shoe inserts (such as orthotics). Participants were recruited through Illawarra Coal (NSW, Australia) by advertising on work noticeboards, work newsletters and during mine training sessions. Advertisements were also placed on University of Wollongong notice boards at the University of Wollongong. A priori analysis confirmed that a cohort of 20 participants was sufficient to demonstrate a significant difference between the two footwear conditions with a power of 80% (at an alpha level of 0.05).

5.1.2 Experimental Procedures

After providing written informed consent each participant completed a questionnaire to characterise their normal work footwear patterns. Anthropometric and foot structure measurements and ankle strength and range of motion were then manually recorded. After familiarisation, participants walked at a self-selected pace around a test walking circuit set out at Woonona Coal Services. Perceived comfort, muscle activity, joint angle data and in-shoe pressure data were collected while each participant completed three loops of the entire walking circuit while wearing two different boot types: (i) a slip-on rubber gumboot, and (ii) a leather lace-up boot. These boots were chosen as they are the two main styles of mining work boots provided to underground coal miners in the Illawarra. The University of Wollongong Human Research Ethics Committee (HE13/050) approved all study procedures.

Perceived Comfort: After each loop of the walking circuit the participants rated their perceptions of boot comfort; boot stability; freedom of ankle, knee and hip movement; and difficulty of walking in the boot using a 10 cm visual analogue scale (VAS; Lesage et al., 2012). Following testing, participants were then required to complete a questionnaire, where they were asked to select their preferred boot and comment on why they made this choice.

Muscle Activity: Surface electromyography (EMG) data were recorded for the quadriceps and hamstring muscles. These muscles were selected for analysis due to their superficial location and their role in controlling the knee and hip joints during gait. Furthermore, when negotiating inclined and declined surfaces, previous studies have found that any changes in lower limb muscle activity primarily occur at the knee joint and secondarily at the hip joint, with minimal to no differences at the ankle joint. The filtered signals were analysed in a custom LabVIEW program to measure how hard the muscles were working when the participants walked around the circuit.

Joint Angle Data: A digital video camera was used to film the participants walking the circuit. Two-dimensional knee joint (between the thigh and shank segments) and hip joint (between the thigh and trunk segments) angles at the video frames representing initial contact and at pre-swing were measured directly from the video images.

In-shoe Pressure Data: In-shoe pressure was measured (50 Hz) using Pedar-X (novel$_{\text{gmbh}}$, Germany) insoles. The in-shoe pressure data were used to calculate the timing of initial contact (first contact of the dominant limb with the ground) and pre-swing (dominant limb loses contact with the ground) for participants throughout the specific sections of the walking circuit. Initial contact and pre-swing were selected for analysis in the present study as they rely on co-ordination of the lower limb muscles to position the foot at an appropriate angle to decelerate and to clear the ground, respectively. If abnormal foot contact occurs at initial contact, the risk of slipping is increased and if adequate clearance of the foot is not achieved throughout pre-swing, the risk of tripping is increased. The steps recorded by the in-shoe pressure device were also used to calculate the amount of time participants spent in the stance phase (foot in contact with the ground) and the swing phase (foot swinging through the air) of walking.

The test walking circuit at Woonona Coal Services was designed to replicate the environmental surface conditions that underground coal mine workers typically navigate during their daily work tasks. The specific walking circuit used in this study included approximately 6 m of level walking on a gravel surface, 6 m of incline and 6 m of decline walking on a rocky/gravel surface and 6 m of level walking on a dry compacted dirt surface in order to return to the starting position (see Figure 21)

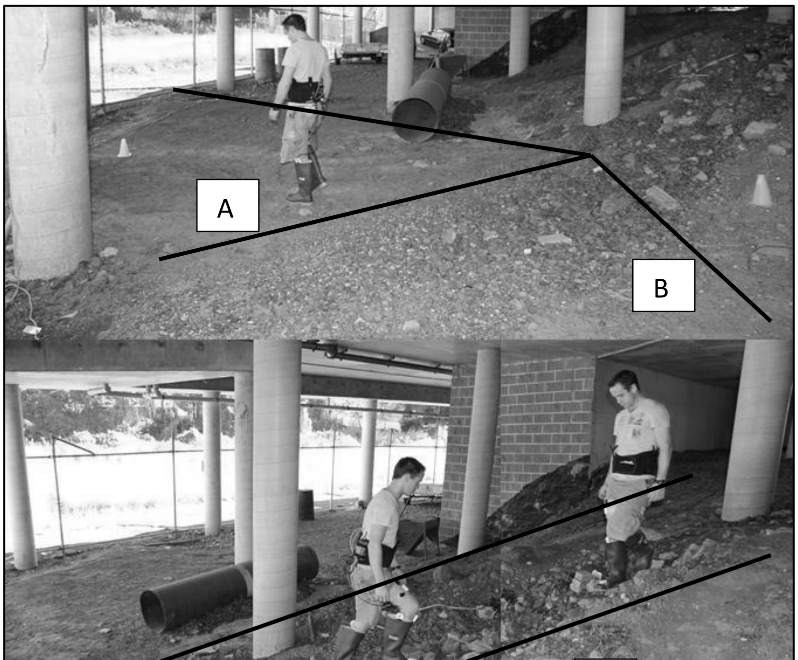


Figure 21: Test walking circuit. A: Flat hard dirt section, B: Flat gravel section and C: Inclined and declined rocky, gravel sections.

5.1.3 Statistical Analysis

A series of paired *t*-tests were initially used to compare the data obtained for the cohort's dominant and non-dominant limb. As there were no significant differences between the dominant and non-dominant limb for foot structure and function, further analyses were restricted to the dominant limb of each participant.

Means and standard deviations of the perceived comfort, muscle activity, joint angle data and in-shoe pressure were calculated over the three walking trials per boot condition per surface condition. Paired *t*-tests were used to compare the comfort results obtained when the participants walked in the two boot conditions. A two-way repeated measures ANOVA design, with two within factors of boot type (gumboot versus leather lace-up boot) and surface (flat gravel, incline, decline and flat dirt) was then used to determine whether there were any significant main effects or interactions of either boot type or surface on the muscle activity, joint angle data and in-shoe pressure displayed by the participants. This design determined whether any of the data were significantly different between the boot types and whether any of these differences were influenced by what surface the participant was walking on and, in the case of the in-shoe pressure data, whether the data was influenced by foot region. An alpha level of $p \leq 0.05$ was used for all statistical comparisons and all tests were conducted using SPSS statistical software (Version 19, SPSS, USA).

5.2 Results

5.2.1 Perceived Comfort

Compared to the leather lace-up boot, participants perceived the gumboot to be significantly easier to walk in as they felt it allowed significantly more ankle and knee movement. The leather lace-up boot, however, was perceived as significantly more stable compared to the gumboot. There were no significant differences between the two boots in regards to perceived comfort and hip range of motion (see Figure 22).

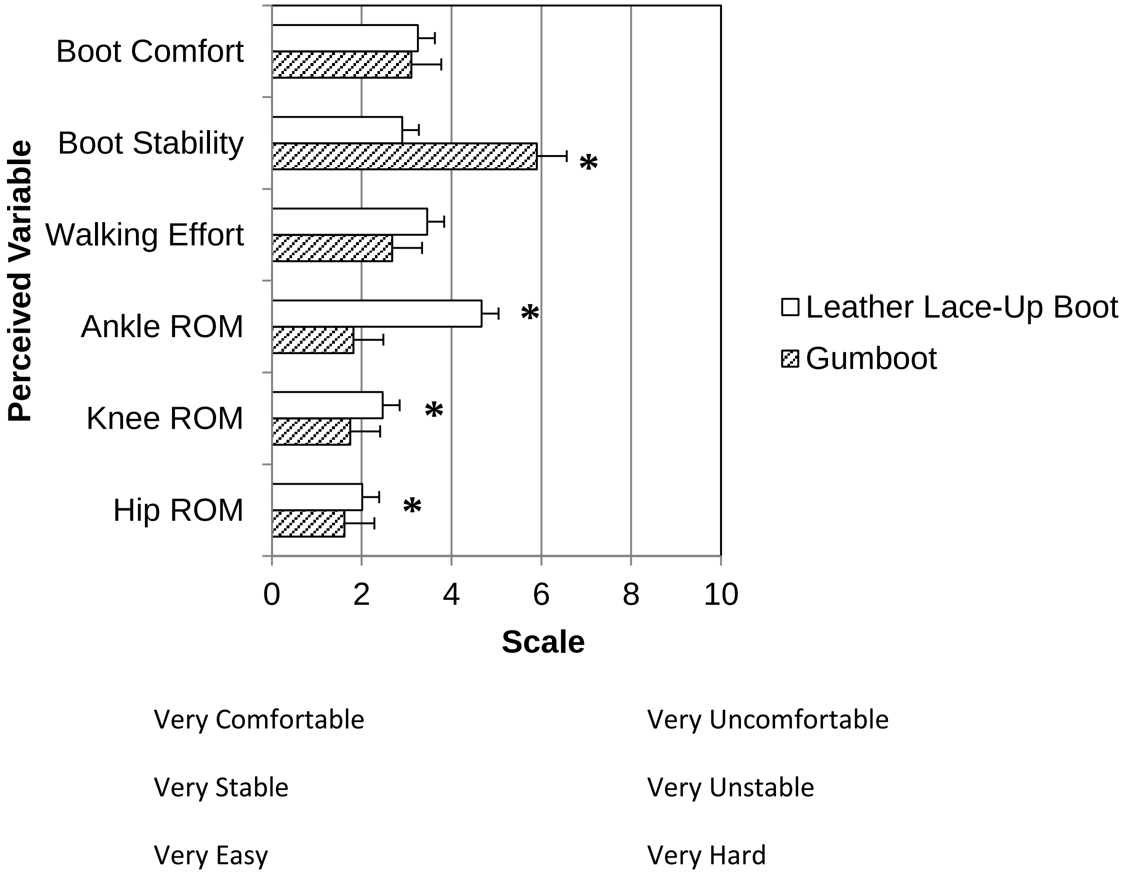


Figure 22: Mean (+ standard error of the mean) scores reported by the participants for their perceptions of boot comfort, boot stability, walking effort and available range of motion (ROM) at the ankle, knee and hip when wearing the gumboot and the leather lace-up boot (n = 20). * indicates a significant difference between the two boots ($p \leq 0.05$).

Of the 19 participants who completed the post-testing questionnaire, 8 participants (42%) preferred the gumboot, 10 participants (53%) preferred the leather lace-up boot and only one participant (5%) did not like either boot. The justifications for boot preference are displayed in Figure 23. When asked about how to the boots could be improved, more ankle support and more breathability were the most common recommendations by the participants for the gumboot, whereas the participants thought that the leather lace-up boot could be improved with changes to the fastening method and flexibility of the boot.

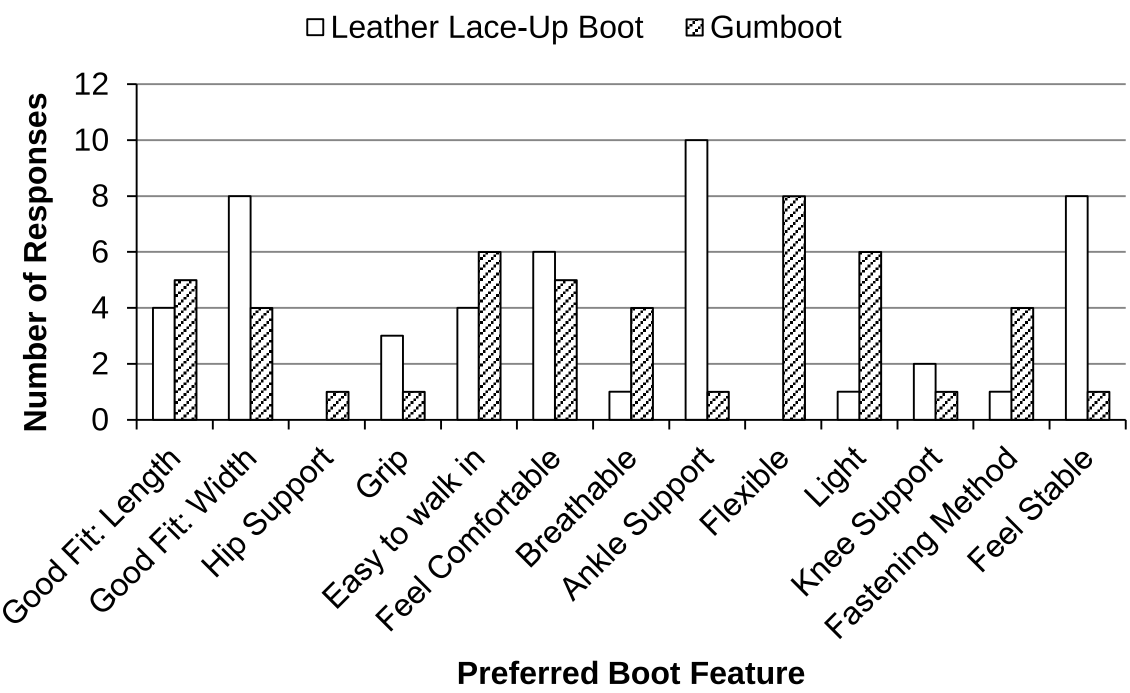


Figure 23: Post-testing questionnaire item responses pertaining to features of the boots that the participants reported they preferred (gumboot n = 8, leather lace-up boot n = 10, neither boot = 1).

5.2.2 Muscle Activity

When participants walked across the flat surfaces (gravel and compacted dirt), no significant differences were found between the gumboot and leather lace-up boot conditions in the average muscle activity for any of the muscles analysed. The inclined and declined walking surfaces, however, revealed significant differences between the gumboot and leather lace-up boot mean muscle activity. Quadriceps (vastus lateralis) and hamstring (bicep femoris) muscle activity significantly increased when participants walked down the declined surfaces while wearing the leather lace-up boot compared to when participants walked down the declined surface wearing the gumboot. Hamstring muscle activity also increased in the leather lace-up boot when participants walked up the inclined surface (see Figure 24).

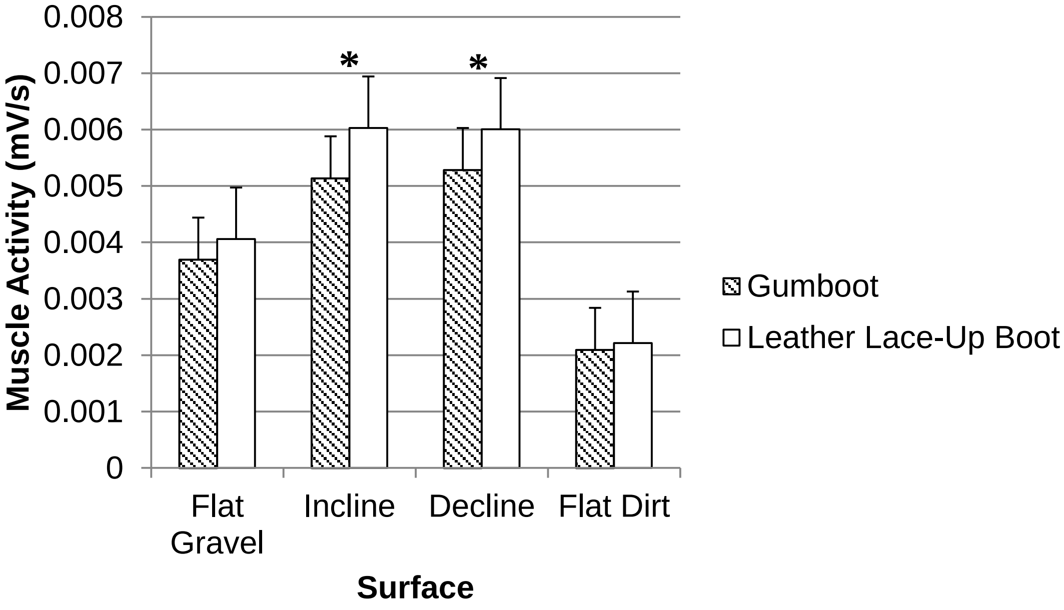


Figure 24: Mean (+ standard error of the mean) muscle activity (mV) of biceps femoris (hamstring) while the participants walked in the gumboot and leather lace-up boot on the different surface conditions. * indicates a significant difference between the two boot conditions ($p \leq 0.05$).

5.2.3 Joint Angle and In-Shoe Pressure

When the participants walked up the incline, their knee was more extended when their foot contacted the ground while wearing the gumboot compared to wearing the leather lace-up boot (see Figure 25). However, when the participants walked in gumboots, compared to the leather lace-up boots, pressure was significantly higher under the mid-foot when walking up the incline and under the forefoot, mid-foot and heel when walking down the decline (see Figure 26).

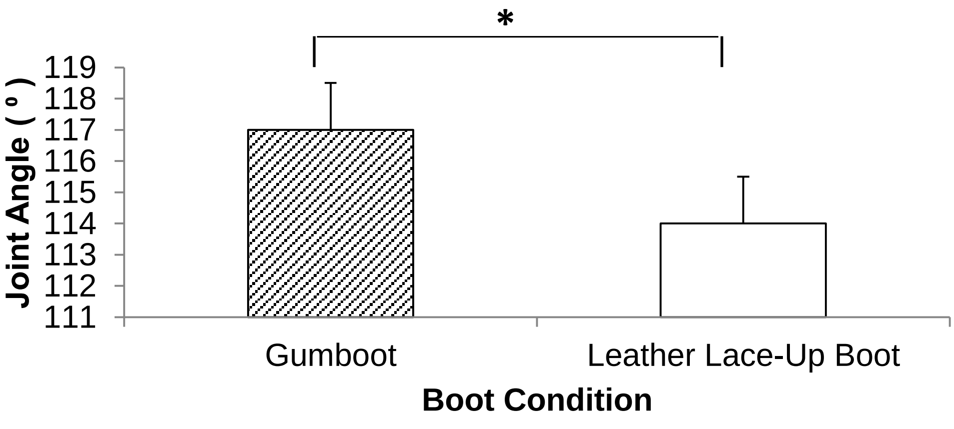


Figure 25: Mean (+ standard error of the mean) knee joint angles (°) when the foot contacted the ground while the participants walked up the incline in the gumboot and leather lace-up boot. * indicates a significant difference between the two boot conditions ($p < 0.05$).

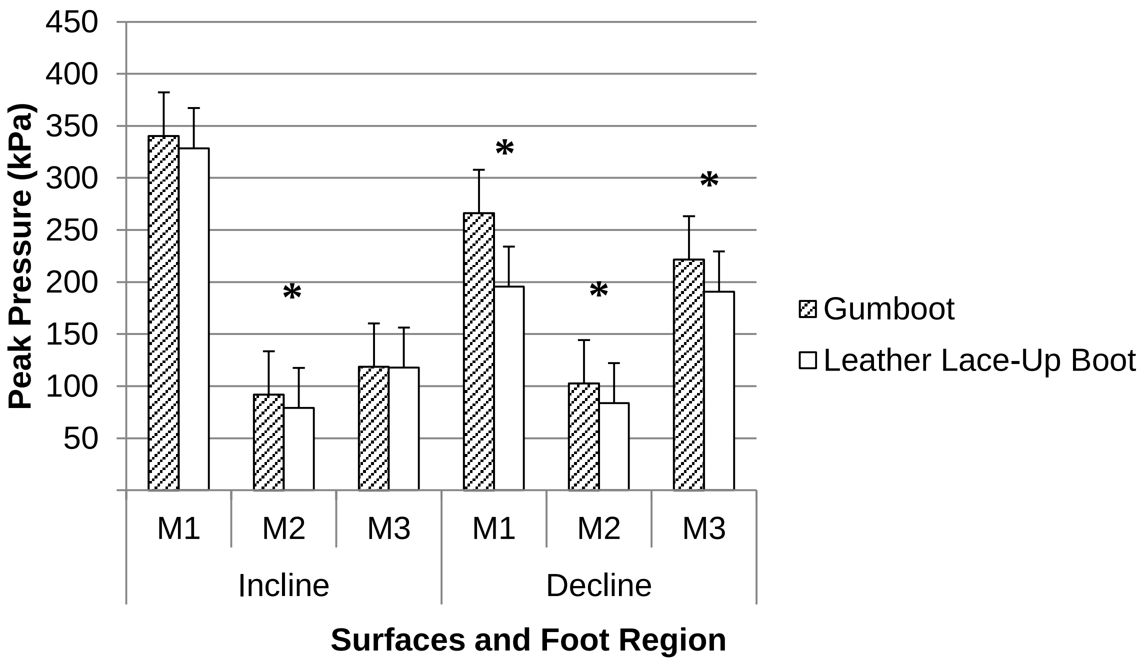


Figure 26: Mean (+ standard error of the mean) forefoot (M1), mid-foot (M2) and heel (M3) peak pressure (kPa) while the participants walked up the incline and down the decline in the gumboot and leather lace-up boot (n = 20). * indicates a significant difference between the two boots ($p < 0.05$).

5.3 The "Take-Home Message"

The aim of this study was to investigate the effects of wearing two different standard steel capped underground coal mining work boots (gumboots and leather lace-up boots) on walking and perceived comfort when walking across simulated underground coal mining surfaces (gravel and compacted dirt). It was found that the structure of an underground coal mining work boot can significantly influence walking and perceptions of comfort when participants walk on uneven surfaces that are typically encountered by underground coal mine workers. It was concluded that walking in a leather lace-up boot resulted in increased muscular activity and increased perceptions of stability due to a perceived reduction in joint range of motion. In contrast walking in a gumboot resulted in increased in-shoe pressure and decreased perceptions of walking effort due to a perceived increase in joint range of motion. As no significant differences were found between the two boots in regards to comfort, we recommended that the preferred features inherent in the two boots were combined into one boot to provide an effective and comfortable boot for walking on underground coal mining surfaces.

There are obviously multiple differences in boot design between the gumboot and leather lace-up boot (e.g. mass, shaft stiffness and sole flexibility). Therefore, to identify which specific features of a boot affect comfort and walking mechanics, it is necessary to systematically alter one structural feature (e.g. boot mass, shaft stiffness, and sole stiffness) at a time, while controlling all other boot features. This research was undertaken in Study 4, and is described below in Section 6.

5.4 Outputs[5]

5.4.1 Publications

- Dobson JA. Effects of wearing gumboots and leather lace-up boots on gait and perceived comfort when walking on simulated underground coal mine surfaces. *Bachelor of Science (Honours) Thesis*, University of Wollongong, 2013.
- Dobson JA, Riddiford-Harland DL & Steele JR. Effects of wearing gumboots and leather lace-up boots on lower limb muscle activity when walking on simulated underground coal mine surfaces. *Applied Ergonomics* **49**: 34-40, 2014.
- Dobson JA, Riddiford-Harland DL & Steele JR. Effects of wearing gumboots and leather lace-up boots on plantar pressures when walking on a simulated underground coal mine surface. To be submitted to *Footwear Science*, 2017.

5.4.2 Conferences

- Dobson JA, Riddiford-Harland DL & Steele JR. The influence of boot and surface type on in-sole pressure and comfort when walking on simulated coal mining surfaces. *7th World Congress of Biomechanics*, Boston, Massachusetts, 6-11 July, 2014.
- Dobson JA, Riddiford-Harland DL & Steele JR. The influence of boot and surface type on in-sole pressure and comfort when walking on simulated coal mining surfaces". *Proceedings of the Expert Scientific Meeting on Load Distribution Measurement*, Cambridge, Massachusetts, USA, 2-6 July, 2014.

[5] The publications and conference abstracts listed here are included in the appendices. Publications accepted after this report has been submitted will be sent to the Coal Services Health and Safety Trust Board.

6. Study 4

- Do changes in work boot shaft stiffness and sole flexibility affect walking on simulated underground coal mining surfaces?

6.1 Methodology

6.1.1 Participants

Twenty male underground coal miners (age 36 ± 13.8 years; height 174.8 ± 6.3 cm, body mass 76.9 ± 9.2 kg) volunteered to participate in this study. Exclusion criteria included lower limb injuries or foot pain/discomfort that impaired their ability to perform the experimental procedures, or habitual wearing of corrective shoe inserts (such as orthotics). Participants were recruited through South32 (NSW, Australia) by advertising on work noticeboards, work newsletters and during mine training sessions. A priori analysis confirmed that a cohort of 20 participants was sufficient to demonstrate a significant difference between the boot conditions with a power of 95% (at an alpha level of 0.05).

6.1.2 Experimental Procedures

After providing written informed consent each participant completed a demographics survey to confirm they satisfied the inclusion criteria and to characterise their normal work footwear patterns. Anthropometric and foot structure measurements and ankle, knee and hip range of motion were then manually recorded. All participants were provided with a new pair of socks (Miners Corp. Essentials Pty Ltd, Australia). Before data collection began, participants completed a functional circuit set out in the Biomechanics Research Laboratory at the University of Wollongong. This circuit (see Figure 27) was designed to replicate common working tasks performed by underground coal miners and was used to familiarise the miners with each new boot condition. After completing the functional circuit, participants performed six walking trials on an uneven and soft surface (see Figure 28). Perceived comfort, muscle activity, three-dimensional motion and in-shoe pressure data were collected for four test boot conditions (see Figure 29). To ensure order effects did not influence the results, boot condition order and surface condition order were randomised. To minimise fatigue, each participant was allowed to rest between completing the functional circuit and each walking trial. The University of Wollongong Human Research Ethics Committee (HE14/396) approved all study procedures.

Perceived Comfort: After each boot condition the participants were asked to rate their perceptions of boot comfort; boot stability; freedom of foot, ankle and knee movement; and difficulty of walking in the boot using a 12 cm visual analogue scale (VAS; Lesage et al., 2012). Following testing, participants were then required to complete a questionnaire, where they were asked to select their preferred boot and comment on why they made this choice.

Muscle Activity: Surface electromyography (EMG) data were recorded for the following muscles: vastus lateralis, semitendinosus, gastrocnemius, tibialis anterior and peroneus longus. These muscles were selected for analysis due to their superficial location and their role in controlling the ankle and knee joints during walking. The filtered signals were analysed in a custom MatLab program to measure how hard the muscles were working when the participants walked along the surfaces.

Three-Dimensional Motion: The three-dimensional motion of each participant's dominant leg was measured using an OPTOTRAK® Certus motion analysis system (Northern Digital Inc., Canada). Twenty-one markers were attached to specific landmarks on each participant's leg to track their leg movement while they walked. This allowed the participant's ankle, knee and hip range of motion to be calculated. How each participant's ankle moved within their boot was also captured using a twin-axis electronic goniometer (Biometrics Ltd, UK).

In-shoe Pressure Data: In-shoe pressure was measured using Pedar-X (novel$_{gmbh}$, Germany) insoles. The in-shoe pressure data were used to calculate how much pressure and force was being loaded through the foot while walking and the area of the foot that contacted the ground.

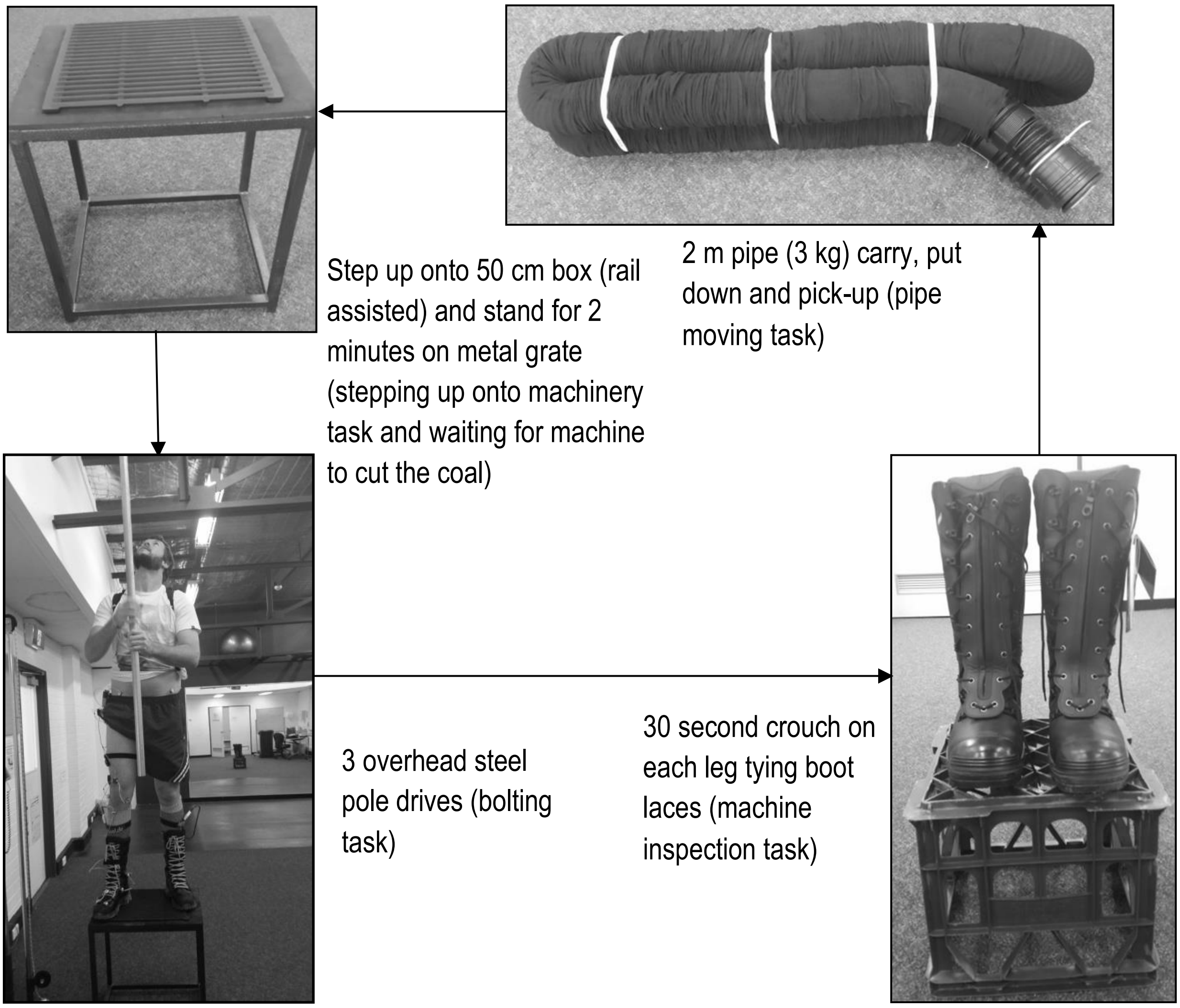


Figure 27: Simulated working task circuit including stepping up onto a box, carrying a pipe, driving a pole overhead and crouching down.

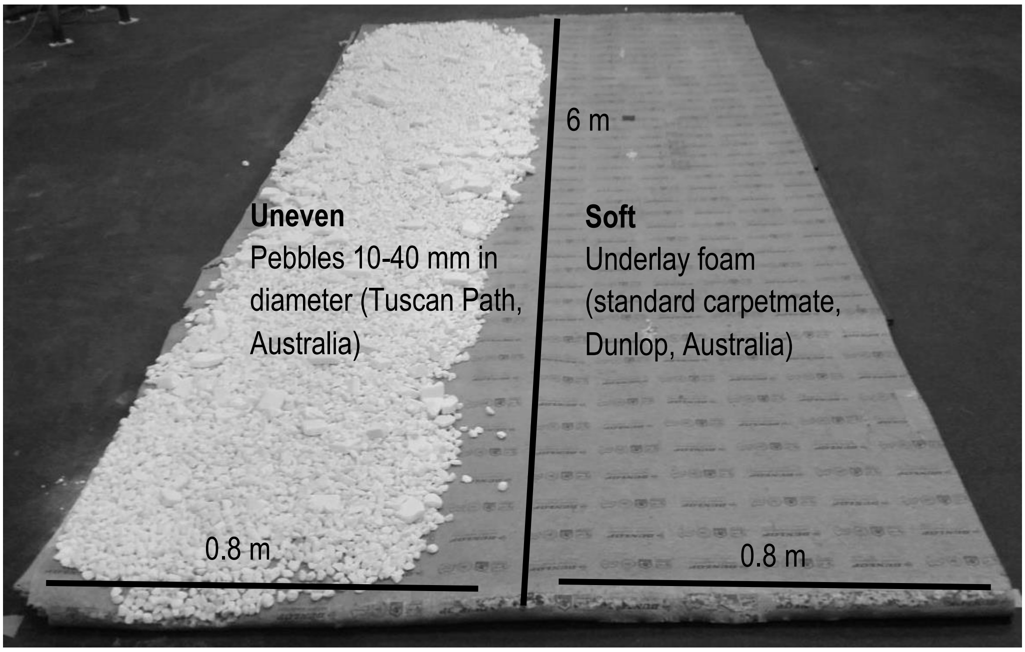
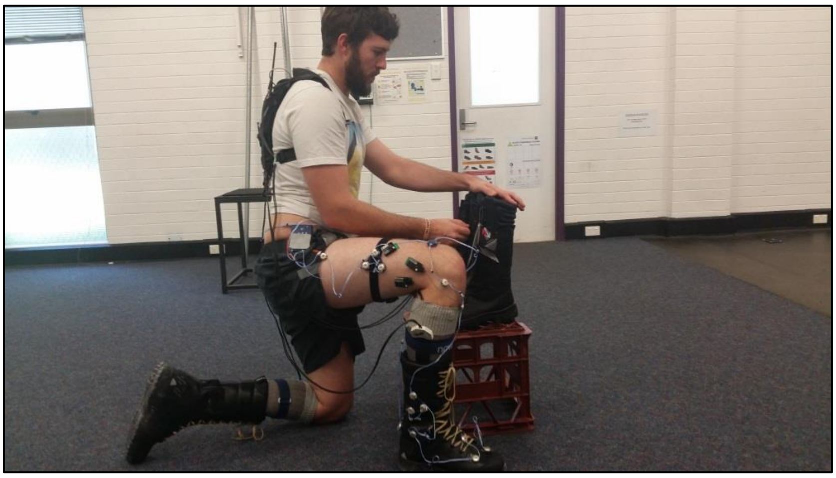


Figure 28: Uneven and soft surfaces used for the walking trials. These surfaces were designed to simulate the "feel" of underground coal mining surfaces in a laboratory environment.

6.1.3 Boot Conditions

The four boot conditions included a boot with a flexible shaft and stiff sole (Boot 1), a stiff shaft and stiff sole (Boot 2), a stiff shaft and flexible sole (Boot 3), and a flexible shaft and flexible sole (Boot 4; see Figure 29). These boot conditions were selected as shaft stiffness and sole flexibility are two key boot design features that affect walking and appear to interact with one another (Dobson et al., 2017b). Differences in the materials the boot shafts were made out of created differences in shaft stiffness (see Table 4). A Stanley knife was used to create slits across the sole of the boot at the approximate point where the metatarsophalangeal joint flexes during walking to create the flexible sole conditions. The full details of the boots are presented in Table 4. Participants were blinded to the test boot conditions to prevent bias in their scores of comfort. The boots were colour coded during testing (red, blue, green and yellow) to also blind the researchers during testing and during analysis.



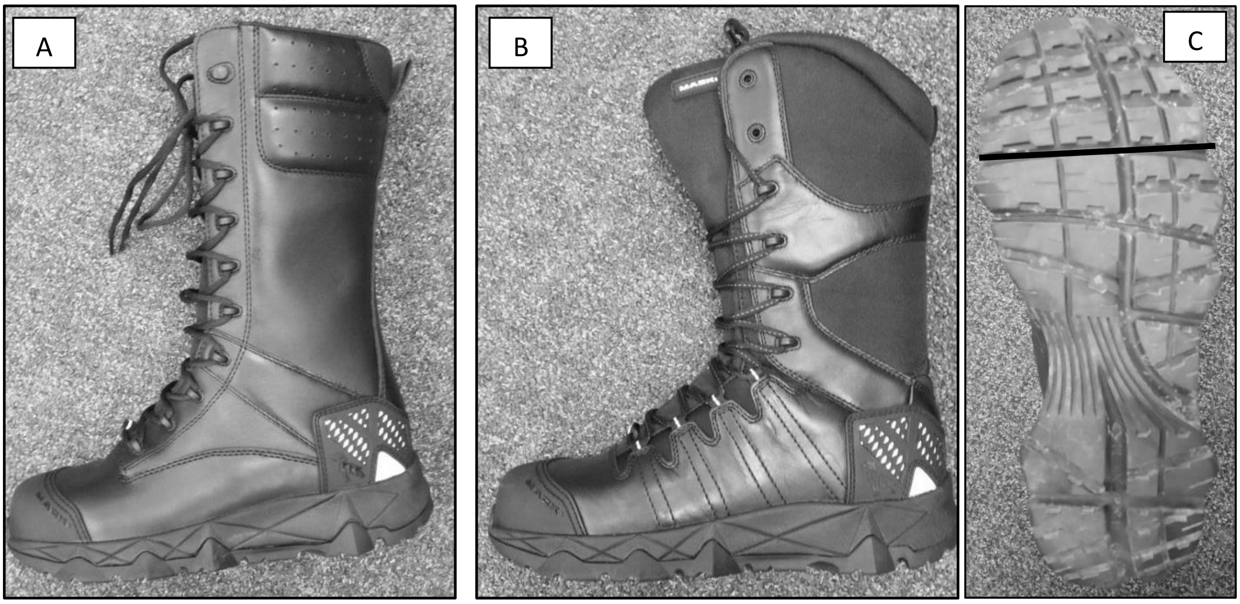


Figure 29: The test boots: (A) the stiff shaft condition, (B) flexible shaft condition, and (C) line where sole was cut to be create the flexible sole condition. The boots were custom made for the study by Mack Boots, Bunzl Brands and Operations, Erskine Park, NSW.

In order to systematically test the effects of shaft stiffness and sole flexibility, all other boot design features were kept the same. Due to the lighter material in the flexible shaft boots there was a 40 g difference in weight between the boots. Therefore, small fishing sinkers (Size 1, Rogue, Australia) were attached to several points across the shaft of the boots with flexible shafts to make sure the boots had the same overall mass. Based on our earlier studies, the boots were made wider across the forefoot and heel relative to standard safety work boots.

Table 4: Boot design characteristics (Mack Boots, Bunzl Brands and Operations Pty Ltd, Australia).

Boot 1 and 2

Variable	Boot 1 (Flexible Shaft+ Stiff Sole)	Boot 2 (Stiff Shaft+ Stiff Sole)
Mass (kg)	0.94	0.98
Shaft Height (cm)	29.5	30
Shaft Stiffness (N)*	1.1	1.7
Shaft Material	Nappa leather: full leather with reinforced sections around ankle	Nappa leather + nylon: elasticised material between each eyelet to allow expansion and contraction
Midsole Hardness (Shore)	58	58
Midsole Material	Phylon	Phylon
Outsole Hardness (Shore)	68	68
Outsole Material	Nitrate rubber (resistant to 300°C)	Nitrate rubber (resistant to 300°C)
Sole Flexibility (°)**	30.2	20.3
Heel Height (cm)	4	4
Heel Sole Width (cm)	10	10
Forefoot Sole Width (cm)	13	13
Footbed Material	Breathable PU sole response foam	Breathable PU sole response foam
Insole Material	Woven polyester (penetration resistant)	Woven polyester (penetration resistant)
Fastening Method	Laces – Flat waxed 5 mm extra-long (270 mm; TZ Laces ltd, Australia)	Laces - Flat waxed 5 mm extra-long (270 mm; TZ Laces ltd, Australia)
External Waterproofing	Waterproof	Waterproof
Toe Cap	Composite steel	Composite steel
Metatarsal Guard	Poron XRD	Poron XRD
Fit	Wide	Wide
Safety Standards	Penetration resistant, metatarsal guard, antistatic, water resistant, slip resistant C	Penetration resistant, metatarsal guard, antistatic, water resistant, slip resistant C

*Force to flex shaft to 25°

** Flex angle achieved when 30 N of force applied

Boot 3 and 4

Variable	Boot 3 (Stiff Shaft+ Flexible Sole)	Boot 4 (Flexible Shaft+ Flexible Sole)
Mass (kg)	0.98	0.94
Shaft Height (cm)	30	29.5
Shaft Stiffness (N)*	1.7	1.1
Shaft Material	Nappa leather: full leather with reinforced sections around ankle	Nappa leather + nylon: elasticised material between each eyelet to allow expansion and contraction
Midsole Hardness (Shore)	58	58
Midsole Material	Phylon	Phylon
Outsole Hardness (Shore)	68	68
Outsole Material	Nitrate rubber (resistant to 300^{o}C)	Nitrate rubber (resistant to 300^{o}C)
Sole Flexibility (^{o})**	30.2	30.2
Heel Height (cm)	4	4
Heel Sole Width (cm)	10	10
Forefoot Sole Width (cm)	13	13
Footbed Material	Breathable PU sole response foam	Breathable PU sole response foam
Insole Material	Woven polyester (penetration resistant)	Woven polyester (penetration resistant)
Fastening Method	Laces – Flat waxed 5 mm extra-long (270 mm; TZ Laces ltd, Australia)	Laces - Flat waxed 5 mm extra-long (270 mm; TZ Laces ltd, Australia)
External Waterproofing	Waterproof	Waterproof
Toe Cap	Composite steel	Composite steel
Metatarsal Guard	Poron XRD	Poron XRD
Fit	Wide	Wide
Safety Standards	Penetration resistant, metatarsal guard, antistatic, water resistant, slip resistant C	Penetration resistant, metatarsal guard, antistatic, water resistant, slip resistant C

*Force to flex shaft to 25^{o}

** Flex angle achieved when 30 N of force applied

6.1.5 *Statistical Analysis*

A series of paired *t*-tests were initially used to compare foot structure and in-shoe pressure data for the cohort's right and left foot. As there were no significant differences between the two feet for any of the measures, further analyses were restricted to the right limb of each participant.

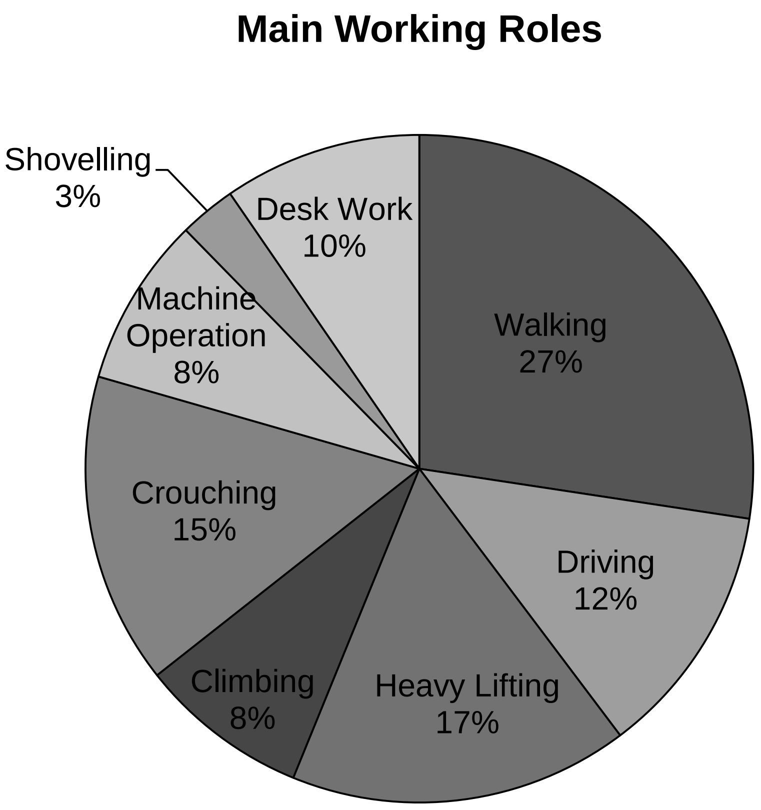
Means and standard deviations of the perceived comfort, muscle activity, three dimensional motion and in-shoe pressure were calculated per boot condition. A one-way ANOVA used to compare the perceived comfort results obtained when the participants walked in the four boot conditions. A two-way repeated measures ANOVA, with within factors of boot type (Boot 1, Boot 2, Boot 3, Boot 4) and surface (uneven, soft) was then used to determine whether there were any significant main effects or interactions of either boot type or surface on the muscle activity, three-dimensional motion and in-shoe pressure displayed by the participants. A Wilks' Lambda multivariate test was used to determine any significant main effects and interactions. Paired *t*-tests further investigated any significant main boot effects and interactions. This statistical design determined whether any of the data were significantly different between the boot types and whether any of these differences were influenced by what surface the participant was walking on. An alpha level of $p < 0.05$ was used for all statistical comparisons and all tests were conducted using SPSS statistical software (Version 21, SPSS, USA).

6.2 Results

Mean age and body stature measurements derived for the participants (age 36 ± 13.8 years; height 174.8 ± 6.3 cm, body mass 76.9 ± 9.2 kg) were consistent with those reported for underground coal mine workers and our previous studies. The mean BMI of 25.2 ± 3.4 kg/m^2 indicated that, on average, the cohort was classified as overweight. The foot structure and ankle, knee and hip range of motion data are presented in Table 5. The main working roles listed by the participants and the main surfaces they work on are displayed in Figure 30. During a typical 8-10 hour shift, the participants spent the most time walking and standing and minimal time sitting (see Figure 31).

Table 5: Foot structure and ankle, knee and hip range of motion data for the participant's dominant limb (n = 20).

Foot Structure	Mean	S.D	Range of Motion	Mean	S.D
Foot Length	23.8 cm	0.6	Ankle	79.6°	15.6
Forefoot Breadth	9.2 cm	0.4	Knee	132.1°	9.7
Heel Breath	5.0 cm	0.3	Hip	95.7°	10.4



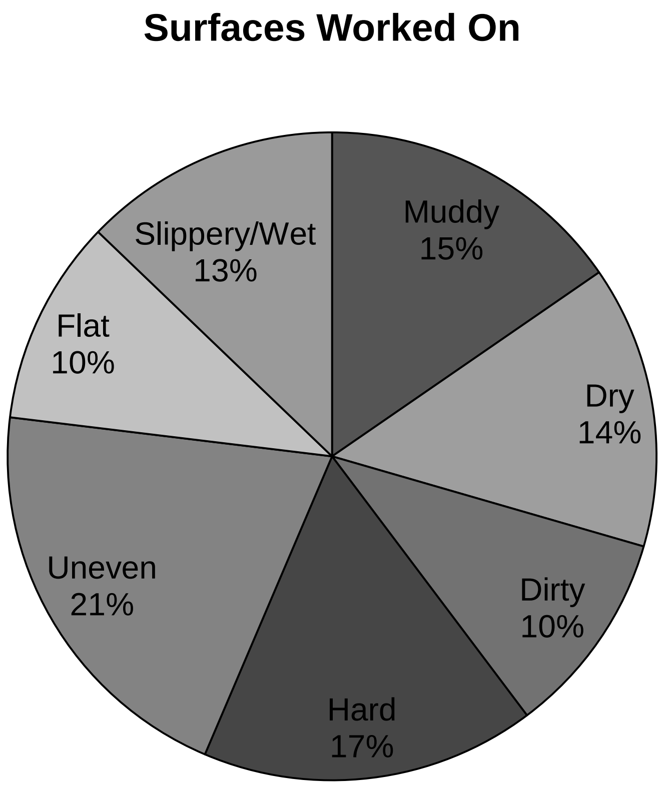


Figure 30: Main working roles performed and surfaces worked on by the participants (n = 20).

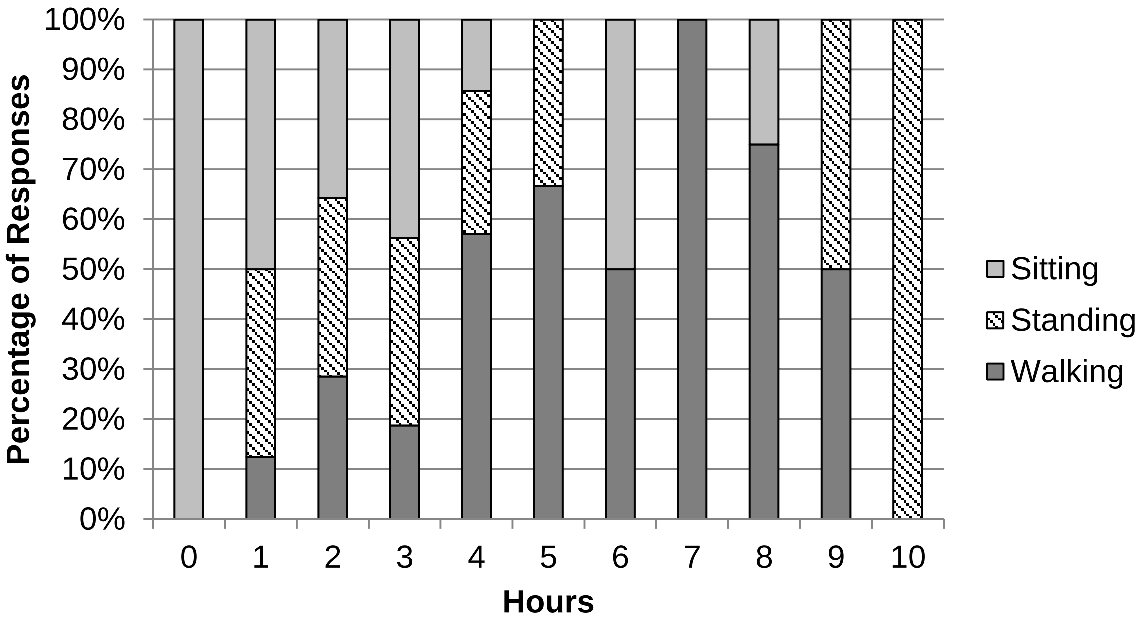
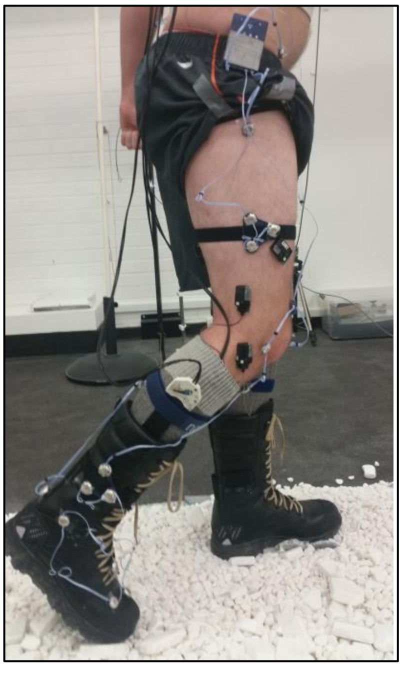
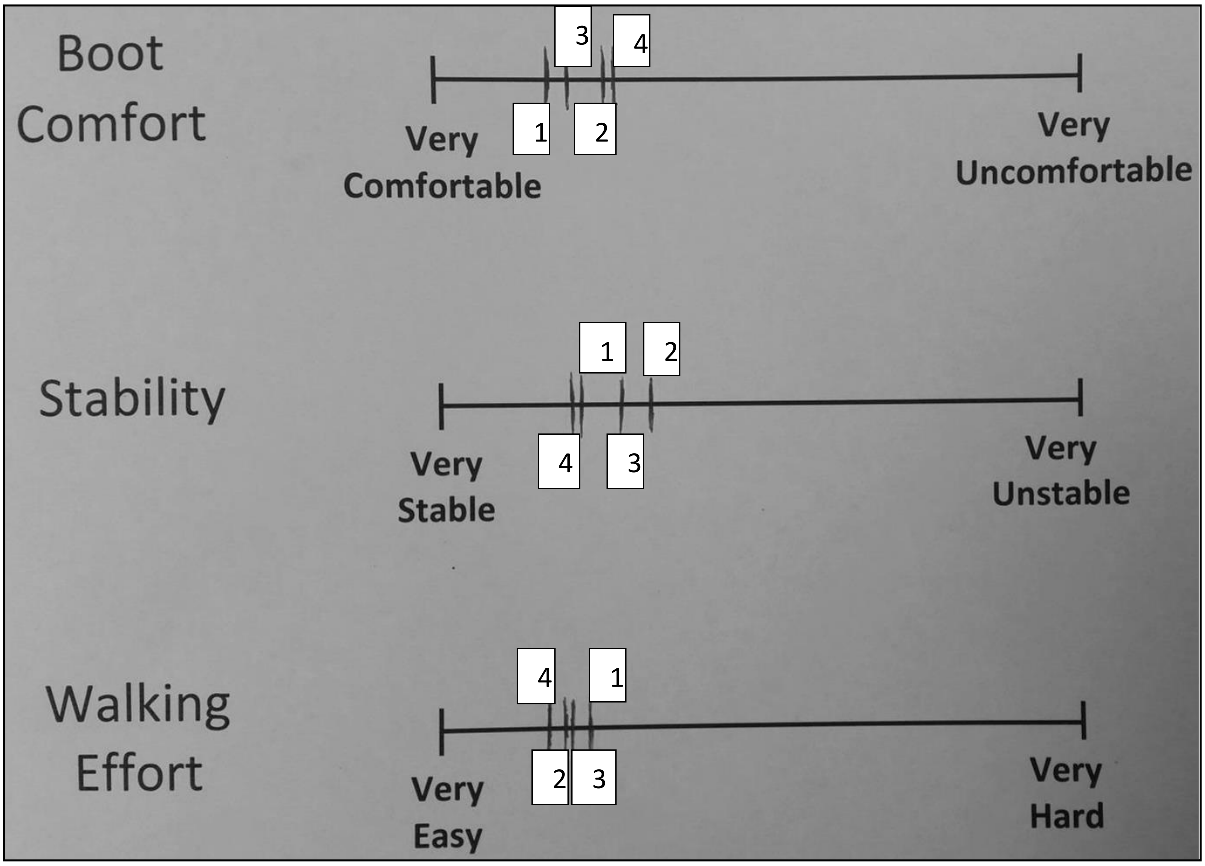


Figure 31: Amount of hours participants spend walking, standing and sitting during a typical 8-10 hour shift (n = 20).

6.2.1 Perceived Comfort

No significant differences were found between the boot conditions when comparing the participants' perceptions of boot comfort, stability, walking effort, shaft tightness, ankle support and foot, ankle and knee range of motion (see Figure 32).




Boot
Comfort
Very
Comfortable
Very
Uncomfortable
Stability
Very
Stable
Very
Unstable
Walking
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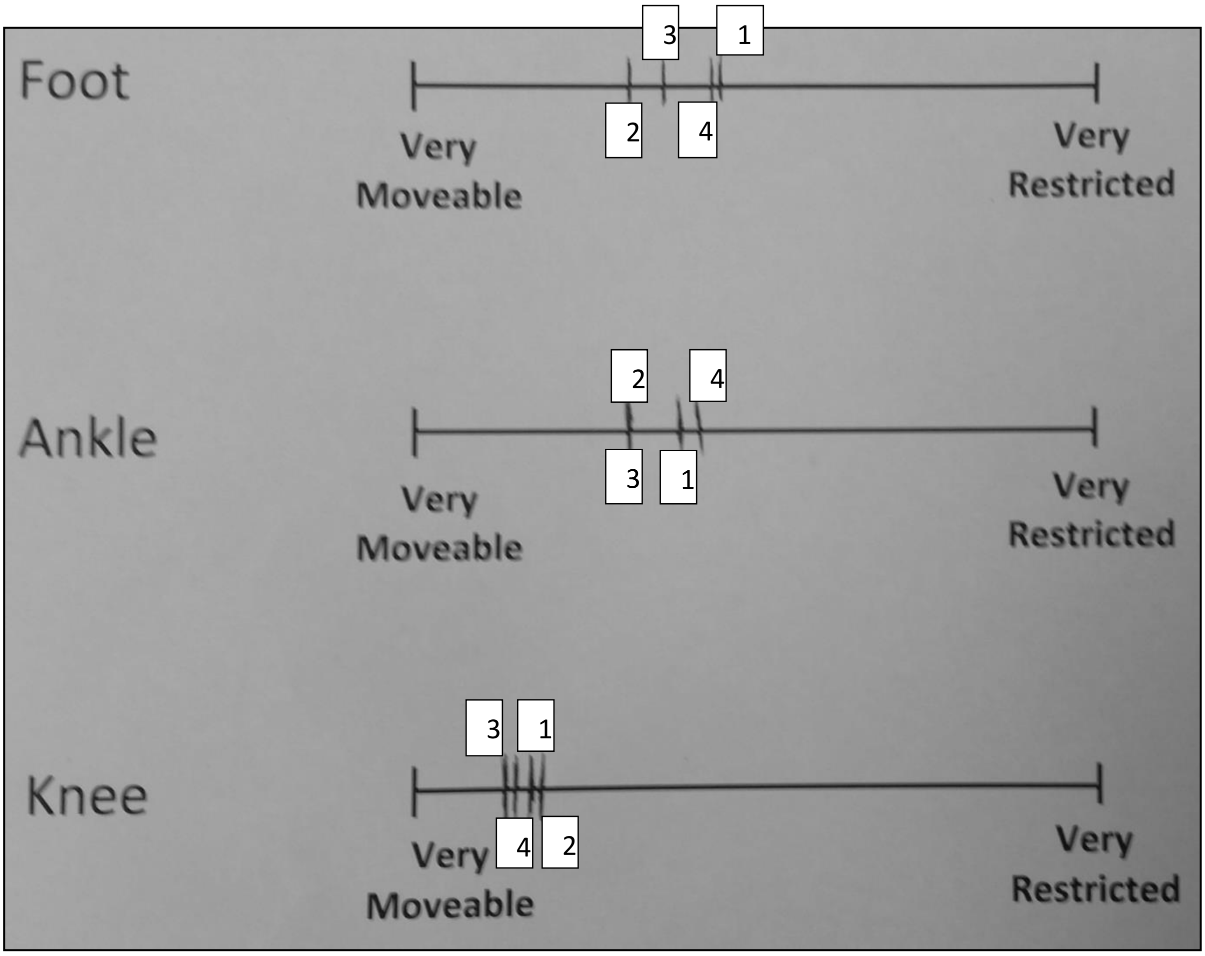
Foot
Very
Moveable
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Restricted
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Knee
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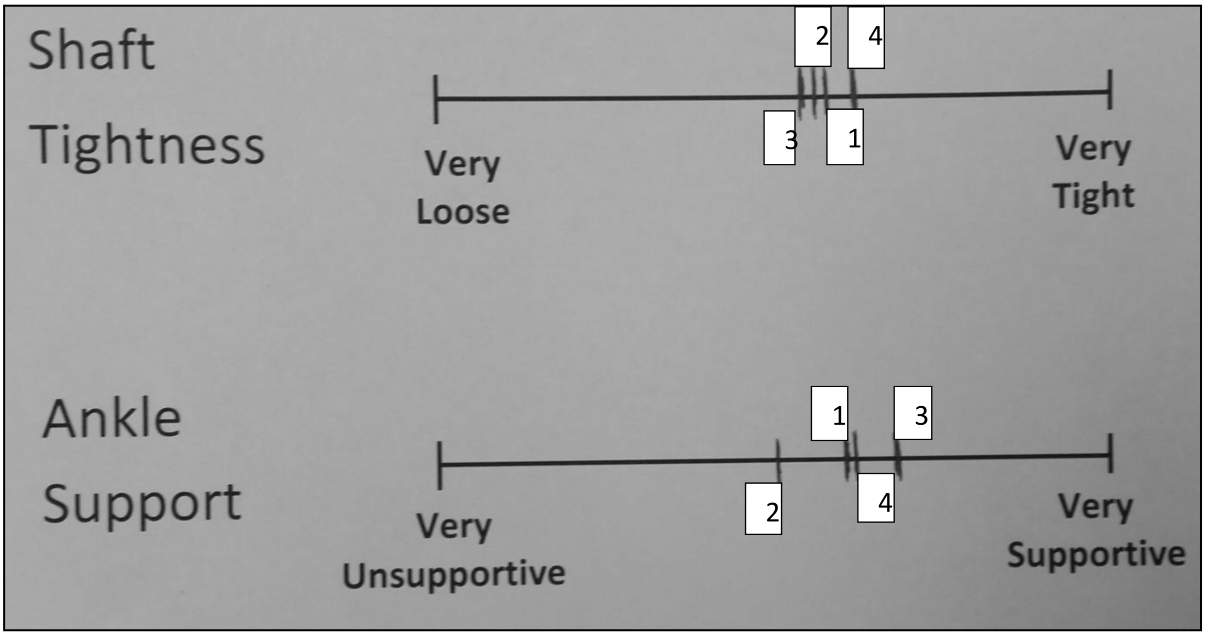

Figure 32: Mean Visual Analogue Scores (VAS) per boot condition (1 = flexible shaft + stiff sole, 2 = still shaft + stiff sole, 3 = stiff shaft + flexible sole and 4 = flexible shaft + flexible sole).

Overall Boot 1 (flexible shaft + stiff sole) was selected as the best boot by most of the participants and Boot 3 (stiff shaft + flexible sole) was selected as the worst (see Figure 33). No participants picked boot 2 (stiff shaft + stiff sole) as the best boot (see Figure 33). Participants mostly liked Boot 1 because of the fit and ankle support, and that it was comfortable and easy to walk in (see Figure 34). When compared to their current work boot, 85% of participants liked their favourite test boot better, 10% liked their current boot and test boot the same, and 1% like their current work boot more than the test boots. The main reason participants liked the test boots better than their current work boot was that the test boot provided more support, particularly to the foot and ankle and, overall, were more comfortable.

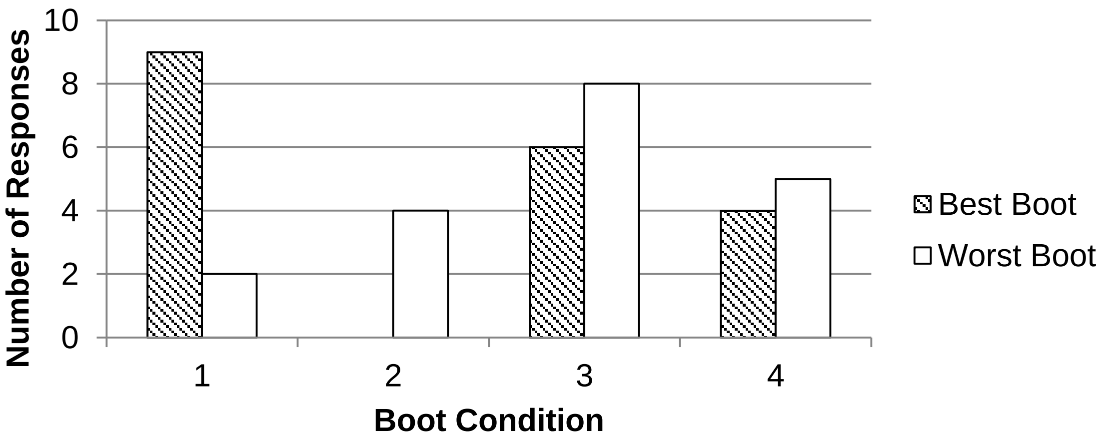

Figure 33: Post-testing questionnaire results displaying which boot participants thought was the best boot and which boot they thought was the worst boot (1 = flexible shaft + stiff sole, 2 = still shaft + stiff sole, 3 = stiff shaft + flexible sole and 4 = flexible shaft + flexible sole; n = 19).

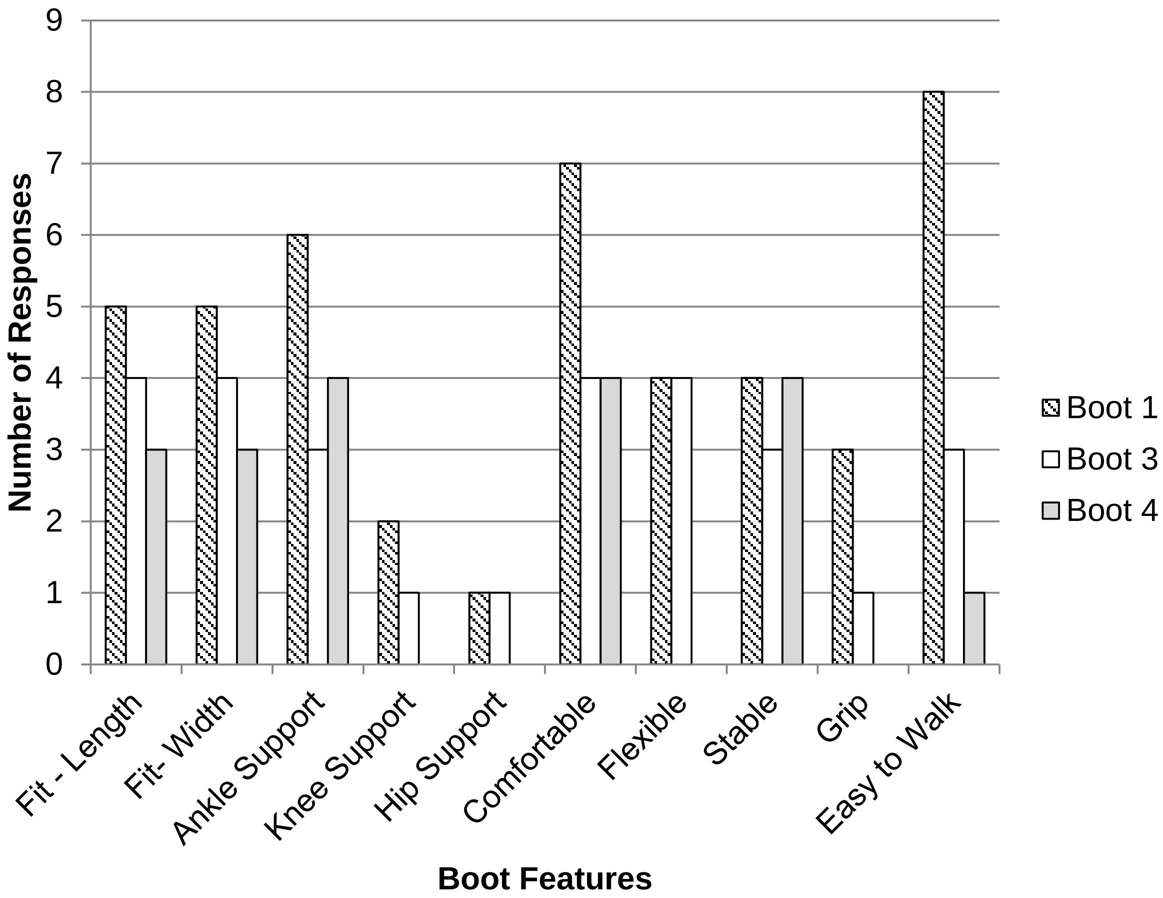

Figure 34: Post-testing questionnaire results displaying which features participants liked about the boot they selected as the best boot (1 = flexible shaft + stiff sole, 2 = still shaft + stiff sole, 3 = stiff shaft + flexible sole and 4 = flexible shaft + flexible sole; n = 19).

6.2.2 Muscle Activity, Ankle Range of Motion and In-Shoe Pressure

Extensive amounts of biomechanical data (three-dimensional motion, muscle activity and in-shoe pressure) were collected during this study. To-date muscle activity and in shoe-pressure data have been analysed for 10 participants and these data are presented below. It is anticipated that all data analysis will be completed by the end of 2017. Once completed, the results and associated publications will be sent to the Coals Services Health and Safety Trust Board.

Hamstring muscle activity (semitendinosus) duration when the foot first contacted the ground was significantly longer when the participants walked in Boot 3 and 4 (boots with flexible soles) compared to Boot 1 and 2 (boots with stiff soles). However, the participants displayed greater ankle range of motion when walking in Boot 1 and 4 (boots with flexible shafts) compared to Boot 2 and 3 (boots with stiff shafts), although this result was not statistically significant. The highest pressure and force values were generated across the whole foot when participants walked in Boot 4 (flexible shaft and sole) (see Figure 35), whereas the lowest pressure and force values were generated in Boot 2 (see Figure 35). The highest amount of the foot contacting the ground occurred while walking in Boot 3 (see Figure 35).

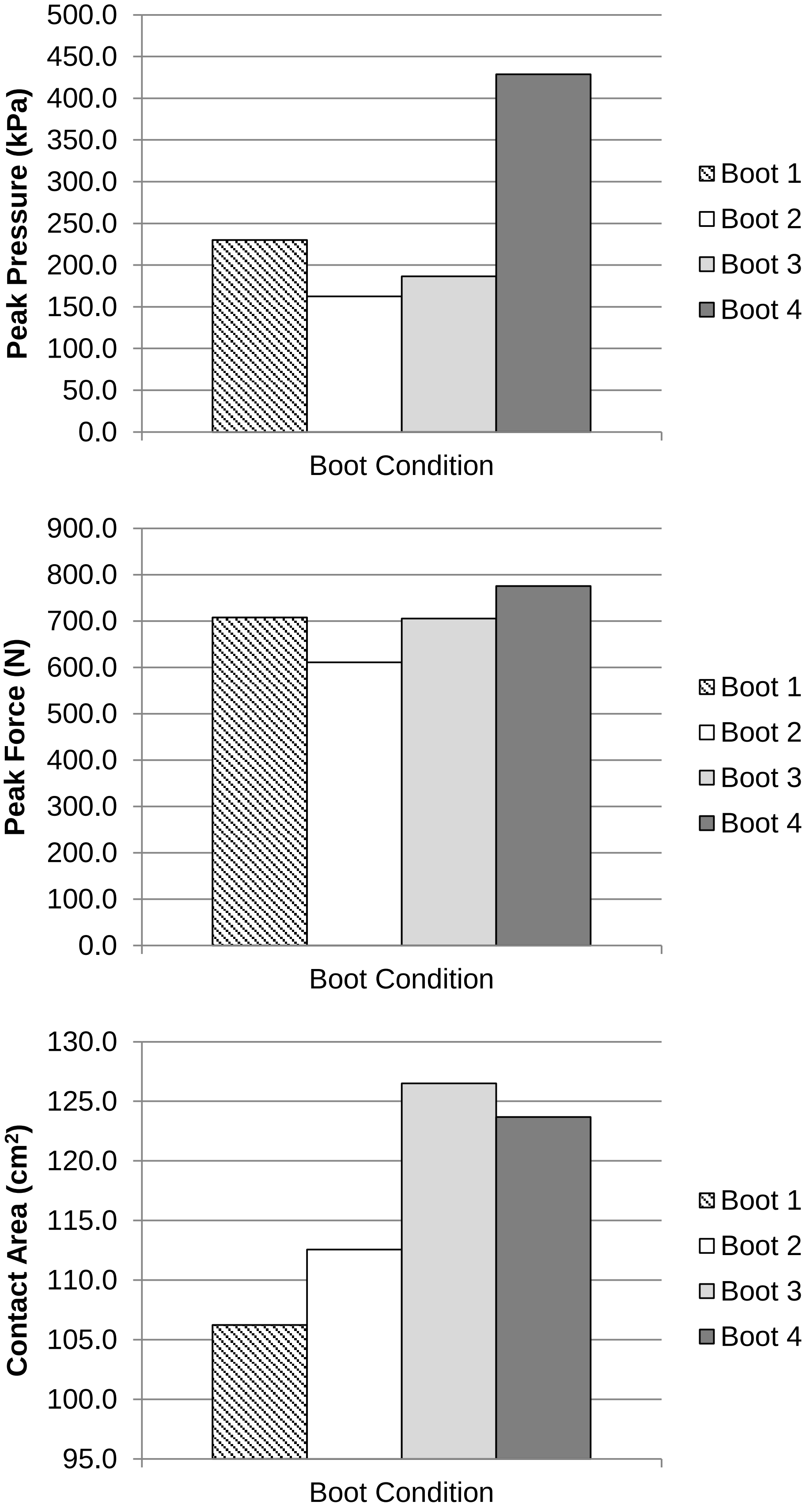

Figure 35: In-shoe pressure mean peak pressure (kPa), peak force (N) and contact area (cm^2) when participants walked. Boot 1 = flexible shaft + stiff sole, Boot 2 = still shaft + stiff sole, Boot 3 = stiff shaft + flexible sole and Boot 4 = flexible shaft + flexible sole. NOTE: These data are for 10 participants only.

6.3 Key Findings to Date

The aim of this study was to investigate the effects of systematic variations to shaft stiffness and sole flexibility in work boots when underground coal miners walked across simulated underground coal mining surfaces (gravel and soft). We found underground coal miners preferred a boot with a flexible shaft and a stiff sole because they perceived that it provided a good fit (length and width wise), good ankle support and was comfortable and easy to walk in. Overall, most participants liked the test boot conditions better than their current underground coal mining work boot, despite the fact they had only limited time to become accustomed to the boot (i.e. there was insufficient time to "wear the boots in"). This preference for the test boots appears to be due to improved support, particularly to the foot and ankle, and improved comfort. Further investigation is needed to confirm how much of a role the wider forefoot and heel design in the test boots compared to their current work boots played in this result.

Boots with a stiff shaft were the least preferred among the participants, particularly when combined with a stiff sole. Interestingly, current leather lace-up boots provided to underground coal miners have a stiff shaft and stiff sole, potentially explaining why such a high percentage of underground coal miners currently rate their work boots as uncomfortable.

The preliminary biomechanical data has revealed differences between the test boot conditions, highlighting that differences in shaft stiffness and sole flexibility affect the way coal miners walk. For example, the participants generated much higher peak pressures when walking in a boot with a flexible shaft and flexible sole compared to the other three boot conditions. Completing the biomechanical analysis is needed before specific recommendations about how differences in shaft stiffness and sole flexibility affect walking can be made.

6.4 Outputs[6]

6.4.1 Publications

- Dobson JA, Riddiford-Harland DL, Bell AF & Steele JR. Work boot design affects the way workers walk: A systematic review of the literature. *Applied Ergonomics* **61**: 53-68, 2017.

[6] The publications and conference abstracts listed here are included in the appendices. Publications accepted after this report has been submitted will be sent to the Coal Services Health and Safety Trust Board.

7. Recommendations to Date

- During a typical working shift, underground coal miners spend extensive amounts of time walking. It is therefore imperative that they have access to footwear that fit their feet properly, are comfortable to wear, and are suitable to the work tasks to be performed in a underground coal mining environment.
- Underground coal mining work boots need to be redesigned. Not only do miners find their current work boots uncomfortable, but quantitative evidence shows the shape of miners' feet do not match the shape of the inside of their work boots. Miners are also still reporting a myriad of foot problems that they attribute to their current work boots.
- Underground coal mining work boots need to be wider, particularly in the forefoot and heel area of the boot.
- The shape of the feet of underground coal miners vary extensively, with outliers in shape due to the presence of factors such as foot deformities (e.g. hammertoe). These outliers highlight the broad range of feet displayed by underground coal miners and the need for some miners to seek custom boots.
- Miners need to be better educated on how to select a boot that fits properly. Miners are currently selecting boots that are too long (i.e. a larger size) to accommodate for the width of their foot but then reporting their work boots fit.
- The structure of an underground coal mining work boot can significantly influence walking and perceptions of comfort when participants walk on uneven surfaces typically encountered by underground coal mine workers. Preliminary results show that underground coal miners prefer a work boot with a flexible shaft and a stiff sole. This differs to current work boots used in the industry, which feature either a stiff shaft and stiff sole (leather lace-up boot) or a flexible shaft and flexible sole (gumboot)

8. Where to from here?

- Extensive amounts of biomechanical data (three-dimensional motion, muscle activity and in-shoe pressure) were collected during this study. We will continue to analyse these data and anticipate completing the analysis by the end of 2017. Once completed, the results and associated publications will be sent to the Coals Services Health and Safety Trust Board.
- Based on the final study results we will develop work boot fitting guidelines to assist miners when selecting a work boot suitable for their foot shape.
- During the later stages of this grant we have developed a strong working relationship with Mack Boots, who provided the prototype test boots for Study 4. We aim to continue working with this industry partner to translate the findings of the present research into boots available to coal miners.

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10. Appendices

1. Publication: Effect of work boot type on work footwear habits, lower limb pain and perceptions of work boot fit and comfort in underground coal miners.
2. Conference abstract: Effects of underground coal mining work boot preference on boot satisfaction and discomfort.
3. Conference abstract: Does the 3D shape of underground coal miner's feet match their internal boot dimensions.
4. Conference abstract: How do we fit underground coal mining work boots?
5. Conference abstract: Improving work boot fit for underground coal miners.
6. Publication: Effects of wearing gumboots and leather lace-up boots on lower limb muscle activity when walking on simulated underground coal mine surfaces.
7. Conference abstract: Effects of wearing gumboots & leather lace-up boots on gait & perceived comfort when walking on simulated underground coal mine surfaces.
8. Conference abstract: The influence of boot and surface type on in-sole pressure and comfort when walking on simulated coal mining surfaces.
9. Publication: Work boot design affects the way workers walk A systematic review of the literature.

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Effect of work boot type on work footwear habits, lower limb pain and perceptions of work boot fit and comfort in underground coal miners

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ABSTRACT

Lower limb injuries are highly prevalent in underground coal mining. Wearing gumboots with inadequate ankle support was thought to contribute to these injuries. Despite the uptake of leather lace-up boots, which provide more ankle support, no recent research could be found investigating the effect of this alternative work boot in underground coal mining. Consequently, this study aimed to determine whether boot type (gumboot, leather lace-up boot) influenced work footwear habits, foot problems, lower limb pain, lower back pain, or perceptions of work boot fit and comfort in underground coal miners. Chi-squared tests were applied to 358 surveys completed by underground coal miners to determine whether responses differed significantly ($p < 0.05$) according to boot-type. There were no significant between-boot differences in regards to the presence of foot problems, lower limb pain or lower back pain. However, the types of foot problems and locations of foot pain differed according to boot type. Gumboot wearers were also more likely to state that their work boot comfort was either 'uncomfortable' or 'indifferent', their work boot fit was 'poor' and their current boot did not provide enough support. The introduction of more structured leather lace-up boots appears to have positively influenced the support and fit provided by mining work boots, although foot problems, lower limb pain and lower back pain continue to be reported. Further investigation is recommended to identify which specific boot design features caused these observed differences in work boot fit, comfort and locations of foot pain and how these design features can be manipulated to create an underground coal mining work boot that is comfortable and reduces the high incidence of foot problems and lower limb pain suffered by underground coal miners.

1. Introduction

During a typical 8 h shift, underground coal miners spend most of their time standing and walking on challenging surfaces that are uneven, wet and unstable (Dobson et al., 2016; Marr, 1999). As a result, lower limb injuries are highly prevalent with sprains and strains accounting for over half of all WorkCover claims annually (WorkCoverNew South Wales, 2010). Of these sprain/strain related lower limb injuries, 49.2% occur at the knee and 36.5% occur at the ankle (Smith et al., 1999). An unstructured gumboot that lacked ankle support and allowed too much foot movement within the boot was thought to explain this high lower limb injury incidence in the coal mining industry (Marr, 1999; Smith et al., 1999). Indeed, a report to the Joint Coal Board Health and Safety Trust (Smith et al., 1999) revealed that almost 40% of miners who sustained lower limb injuries identified their mining work boots as the main contributing factor to these injuries.

Underground coal miners (n = 400, aged 20–70 years) who habitually wore gumboots reported excessive foot movement within their work boot and a lack of ankle support (Marr, 1999). Of the miners surveyed, 41% reported their feet slid within their work boot, 46% stated that their ankle did not feel stable and 35.5% felt unstable when walking on uneven ground. Marr (1999) suggested the inability of gumboots to stabilise the foot within the boot also contributed to the high incidence of calluses (48%) and lower back stiffness (34%) reported by coal miners. These findings are consistent with the results of a survey of 589 miners in which insufficient ankle support (63.5%) and inadequate boot fit (52.1%) were cited as the two main reasons miners thought their gumboots contributed to their lower limb injuries (Smith et al., 1999). Consequently, 71.4%

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0003-6870/

of the miners wanted their work boots changed (Smith et al., 1999).

Based on this previous research (Smith et al., 1999; Marr, 1999), leather lace-up boots were introduced as a work boot option for underground coal miners, providing them with an alternative that delivered a tighter fit and more ankle support than gumboots. Due to variations in the materials that a gumboot and leather lace-up boot are made out of, they substantially differ structurally, particularly in regards to shaft stiffness (upper part of the boot; see Fig. 1 and Table 1). It was hypothesised that introducing a mining work boot with a stiffer shaft that provided a tighter fit and more support around the ankle/shank would improve the miners' perceptions of comfort and stability while minimising lost time at work due to injury (including lower back, hip, knee, ankle and foot injury; Marr, 1999). Previous research has shown that 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 pressing against the shank would yield the same result (You et al., 2004). Nevertheless, differences in boot shaft design have been shown to limit lower limb motion and, consequently, lower limb pain (Böhm and Hösl, 2010; Jefferson, 2013; Dobson et al., 2015). The literature, however, is inconclusive and it is unknown whether a tighter fit due to a stiffer shaft is in fact beneficial in regards to reducing lower limb pain occurrence.

Manipulation of shaft stiffness in hiking boots (Böhm and Hösl, 2010; Cikajlo and Matjačić, 2007), military boots (Hamill and Bensel, 1996), work boots (Simeonov et al., 2008), basketball boots (Robinson et al., 1986), ski boots (Noé et al., 2009) and snowboarding boots (Delorme, 2004) has been found to significantly alter ankle range of motion. That is, a more flexible shaft has been shown to increase ankle range of motion during walking and a stiffer shaft can reduce it. The amount of ankle range of motion allowed by a boot shaft appears crucial to both efficient walking biomechanics, as well as reducing lower limb injury occurrence. Although adequate ankle range of motion is vital to efficient gait, excessive ankle motion is 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 Bensel, 1996), increasing the risk of lower limb sprain/strain injuries (Neely, 1998). Conversely, 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 or hip (Böhm and Hösl, 2010; Horak and Nashner, 1986). For example, a lace-up hiking boot, with 50% less passive shaft stiffness, decreased eccentric energy absorption at the ankle joint while simultaneously increasing eccentric energy absorption at the knee joint, indicating that when the ankle joint's ability to absorb the ground reaction force is impaired, the knee joint has to compensate (Böhm and Hösl, 2010). Therefore, although the leather lace-up boot with its stiffer shaft might positively impact the ankle by providing more support, it could potentially have negative implications for the knee and more proximal joints by restricting normal ankle motion and causing compensations further up the lower limb chain.

Despite the introduction of a leather lace-up boot for coal miners over a decade ago, no research could be found investigating whether this more fitted and supportive work boot affected their lower limb pain or their perceptions of fit and comfort. Given the gap in the current literature, the aim of this study was to determine whether boot type (gumboot versus leather lace-up boot) influenced self-reported work footwear habits, lower limb pain, lower back pain, or perceptions of fit and comfort in underground coal miners. It was hypothesised that miners who wore leather lace-up boots would report more ankle support, fewer foot problems, less pain, and improved comfort and fit ratings when compared to gumboot wearers. However, due to restricted ankle motion, leather lace-up boot wearers would report more knee and hip pain compared to gumboot wearers.

2. Methods

2.1. Participants and survey implementation

Three hundred and fifty eight underground coal miners ($n = 355$ men and 3 women; age $= 39.1 \pm 10.7$ years; height $= 1.78 \pm 0.31$ m; mass $= 92.1 \pm 13.7$ kg) employed by Illawarra Coal at the Dendrobium and West Cliff sites (NSW, Australia) volunteered to complete a survey which collected job details, work boot habits, foot problems and lower limb pain history, boot likes/dislikes and ideal boot preferences. Underground coal mining remains a male dominated occupation with workers generally being middle aged (personal communication with industry, March 2016). Over half of the participants had worked underground (54.8%), and performed their current working role (52.6%), between 3 and 10 years. Nearly a fifth had worked underground for over 16 years (18.8%). The most common mining work boot sizes worn were sizes 8–12 with 90% of participants falling within this size range. Surveys were handed out to the participants at scheduled work health and safety meetings and training days or immediately prior to commencing a shift at the mines. The participants completed the survey under the guidance of the research team, who clarified any questions the participants had and ensured all questions were completed. All 358 participants who volunteered to fill out the survey completed it.

Participants were divided into two groups for analysis based on whether they chose to wear the employer-provided gumboot ($n = 219$ men and 3 women; age $= 38 \pm 9.8$ years; height $= 1.77 \pm 0.67$ m; mass $= 91.6 \pm 13.8$ kg) or the other mandatory boot option of the leather lace-up boot ($n = 109$ men; age $= 37.8 \pm 10.1$ years; height $= 1.78 \pm 0.63$ m; mass $= 92.6 \pm 14.9$ kg; see Fig. 1 and Table 1). Those who did not answer the question or selected wearing both boots were not included for analysis.

Fig. 1. The two different underground coal mining work boots provided by Illawarra Coal (NSW, Australia) at the time of the study. A: Gumboot (Blundstone®, Australia) and B: Leather lace-up boot (Oliver, Australia).

Table 1
Characteristics of the gumboot (Style 015; Blundstone®, Australia) and leather lace-up boot (Style 65–691; Oliver, Australia).

Variable	Gumboot	Leather Lace-Up Boot
Mass (kg)[a]	2.7	3.1
Shaft Height (cm)[a]	37.5	35
Heel Height (cm)[a]	3.2	4.2
Materials	PVC/nitrile rubber (resistant to chemical, oil and acid)	Full grain (hide hasn't been sanded, buffed or snuffed) water resistant leather
Fastening Method	Nil: Slip-on	Laces
External Waterproofing	Waterproof	Water resistant
Internal Lining	Plush knitted mesh	SympaTex (SympaTex Technologies, GmbH) fabric (waterproof, windproof and breathable membrane)
Foot Bed	Soft polyurethane, covered with a full length cushion of foam polyurethane, topped with a mesh cover	Combination of cellular urethane and PORON® urethane
Sole	Combination of PVC/nitrile rubber and PORON®xRD™ material	Low density polyurethane
Toe Cap	Type 1 (heavy work environment) steel	High carbon steel with a latex cap liner
Sizes Available	AU 4-13 Wide fit to accommodate broad feet	AU 5-14, 6.5-10.5

[a] Averaged across the five most common boot sizes (8–12).

2.2. Survey design and development

The design of the survey was based on previously validated surveys that had investigated underground coal mining work boots (Marr and Quine, 1993; Marr, 1999; Smith et al., 1999), and modified after discussions with coal mining industry representatives. The survey was trialled by 15 participants (age = 18–40 years) to ensure questions were readily understood.

The final survey instrument included 54 items (15 closed-ended and 39 open-ended items), divided into six sections that sought information pertaining to the underground coal miners' job details; work footwear habits; foot problems and lower limb pain history; low back pain; orthotic use; work footwear fit and comfort; and foot and footwear knowledge. The University of Wollongong Human Research Ethics Committee (HE11/198) provided approval of the survey content and administration procedures. The specific variables investigated in this study are discussed below.

2.3. Analytical variables

2.3.1. Work footwear habits

To determine the participants' footwear preferences open-ended questions 'what is your current mining footwear' and 'what don't you like about your current work footwear', as well as a closed-ended question identifying preferred boot features were used.

2.3.2. Foot problems, lower limb pain, and lower back pain history

Close-ended questions were used to determine current foot problems reported by the participants and whether a participant had foot, ankle and/or any other pain (lower back, knee, and hip). From a list, participants circled any problems/pain they had or circled 'no' if they did not have any current problems/pain. A five point Likert scale asked participants to elaborate on how often they experienced foot and/or ankle pain (1 'rarely' to 5 'always') and an image of the foot was provided for participants to mark specific pain locations. Finally, a close-ended question asked participants to circle 'yes' or 'no' in regards to whether they believed any foot pain they experienced was related to their work footwear.

2.3.3. Work footwear fit and comfort

Overall work footwear fit (1 'very poor' to 5 'very good') and comfort (1 'very uncomfortable' to 5 'very comfortable') were determined via markings on a five point Likert scale. Participants then ranked 11 boot design features (1 being most important) they believed would enhance the comfort on an ideal work footwear. Two open-ended questions 'what is your everyday shoe size' and 'what is your current work footwear size', then recorded the participants' shoe sizes.

2.4. Survey analysis

2.4.1. Descriptive analysis

Descriptive statistics were calculated after coding and counting the close-ended item responses. Thematic analysis was used to calculate response frequencies to open-ended questions. Non-responses, multiple answer selection or when questions did not require an answer from all participants caused variations in the number of responses. Only data for participants who provided a response to that question were analysed.

2.4.2. Relationship analysis

Chi-squared tests were applied to data related to work footwear habits, foot problems, lower limb pain, lower back pain history and work footwear fit and comfort. The purpose of this statistical design was to determine whether the participants' lower limb pain and perceptions of fit and comfort differed significantly ($p < 0.05$) based on boot type worn (gumboot, leather lace-up boot; SPSS Version 21, USA).

3. Results

3.1. Work footwear habits

Leather lace-up boot wearers were more likely to select fit - length ($\chi^2 = 23.75$, $p < 0.001$), fit - width ($\chi^2 = 12.87$, $p < 0.05$), ankle support ($\chi^2 = 128.12$, $p < 0.001$), comfortable ($\chi^2 = 100.08$, $p < 0.001$), flexible ($\chi^2 = 8.44$, $p < 0.05$), fastening method ($\chi^2 = 10.65$, $p < 0.05$), grip ($\chi^2 = 8.6$, $p < 0.05$) and breathable ($\chi^2 = 21.1$, $p < 0.001$) as preferred features of their current work boot (see Fig. 2). Conversely, gumboot wearers were more likely to select waterproof ($\chi^2 = 7.07$, $p < 0.05$) and only option available ($\chi^2 = 29.8$, $p < 0.001$) as why they preferred their current work boot (see Fig. 2).

In regards to what underground coal miners did not like about their current work boot, those who wore a leather lace-up boot were more likely to select boot gets wet ($\chi^2 = 14.95$, $p < 0.05$), shrinks ($\chi^2 = 27.2$, $p < 0.001$) and hard to get on/off ($\chi^2 = 9.4$,

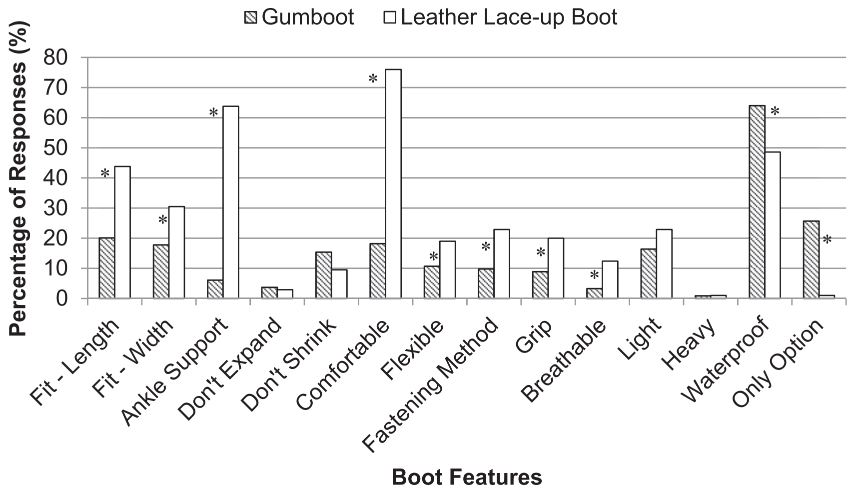

Fig. 2. Factors participants preferred about their current mining work boots based on work boot worn (gumboot or leather lace-up boot; n = 323). * indicates a significant difference between boots ($p < 0.05$).

$p < 0.05$; see Fig. 3). In contrast, gumboot wearers were more likely to select hot/sweaty ($\chi^2 = 10.8$, $p < 0.05$) and no support ($\chi^2 = 26.95$, $p < 0.001$) as what they did not like about their current work boot (see Fig. 3).

3.2. Foot problems, lower limb pain and lower back pain history

There was no significant difference between the gumboot wearers compared to the leather lace-up boot wearers in regards to the reported presence of lower back pain ($\chi^2 = 2.76$, $p = 0.25$), hip pain ($\chi^2 = 0.62$, $p = 0.73$), knee pain ($\chi^2 = 1.15$, $p = 0.56$), ankle pain ($\chi^2 = 1.04$, $p = 0.60$) or foot pain ($\chi^2 = 1.9$, $p = 0.38$; see Fig. 4). The existence of foot problems also did not differ significantly between wearers of the two boot types ($\chi^2 = 0.88$, $p = 0.65$). However, of those who reported having a foot problem and/or foot pain, there were significant differences between the gumboot and leather lace-up boot wearers in regards to the type and location of the foot problems and pain (see Fig. 5). Furthermore, of those participants who reported having ankle pain, leather lace-up boot wearers were more likely to report it occurred 'rarely' (55.3% vs 24.7%) compared to gumboot wearers who were more likely to report their ankle pain as occurring occasionally (50.6% vs 21.3%; $\chi^2 = 15.64$, $p < 0.05$).

There was no significant difference between gumboot wearers and leather lace-up boot wearers in whether they experienced calluses ($\chi^2 = 3.12$, $p = 0.21$) or blisters ($\chi^2 = 3.12$, $p = 0.21$). Furthermore, there was no significant difference between gumboot wearers and leather lace-up boot wearers in whether they thought their work boots contributed to their foot pain ($\chi^2 = 2.30$, $p = 0.22$).

3.3. Work footwear fit and comfort

Comparing responses from participants who wore gumboots versus leather lace-up boots revealed significant differences in regards to ratings of mining work boot fit ($\chi^2 = 42.29$, $p < 0.001$; see Fig. 6) and comfort ($\chi^2 = 57.72$, $p < 0.001$; see Fig. 7). Participants who wore gumboots, compared to leather lace-up boots, stated the fit of their mining work boots was 'poor' (14.5 vs 3.6%; see Fig. 6) and their mining work boot comfort was either 'uncomfortable' (24.9% vs 4.6%) or 'indifferent' (45.0% vs 25.7%; see Fig. 7). Conversely, leather lace-up boot wearers were more likely to rate their mining work boot comfort as 'comfortable' when compared to gumboot wearers (59.6% vs 27.1%; see Fig. 7).

Leather lace-up boot wearers were more likely to select a work boot that was larger than their everyday shoe size (40.0% vs 27.1%; $\chi^2 = 17.21$, $p < 0.05$) compared to gumboot wearers, who were more likely to select a smaller sized work boot (29.4% vs 10.0%).

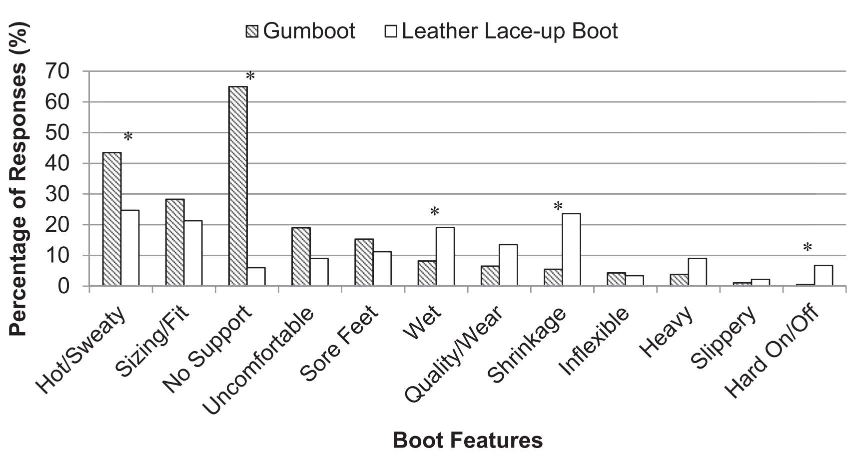

Fig. 3. Factors participants did not like about their current mining work boots based on work boot worn (gumboot or leather lace-up boot; n = 276). * indicates a significant difference between boots ($p < 0.05$).

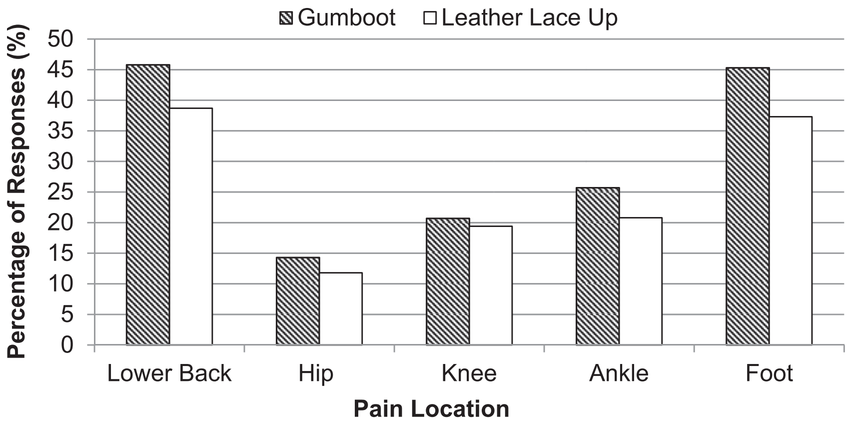

Fig. 4. Reported pain incidence based on work boot worn (gumboot or leather lace-up boot; n = 319 foot and ankle pain, n = 263 lower back, hip and knee pain).

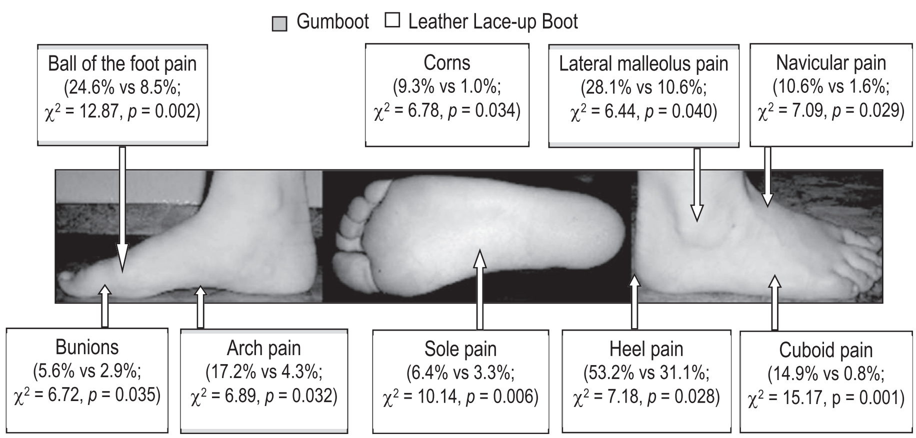

Fig. 5. Specific pain locations and foot problems based on the work boots participants reported they were more likely to occur in (percentage of responses; Chi-squared result; n = 159 foot problems and n = 136 foot pain location).

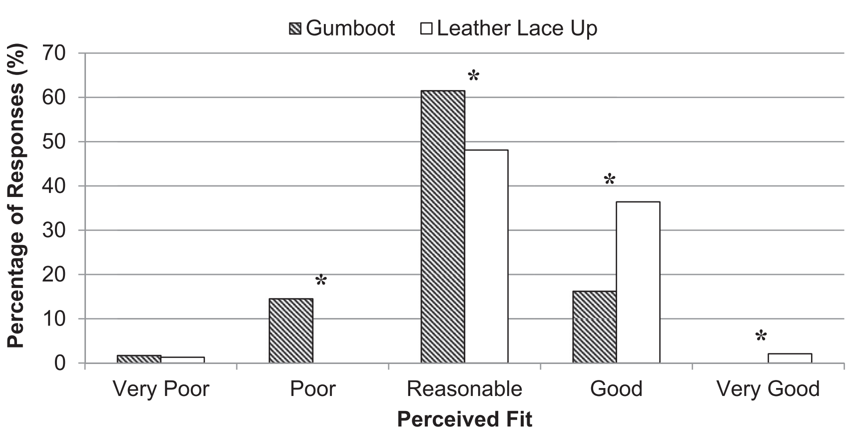

Fig. 6. Mining work boot fit ratings based on work boot worn (gumboot or leather lace-up boot; n = 329). * indicates a significant difference between boots ($p < 0.001$).

There was no significant difference between what gumboot wearers and leather lace-up boot wearers selected as their first ($\chi^2 = 20.36$, $p = 0.44$) or second ($\chi^2 = 10.98$, $p = 0.90$) choices in regards to what design features would make an ideal work boot more comfortable. Waterproofing was the most common first choice and ankle support the most common second choice across the responses from wearers of both boots type.

4. Discussion

Over a decade ago leather lace-up boots, which had greater ankle support than gumboots, were made available for underground coal miners in an attempt to reduce the high incidence of lower limb injuries. As no research could be found investigating whether this more fitted and supportive work boot affected coal

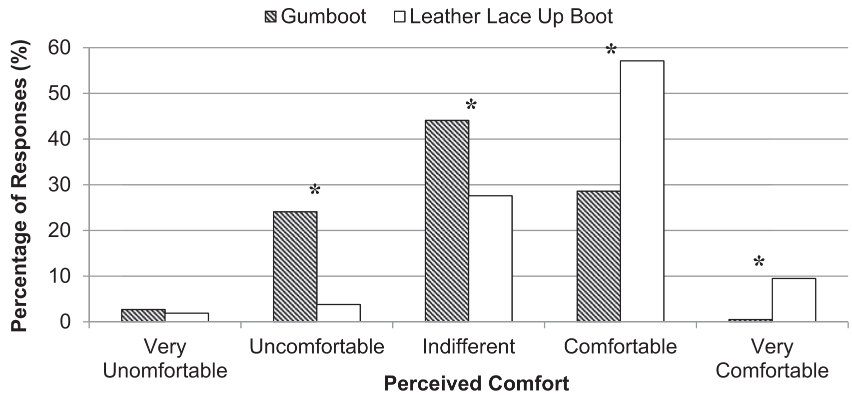

Fig. 7. Mining work boot comfort ratings based on work boot worn (gumboot or leather lace-up boot; n = 329). * indicates a significant difference between boots ($p < 0.001$).

miners' lower limb pain or perceptions of fit and comfort this study investigated whether boot type (gumboot versus leather lace-up boot) influenced self-reported work footwear habits, lower limb pain, lower back pain and perceptions of fit and comfort in underground coal miners. Results of the present study revealed that although leather lace-up boots positively influenced coal miners' perceptions of support and fit provided by their mining work boots, lower back pain, foot pain and calluses are still frequently report by underground coal miners, irrespective of boot type. The implications of these findings are discussed below.

Prior to the availability of leather lace-up boots, 46.3% of underground coal miners listed poor support as a limitation of their current mining work boots (Marr, 1999), with 65.3% specifically listing inadequate ankle support as the limitation (Smith et al., 1999). A work boot that does not provide adequate support to limit excessive inversion and rotation of the ankle is likely to increase the risk of ankle sprain (Barrett and Bilisko, 1995). In support of our hypothesis, gumboot wearers were more likely to report their boots as providing inadequate support and leather lace-up boot wearers were more likely to list 'ankle support' as a feature they preferred about their current work boots. Leather lace-up boot wearers were also more satisfied with the comfort of their underground coal mining work boots when compared to gumboot wearers. Regardless of what boot underground coal miners wore, participants prioritised ankle support as a design feature required to make an ideal boot comfortable. It is therefore likely that ankle support substantially influenced the difference in comfort ratings between the two boots. However, further research is needed to confirm this theory as the underground coal miners in this current study were not directly asked to rate their perceived ankle support.

Differences in ventilation might also explain the variance in boot comfort ratings with leather lace-up boot wearers preferring the breathability provided by their boots and gumboot wearers disliking their boot because it was hot/sweaty. Differences in ventilation, however, appeared to be a trade-off in regards to waterproofing. Because waterproofing was the first design feature recommended to make an ideal comfortable boot, leather lace-up boot ratings of comfort could be improved by ensuring the boots are waterproof. Nevertheless, further research is required to determine what specific design features make the leather lace-up boot more comfortable than the gumboot and whether this is consistent across different surfaces and working tasks encountered by underground coal miners.

Leather lace-up boots, which are designed to provide more comfort, stability and support than a gumboot, were introduced as a means to reduce lower back pain in underground coal mining (Marr, 1999). Contrary to our hypothesis, there was no significant difference in the incidence of reported lower back pain between underground coal miners who wore leather lace up boots and those who wore gumboots. In fact, almost half (43%) of the miners, irrespective of work boot type, reported lower back pain, an increase compared to the 34% who reported lower back stiffness in 1999 (Marr, 1999). It is plausible that the high incidence of lower back pain reported in both studies is due to the nature of the working tasks underground coal miners perform and/or the surfaces they work on rather than their work boots *per se*. For example, in a survey of 322 airline assembly workers who were required to operate machinery while standing on hard concrete floors, 69.3% of the workers reported having lower back pain within the last year (Jefferson, 2013). The authors were unsure whether the lower back pain was due to working on hard concrete floors, having to maintain a static posture to operate machinery, or a combination of the two (Jefferson, 2013). Machine operation was the most common working role reported by underground coal miners in the present survey, with 36.3% of the miners reporting that they stand between 4 and 8 h each shift (Dobson et al., 2016). Therefore, the high incidence of lower back pain reported by underground coal miners may be related more to the working task and/or environment rather than design differences between leather lace-up boots and gumboots.

Ankle, knee and hip pain incidence also did not differ significantly when comparing gumboot wearers to leather lace-up boot wearers. In fact, the frequency of these pains was similar to the stiffness and injury rates reported by Marr (1999) and Smith et al. (1999) over a decade ago. The current study indicated the increased ankle support provided by the leather lace-up boot did not reduce lower limb pain. Ankle joint motion, however, did appear to have some influence on lower limb pain frequency. That is, of those participants who reported ankle pain, leather lace-up boot wearers were more likely to report the pain occurred 'rarely' whereas gumboot wearers were more likely to report their ankle pain occurred 'occasionally'. Previous research has highlighted that when healthy male participants (29 years of age) wore a lace-up hiking boot with a 50% reduction in passive shaft stiffness, eccentric energy absorption at the ankle joint was decreased (Böhm and Hösl, 2010). Therefore, it is possible that the tighter leather lace-up boot provided more protection to the ankle than the gumboot via restricting ankle joint motion. If ankle joint restriction was the mechanism via which this result occurred, it did not have any effect on knee pain incidence, which is in contrast to previous findings (Böhm and Hösl, 2010). This result could be due to the unique surfaces and working tasks encountered by underground coal miners. Indeed, the influence of boot shaft alterations on ankle motion can vary depending on the surface and task performed. For example, when male construction workers walked on a level surface, boots with varying shank support provided different levels of ankle stability compared to when they walked on an elevated, tilted surface (Simeonov et al., 2008). The authors speculated that this unexpected result was caused by an interaction between the higher boot shaft and ankle joint when the construction workers walked on the tilted surface, resulting in additional moments and lateral forces being generated. It was suggested that more flex in the boot shaft might dampened the generation of additional moments and lateral forces when the boot was tilted at an angle, i.e. when walking on a sloped surface, so that it would not have such a direct impact on ankle joint motion (Simeonov et al., 2008). Therefore, a better understanding of how much ankle support is required to allow pain free lower limb motion when walking on specific underground coal mining surfaces while performing working tasks is vital when designing comfortable and functional work boots for miners. Because the link between ankle joint motion and lower limb pain incidence is purely speculative, further research is needed to investigate boot design features that influence ankle motion, such as shaft stiffness, and how this affects both comfort and function.

In contrast to our hypothesis, underground coal miners still reported that their work boots contributed to their foot pain while working, despite the option to wear a more supportive leather lace-up boot. Over half (61.2%) of participants who reported foot pain believed this pain was related to their mining work boots, an increase since 1999 in which 53.4% of injured workers previously believed their boots contributed to their lower limb injuries (Smith et al., 1999). It is interesting to note, in the current study, of those participants who reported having foot pain, the locations of foot pain differed depending on boot type worn. The design differences between the gumboot and leather lace-up boot appear to be uniquely influencing foot motion and, consequently, locations of foot pain.

Underground coal miners are required to remain on their feet, either standing or walking, throughout most of their work shift (Dobson et al., 2016). If a work boot does not support the longitudinal arch of a miner's foot, this continued loading could lead to arch pain (de Castro et al., 2010). Furthermore, excessive foot movement inside a work boot can increase loading of mediolateral foot structures, such as the lateral malleolus, due to mediolateral movements that occur when walking on uneven surfaces (Thies et al., 2007). Excessive foot movement within a shoe can also cause significantly higher pressure-time integrals under the hallux and toes 2–5 that, over time, are likely to lead to foot pain and discomfort (Fiedler et al., 2011). Therefore, the looser fitting nature of gumboots, the tendency to allow more foot movement inside the boot and a lack of support (Marr, 1999; Smith et al., 1999) could explain why gumboot wearers were more likely to have pain in the arch, lateral malleolus and ball of the foot compared to their counterparts who wore the more structured leather lace-up boots.

Repetitive loading experienced during prolonged walking is a risk factor for cuboid and navicular pain in the foot (Gross and Nunley, 2015; Patterson, 2006). The finding that leather lace-up boot wearers were more likely to have pain around the navicular, cuboid, sole of the foot and heel indicates that the leather lace-up boot might not be providing sufficient cushioning to the plantar surface of the foot (Marr, 1999). This notion is supported by leather lace-up boot wearers being more likely to have corns and bunions, which result from increased pressure at concentrated locations on the foot (Grouios, 2004). Therefore, although introducing leather lace-up boots did not change the incidence of foot pain, the finding that underground coal miners have different locations of foot pain depending on the type of boot they wear indicates work boot design features have the potential to influence foot pain incidence. A better understanding of the influence different boot design features have on foot motion when miners perform common working tasks, such as walking and standing, is therefore needed. Such research could help explain why different boot design features are associated with specific locations of foot pain and how pain in these locations can be prevented.

Over half (52.1%) of underground coal miners in previous studies reported their gumboots did not fit properly and 41.3% said their feet slid inside their boots (Marr, 1999; Smith et al., 1999). The adjustability of the leather lace-up boot, accommodating individual fit preferences, most likely explains the observed improvement in ratings of mining work boot fit in the present study. Indeed, leather lace-up boot wearers were more likely to select 'fastening method' as something they preferred about their current work boots. A more supportive fit provided by laces, however, appears to have hindered the ability to get the boots on/off. Future research into underground coal mining work boot design needs to investigate whether other fastening designs, apart from laces, can be used to maintain a firm fit but still enable the boots to be easy to get on/off.

Improved perceptions of fit in the current study most likely accounted for the decrease in reported calluses (33.1%) compared to previous research (48.5%; Marr, 1999). However, no significant difference was found in the reported occurrence of calluses and blisters between the two boot types. A possible explanation is that leather lace-up boot wearers wore a work boot that was a size bigger than their everyday shoe size and gumboot wearers wore a size smaller than their everyday shoe size. When a boot is either too small or too broad the foot is unable to stabilise within the boot, leading to a high risk of calluses (Marr, 1999). With the gumboot being a wider style design and the leather lace-up boot a narrower style design, it appears that the wearers of each boot type are being forced to compensate boot length to achieve the desired boot width. In order to create a boot that fits comfortably and reduces the high incidence of calluses, further studies are needed to investigate the shape of miners' feet relative to the shape of their underground coal mining work boots to identify possible mismatches. These mismatches can then be used to provide evidence of mining work boot design features that require modification to enable the boots to better fit the feet of underground coal miners. It is acknowledged, however, that given the large variation in the size and shape of the feet of underground coal miners (unpublished research, Dobson et al., 2016) it is unlikely to be feasible to create a generic work boot that would suit the feet of all underground coal miners. However, it is important that future boot designs are based on the foot dimensions of coal miners and include design features which allow the miners to perform their work tasks in their unique work environment.

Regardless of which boot an underground coal miner wore, the participants reported the same top two design features that they considered would make an ideal work boot more comfortable: waterproofing and adequate ankle support. These results were also consistent irrespective of whether an underground coal miner worked in a wet or dry mine (Dobson et al., 2016). Adequate boot ventilation was also deemed an important boot design feature, although achieving both increased ventilation and waterproofing is challenging. It is therefore recommended that boot manufacturers investigate new materials other than the traditional rubber and leather in order to design work boots that are waterproof, and provide adequate ankle support and ventilation.

4.1. Limitations

The following limitations of the current study are acknowledged. Due to the cross-sectional and retrospective nature of the survey questions, boot design cannot be concluded as the sole contributing factor to the observed results. Also no mechanical testing was performed on the boots and differences in their structures were not systematically controlled. Therefore, although it was assumed structural design differences between the two underground coal mining work boots caused the observed results, further research with a prospective design should investigate the influence of boot design on lower limb function and comfort when coal miners perform working tasks. The accuracy of self-reported measures, presence of the research team, errors due to non-responses and validity differences between open and closed questions are also acknowledged as possible limitations of the survey. Given this study was compared to previous survey results reported by underground coal miners from the same demographics under similar conditions, we believe the impact of these limitations is minimal.

5. Conclusions

The introduction of a more structured leather lace-up boot as a work boot option has positively influenced perceptions of ankle support, fit and comfort reported by underground coal miners. The frequency of foot problems, lower limb pain and lower back pain reported by these miners, however, are still high, irrespective of the work boot type their wear. Although boot type did not alter the incidence of foot pain, underground coal miners reported different locations of foot pain depending on boot type, indicating differences in work boot design have the potential to influence foot pain. Further investigation is therefore recommended to identify which specific boot design features caused these observed differences in work boot fit, comfort and locations of foot pain and how these design features can be manipulated to create an underground coal mining work boot that is comfortable and reduces the high incidence of foot problems and lower limb pain suffered by underground coal mining.

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Conflict of interest

None.

Acknowledgement

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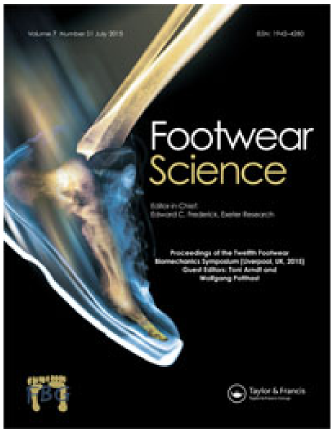

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Effect of underground coal mining work boot preference on boot satisfaction and discomfort

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mechanical variables into account. Datasets revealed high correlations between some variables, and weak correlations between some others. Thus, all variables extracted from a given mechanical test did not deliver the same information. Care should be taken when comparing samples between studies using different variables, even if the method is the same. Moreover, a given variable (computed in the same way) extracted from two distinct methods can lead to different conclusions. This could be due to the way the machines are driven (gravity or force), which should also be taken into account when comparing results from various studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Effect of underground coal mining work boot preference on boot satisfaction and discomfort

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Introduction

Workplace injuries in mining are highly prevalent (Smith et al., 1999) and, in Australia, occur most frequently in underground coal mines (Government of Western Australia, 2011). The most common of these injuries are to the lower limbs, contributing to almost 18,900 lost working days and incurring $28 million in compensation claims annually. Approximately, 40% of miners who sustained lower limb injuries identified their work boots as the main causal factor. As a consequence, laced leather work boots were introduced as an alternative to the steel-capped gumboot (Marr, 1999; see Figure 1). Despite the uptake of this recommendation, no research has investigated whether the introduction of a leather lace-up boot for underground coal miners has positively influenced work boot satisfaction.

Purpose of the study

The purpose of this study was to document what work boots underground coal miners selected to wear and determine whether boot-type influenced work boot satisfaction and self-reported discomfort.

Methods

Underground coal miners (n = 355 men and 3 women; 39.1 ± 10.7 years of age) employed by Illawarra Coal volunteered to complete a survey designed to derive work boot habits and fit, foot problems, discomfort and boot preferences. Survey questions were developed from previously validated survey instruments (Marr, 1999; Marr & Quine, 1993; Smith et al., 1999) and following discussion with industry representatives. Responses to survey questions were coded and counted to determine the frequency of responses. The number of responses for each question varied due to non-responses, multiple answer selection and when questions did not require an answer from all participants. A series of chi-square tests were applied to determine whether boot satisfaction and discomfort differed significantly ($p < 0.05$) according to boot type (gumboot vs. leather lace-up boot).

Results

Of those participants who reported a clear boot preference, the most frequently worn boot was the gumboot (71%) compared to the leather lace-up boot (29%). Foot problems were reported by 68.6% of the study population and more than 50% of participants identified the presence of hip, knee or ankle pain. Of those who listed foot and/or ankle pain, over half (56.7%) believed the pain was related to their work boots. Participants who specifically experienced pain during their underground mining shifts indicated lower back pain (49.0%) and foot pain (30.0%) as the most prevalent type of pain. There was no

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Figure 1. Underground coal mining work boots. (A) Gumboot and (B) leather lace-up boot.

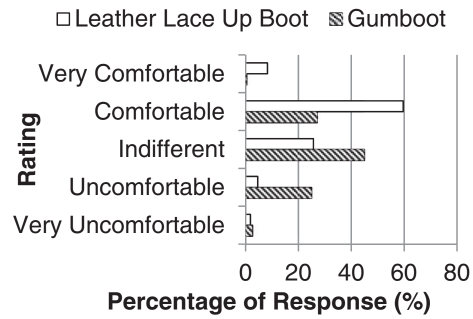

Figure 2. Work boot comfort ratings for participants who wore gumboots and leather lace-up boots ($n = 338$).

significant difference between the gumboot wearers compared to the leather lace-up boot wearers with regards to the presence of lower back pain ($\chi^2 = 0.73$, $p = 0.95$) or the presence of foot and/or ankle pain ($\chi^2 = 3.2$, $p = 0.37$).

There were significant differences in the ratings of work boot comfort ($\chi^2 = 53.2$, $p < 0.001$) and fit ($\chi^2 = 45.1$, $p > 0.001$) between the two boot types. That is, participants who wore the gumboot, compared to the leather lace-up boot, were more likely to state that their work boot comfort was either 'uncomfortable' or 'indifferent' (see Figure 2) and their work boot fit was 'poor' (14.5% vs. 3.6%). Conversely, leather lace-up boot wearers were more likely to rate their work boot comfort as 'comfortable' when compared to gumboot wearers (see Figure 2).

Overheating combined with poor ventilation, not enough support and sore feet were the main three characteristics participants listed as problematic with their current work boots. Compared to the leather lace-up boot, gumboot wearers were also more likely to report that their current boot did not provide enough support (15.0% vs. 4.3%, $\chi^2 = 52.3$, $p < 0.001$).

Discussion and conclusion

Underground coal miners are required to remain on their feet for long periods of time and work on uneven, moveable and wet surfaces (Marr, 1999). Based on the survey results, current work boot design does not appear to meet the demands of miners while they are working underground. More importantly, underground coal miners believe their work boots are contributing to their lower limb injuries and discomfort. Although miners who wear leather lace-up boots appeared to be more satisfied with the comfort, fit and support provided by their work boots than their colleagues who wore gumboots, they still reported suffering lower back pain and foot pain. These results need to be interpreted with caution, however, as only a relatively small percentage of the miners wore the leather lace-up boots.

Further investigation is recommended to identify which specific boot design features are causing the differences in work boot satisfaction and discomfort reported by the underground coal miners.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Does the 3D Shape of Underground Coal Miner’s Feet Match Their Internal Boot Dimensions?

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Although underground coal miners report their mining work boot fit is reasonable-to-good, they state their boot comfort is uncomfortable-to-indifferent. This study aimed provide insight into this discrepancy between boot fit and comfort by comparing the three-dimensional shape (INFOOT scanner, I-Ware Laboratory, Japan) of 270 underground coal miner’s (39 ± 11 years of age) feet to the internal dimensions of their work boots. The underground coal miners’ foot dimensions were significantly different ($p \leq 001$) to the internal dimensions of their mining work boots. On average, the miners’ foot length was 2.5 cm smaller than their work boots, indicating an acceptable fit. The miners’ foot breadth, however, was on average only 0.04 cm smaller and their heel breadth 0.5 cm smaller than their work boots. This finding indicates miners’ work boots are not wide enough to accommodate for the width of their feet, providing a possible explanation for the reported discomfort.

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How do we fit underground coal mining work boots?

Jessica A. Dobson, Diane Harland, Alison F Bell & Julie R. Steele

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Table 1. Correlation analysis and relationship between different aspects and the overall comfort.

	r	*P*	Standard coefficient	*P*
Wrapping	0.84	0.00*	0.43	0.023*
Fit	0.79	0.00*	0.228	0.167
Sole comfort	0.76	0.00*	0.417	0.001*
Air permeability	0.2	0.35	—	—
Support	0.56	0.00*	−0.14	0.907

*means the statistically significance.

Table 2. The multiple regression of sole comfort and the wrapping.

Index	Standard coefficient	*P*
Sole comfort	0.426	0.00*
Wrapping	0.607	0.00*

*means the significant correlation.

Conclusion

(1) The wrapping, the shoe fit, the sole comfort, and the support made great influence to the overall comfort when people evaluate the sport shoes.
(2) The relationship of the shoe wrapping, the sole comfort, and the overall comfort can be described by a multiple regression equation: overall comfort $= 0.426 \times$ (sole comfort) $+ 0.607 \times$ (wrapping).

Disclosure statement

No potential conflict of interest was reported by the authors.

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How do we fit underground coal mining work boots?

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Keywords: 3D scanning; work boots; fit; underground coal mining; comfort

Introduction

Well-fitted footwear provides an appropriate level of protection, support and comfort during walking (de Castro et al., 2010), and reduces the potential for foot problems and foot pain (Manna et al., 2001). To fit properly, the internal footwear shape should match the shape of a wearer's foot. In underground coal miners, however, there are mismatches between the shape of their feet and the internal work boot dimensions. The impact these boot-foot mismatches have on work footwear satisfaction remains unclear (Dobson et al., 2017). Uncomfortable footwear does not have poor fit ratings at every point on a shoe. This indicates that work boot fit might be more important at some areas of the foot rather than others (Au & Goonetilleke, 2007), although this notion remains unexplored.

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Purpose of the study

The purpose of this study was to determine the association between the internal work boot shape–foot shape match and work boot satisfaction in underground coal miners.

Methods

Three-dimensional foot scans (INFOOT; I-Ware, Japan) were collected for 197 underground coal miners (39.2 ± 9.6 years of age; 178.7 ± 5.8 cm; 92.8 ± 12.6 kg). Boot moulds representing the internal dimensions of the standard safety footwear worn by underground coal miners in the Illawarra Region (Aus; gumboot and leather lace-up) were constructed out of Plaster of Paris (Uni-PRO, Australia). These moulds were scanned using the same procedure. The following dimensions of each foot and boot mould were measured: length, ball girth circumference, breadth, instep circumference, heel breadth, height of the instep, ball girth height and heel girth circumference. Differences between these measurements were calculated and grouped into 12 categories. Categories depended on the difference value; 0–10, 10–20, 20–30, 30–40, 40–50, >50 mm, and whether the miner's feet were smaller (−) or larger (+) than the internal dimensions of their work boots.

The participants also completed a survey, which sought information on the their incidence of foot problems, lower limb and lower back pain history and ratings of work footwear fit and comfort.

To assess mining work boot fit relative to underground coal miner boot satisfaction, cross tabulations with a Pearson's Chi-squared test were applied to the survey data (foot problems, lower limb and lower back pain history, and work footwear fit and comfort) and the difference in values between the miner's feet and their internal boot dimensions (SPSS Version 21, USA). This design determined whether the position of a miner's foot inside their work boot was significantly associated ($p < 0.05$) with their incidence of foot problems, lower limb and lower back pain history, and ratings of work footwear fit and comfort.

Results

Lower back pain incidence reported by the coal miners was significantly related to heel breadth ($\chi^2 = 8.1$, $p = 0.015$) and heel girth circumference difference values ($\chi^2 = 15.4$, $p = 0.038$). That is, a gap of 40–50 mm at the heel girth circumference and 10–20 mm at the heel breadth led to an increased incidence of lower back pain. Of the miners who reported having foot pain, heel girth circumference deviations significantly affected this occurrence ($\chi^2 = 45.7$, $p = 0.005$). Comfort ratings were significantly affected by heel girth circumference

Table 1. Significant ($p \leq 0.05$) relationships for the variables instep height, ball girth height and heel girth circumference based on the difference between the dimensions of underground coal miner's feet and their internal work boot dimensions.

	Difference	Instep Height	Ball Girth Height	Heel Girth Circumference
Boot Bigger	-20-30mm	Poor fit	Very comfortable Very good fit	Very comfortable
	-10-20mm	Less likely poor fit	Good fit Less likely indifferent comfort Less likely reasonable fit	Indifferent comfort
	-0-10mm		Uncomfortable - indifferent Poor - reasonable fit	Very uncomfortable

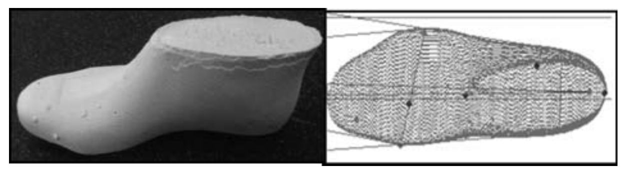

Figure 1. An example mould representing the internal shape of the gumboot and the associated 3D scanned image.

($\chi^2 = 75.6$, $p = 0.001$) and ball girth height ($\chi^2 = 46.4$, $p = 0.000$) deviations (see Table 1). Whereas fit ratings were significantly affected by deviations in instep height ($\chi^2 = 39.8$, $p = 0.001$; see Table 1) and ball girth height ($\chi^2 = 32.2$, $p = 0.009$) (see Table 1). Finally, instep height deviations significantly affected hip pain incidence ($\chi^2 = 12.7$, $p = 0.019$). No significant relationships were found in regards to length or foot breadth.

Discussion and conclusion

Whether the shape of a work boot matches a miner's foot at the heel, ball girth and in-step appears to be more important than the traditional measurements of length and width. Gaps of 0–10 mm between a miner's foot and the edge of their work boots in terms of width were insufficient for a boot to be deemed comfortable. A gap of 10–20 mm between the foot and boot appeared to be the minimum at the in-step and ball girth, whereas 20–30 mm at the heel, to ensure the workers deemed their footwear as satisfactory. This gap dimension may be required to allow for foot changes during work. There is a tendency for the miner's feet to become hot and sweaty over time, leading to swelling inside their boots.

The results of the present study have important implications for the fit of work boots for underground coal miners.

Disclosure statement

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Effect of fore-medial-side thin insole on lower extremities biomechanics in college male basketball players

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Keywords: insoles; metatarsal heads; kinetics; kinematics; athletic performance

Introduction

Injuries most often seen in male and female basketball players were the ankle (male 20.3%, female 17.9%) and knee (male 12.3%, female 16.4%) (Zelisko, Noble, & Porter,. 1982). More than 60% injuries happened in games and practices were ankle ligament sprains, knee injuries (internal derangements and patellar conditions) and upper leg muscle-tendon strains in the lower extremity (Agel *et al.* 2007).

Foot pressure distribution pattern starts from heel to toe with pronation movement. Peak pressure at the hallux increases by 40%, while the lateral forefoot undergoes a 54% decrease during cutting movements compared to running straight (Ellis *et al.* 2004). The main influence of shoes is modifying the behavior of the forefoot by changing the pressure distribution across the metatarsal heads and increasing the contact times for the toes (Soames, 1985). Providing more space for the first metatarsal part in the shoes may curtail first metatarsal stress.

The authors of the present study supposed that thinning the fore-medial side of the insole would allow of more space for the medial forefoot and the incline as resistance on the medial metatarsal would help the cutting of the basketball movement.

Purpose of the study

The purpose of this study was to investigate the effect of fore-medial-side thin insole (TI) on lower extremities kinematics and kinetics in college male basketball players.

Methods

Seven male college basketball players voluntarily participated in the study (heights = 173.1 ± 3.1 cm; weights = 68.6 ± 5.7 kg; age = 21.1 ± 2.0 years).

They wore the same basketball shoes (Nike Zoom Hyperfuse Low X) with two types of insoles (Footdisc Proactive Med Arch): one type was original insole (OI); another one was fore-medial-side TI (Figure 1).

Subjects were asked to perform L-cut (L), V-cut (V), shuttle run (SR) of basketball movement in a 5-metre running way with their maximum speed after 10-min warm-

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Improving Work Boot Fit for Underground Coal Miners

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Well-fitting work footwear protects and supports the foot and is comfortable to wear, thereby reducing the potential for musculoskeletal complications and pain. Our research has found that although underground coal miners rate their work boot fit as 'reasonable to good,' they perceive their work boots as 'uncomfortable'. Underground coal miners remain on their feet for the majority of a typical 12-hour shift working on challenging surfaces that are uneven, wet and unstable. These work requirements highlight the necessity for their work boots to fit properly. The aim of this study was to systematically assess underground coal mining work boot fit and comfort in order to develop recommendations for better work boot designs. 197 underground coal miners (39.2 ± 9.6 years of age) completed a survey detailing self-perceived foot problems, lower limb and lower back pain history; and perceptions of their work boot fit and comfort. Work boot fit was also assessed by comparing 3D scans of the miners' feet to 3D scans of their internal work boot dimensions. Our results indicated that, in addition to foot length, 3D scans also revealed significant differences between the foot and work boot dimensions at the forefoot and heel. Furthermore, fit at the forefoot, instep and heel were key areas that related to the foot pain and discomfort perceived by the miners. To ensure underground coal mining work boots fit properly, future work boot designs should be wider at the forefoot and heel with adequate room at the instep to support underground coal miner's feet. Work boots that more accurately resemble the foot shape of underground coal miners, fitted to allow optimal room for comfort and appropriate foot movement, should not only improve worker satisfaction but reduce the high incidence of foot problems and pain evident in underground coal mining.
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Jessica Dobson is a final year PhD candidate who has been researching underground coal mining work boots for 4 years. Her background is in exercise science and currently she is part of the Biomechanics Research Laboratory at the University of Wollongong. Her main research focus is to improve the fit and comfort of underground coal mining work boots using three-dimensional scanning and biomechanical gait analysis. Her work has been published in Applied Ergonomics and she has presented at international conferences such as Applied Human Factors and Ergonomics (AHFE).

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Effects of wearing gumboots and leather lace-up boots on lower limb muscle activity when walking on simulated underground coal mine surfaces

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ABSTRACT

This study aimed to 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. Quadriceps (rectus femoris, vastus medialis, vastus lateralis) and hamstring (biceps femoris, semitendinosus) muscle activity were recorded as twenty male participants walked at a self-selected pace around a circuit while wearing each boot type. The circuit consisted of level, inclined and declined surfaces composed of rocky gravel and hard dirt. Walking in a leather lace-up boot, compared to a gumboot, resulted in increased vastus lateralis and increased biceps femoris muscle activity when walking on sloped surfaces. Increased muscle activity appears to be acting as a slip and/or trip prevention strategy in response to challenging surfaces and changing boot features.

1. Introduction

Underground coal mine workers incur a high incidence of work-related lower limb injuries (Government of Western Australia, 2011), including sprains and strains caused by slips, trips and falls (Armour, 2003; WorkCover NSW, 2010). Annually, these lower limb injuries contribute to almost 19,000 lost working days (Government of Western Australia, 2011) and an average of $28 million in compensation claims in Australia alone (Armour, 2003). These figures are the highest rate when compared to all other Australian mining industries.

The risk of experiencing a slip (Chambers and Cham, 2007; Lockhart and Kim, 2006; Oates et al., 2010) or trip (Austin et al., 1999) accident is influenced by the shoe–surface interface, particularly at the time of initial contact with the ground and during the pre-swing of the gait cycle. When walking on a level, even surface while wearing everyday footwear, healthy individuals usually make the necessary adjustments to maintain balance in order to avoid a slip or trip (Austin et al., 1999; Chambers and Cham, 2007; Tang et al., 1998). Underground coal mine surfaces, however, are often uneven, unpredictable due to poor light conditions or the surface being occluded by water, incorporate moveable materials such as rocks, and vary in gradient.

To avoid slip and trip injuries while traversing these uneven surfaces, it is vital that underground coal miners recruit the appropriate lower limb musculature (Franz and Kram, 2012). This is particularly important when they negotiate steep gradients because additional muscle activity is needed to raise and lower the centre of gravity (Franz and Kram, 2012; Lay et al., 2007; Patla, 1986). The amount of muscle activity is also dependent upon the design of footwear worn by individuals (Böhm and Hösl, 2010; Noé et al., 2009; Nurse et al., 2005). For example, by manipulating sole flexibility the shoe–surface interface is altered, which can in turn change the lower limb joint angles and muscle activity displayed during walking (Nurse et al., 2005). Changing footwear support also potentially triggers a reorganisation of the muscle activity that is responsible for stabilising the ankle and knee joints (Noé et al., 2009). Mining work boots of varying sole flexibility and boot support may therefore influence how an underground coal miner's feet interact with an uneven surface, thereby dictating the amount of lower limb muscle activity generated to support a joint, such as the ankle or knee, in an attempt to reduce the risk of a slip or trip. This notion, however, is yet to be investigated.

Coal mining work boots are usually made of either leather (e.g. a lace-up boot) or rubber (e.g. a slip on gumboot), and must incorporate a steel-cap to protect the worker's feet from undesirable

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external stimuli, such as rocks, gravel and dirt, and to satisfy minimum personal protective equipment standards (Marr and Quine, 1993). Mining boots also typically incorporate a high shaft (upper part of the boot that covers the shank), particularly in mines that require the miners to walk through water. Combinations of these boot characteristics and materials, while adhering to safety standards, result in structurally different boots in terms of overall mass, shaft stiffness, support and sole flexibility. The effects of these structural differences in boot design, however, on the gait of underground coal miners and their risk of slipping or tripping are unknown.

If the structural characteristics of the underground coal miners' work boots require these workers to use additional muscle activity during walking, the potential for incorrect foot placement onto the supporting surface exists. As a consequence, the risk of incurring a sprain or strain injury, via slipping or tripping, might increase. Despite these negative implications, no study has systematically examined whether boot type affects lower limb muscle activity when walking on surfaces typically encountered by underground coal mine workers. Therefore, the aim of this study was to 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. It was hypothesised that differences in the mass, shaft stiffness and sole flexibility of the gumboot compared to the leather lace-up boot would influence lower limb muscle activity during gait. Specifically, when walking in a gumboot, which has a looser shaft, more flexible sole and lighter mass than a leather lace-up boot, participants would display decreased intensity of the quadriceps (rectus femoris, vastus medialis, vastus lateralis) and hamstring (biceps femoris, semitendinosus) muscle activity.

2. Methods

2.1. Participants

Twenty male participants (33 ± 12 years of age) who matched the demographics of Illawarra Coal (NSW, Australia) underground coal mine workers (unpublished data, 2013) volunteered to participate in this study. Participant exclusion criteria included lower limb injuries or foot pain/discomfort that impaired their ability to perform the experimental procedures. Participants who habitually wore corrective shoe inserts (such as orthotics) were also excluded because a non-standard sole insert could influence the internal properties of the boots. A priori analysis confirmed that a cohort of 20 participants was sufficient to demonstrate a significant difference between the two footwear conditions with a power of 80% (at an alpha level of 0.05). The University of Wollongong Human Research Ethics Committee approved all testing procedures (HE13/050) and written informed consent was obtained from all participants before commencing data collection.

2.2. Footwear conditions

The two footwear conditions included: (i) a gumboot (Style 015; 2.7 kg; 37.5 cm shaft height; rubber; Blundstone®, Australia) and, (ii) a leather lace-up boot (Style 65-691; 3.1 kg; 35 cm shaft height; full grain leather; Oliver, Australia) ranging from sizes 8–12 (see Fig. 1 and Table 1). These boots are standard safety footwear provided to underground coal miners (Illawarra Coal, Australia) and thus were selected as the experimental footwear.

2.3. Experimental procedures

All participants were provided with a new pair of socks (Miners Corp. Essentials Pty Ltd, Australia) and were fitted into the two boot types (sized according to measuring guidelines provided by the boot manufacturers). After familiarisation, each participant walked at a self-selected pace around three loops of a walking circuit while wearing each boot type, with boot condition order randomly allocated to prevent any order effects. The walking circuit was designed to replicate the uneven and moveable surface conditions that underground coal mine workers typically navigate during their daily work tasks when working in a dry underground coal mine. The circuit included four dry surface conditions: (i) level walking on a gravel surface (flat gravel), (ii) level walking on a compacted dirt surface (flat dirt), (iii) walking up an inclined rocky, gravel surface (incline), and (iv) walking down a declined rocky, gravel surface (decline; see Fig. 2). Each loop covered approximately 24 m, took 30–45 s and was performed during daylight conditions. The surface inclination angle was approximately 20°, although it is noted that the inclination angle was not uniform due to the unevenness of the surface. In-shoe pressure and muscle activity data were collected while each participant completed the circuit. To minimise fatigue, participants rested between loops of the walking circuit and between the two boot conditions.

2.3.1. In-shoe pressure data

In-shoe pressure was collected (50 Hz) using Pedar-X (novel$_{gmbh}$, Germany) insoles. Each insole (99 sensors) was attached to the Pedar-X box, secured to the participant's waist. Before data collection began, the insoles were factory calibrated and both insoles were zeroed each time they were placed inside a new boot. The Pedar-X data acquisition software (Version 23.3.4; novel$_{gmbh}$, Germany) was used to collect and filter data from each participant's dominant (as determined by which leg they would kick a ball with) and non-dominant foot during each section of the walking circuit. The in-shoe pressure data were used to calculate the timing of initial contact (first contact of the dominant limb with the ground) and pre-swing (dominant limb loses contact with the ground) for participants throughout the specific sections of the walking circuit. Initial contact and pre-swing were selected for analysis in the present study as they rely on co-ordination of the lower limb musculature to position the foot at an appropriate angle for deceleration and ground clearance, respectively (Perry, 1992). If abnormal foot contact occurs at initial contact, the risk of slipping is increased (Lockhart and Kim, 2006) and if adequate clearance of the foot is not achieved throughout pre-swing, the risk of tripping is increased (Austin et al., 1999). The steps recorded by the in-shoe pressure device were also used to calculate the amount of time participants spent in the stance phase and the swing phase of gait. Alteration to the timing of these phases as a result of boot type could then be determined (Böhm and Hösl, 2010; Mündermann et al., 2001).

2.3.2. Muscle activity during walking

Surface electromyography (EMG) data were recorded (1000 Hz; bandwidth 20–450 Hz) using a Trigno wireless EMG system (Delsys Inc., USA). Delsys sensors (37 mm × 26 mm × 15 mm, < 15 g) were attached (Delsys Adhesive Sensor Interface; Delsys Inc., USA) over the muscle bellies of the quadriceps (rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL)) and hamstring (biceps femoris (BF), semitendinosus (ST)) muscles on each participant's dominant lower limb (see Fig. 3). Sensor placement sites were identified following recommendations by SENIAM (1999) and the guidelines endorsed by the International Society of Electrophysiology and Kinesiology (Merletti, 1999). These muscles were

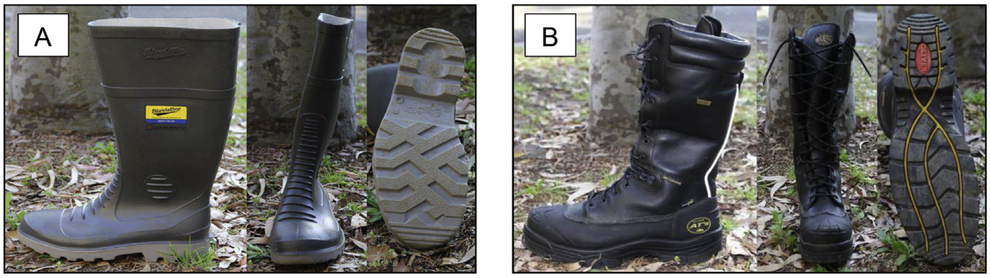

Fig. 1. The two footwear conditions. A: Gumboot (Style 015; Blundstone®, Australia) and B: Leather lace-up boot (Style 65-691; Oliver, Australia).

selected for analysis due to their superficial location and their role in controlling the knee and hip joints during gait (Perry, 1992). Furthermore, when negotiating inclined and declined surfaces, previous studies have found that any changes in lower limb muscle activity primarily occur at the knee joint and secondarily at the hip joint, with minimal to no differences at the ankle joint (Franz and Kram, 2012; Lay et al., 2007). Prior to sensor placement, the skin over each designated muscle belly was shaved, abraded with prep tape and cleaned with an alcohol swab to ensure optimal readings (Cram et al., 1998).

After visual inspection of the data (to exclude any trials grossly contaminated by movement artefact), the raw EMG signals were filtered (fourth-order zero-phase-shift Butterworth low pass; $f_c = 20$ Hz). Due to excess noise, the signals from two participant's VM and one participant's ST muscle were excluded from data analysis. EMG data for one participant was not available for analysis as a result of sensor failure. The filtered signals were then processed in a custom LabVIEW program (Larkin, 2013) to determine a 200 ms window either side of initial contact and either side of pre-swing in each section of the walking circuit. The area under this 400 ms

Table 1
Characteristics of the Gumboot (Style 015; Blundstone®, Australia) and Leather lace-up boot (Style 65-691; Oliver, Australia).

Variable	Gumboot	Leather lace-up boot
Mass (kg)[a]	2.7	3.1
Shaft height (cm)[a]	37.5	35
Heel height (cm)[a]	3.2	4.2
Materials	PVC/nitrile rubber (resistant to chemical, oil and acid)	Full grain (hide hasn't been sanded, buffed or snuffed) water resistant leather
Fastening method	Nil: Slip-on	Laces
External waterproofing	Waterproof	Water resistant
Internal lining	Plush knitted mesh	SympaTex (SympaTex Technologies, GmbH) fabric (waterproof, windproof and breathable membrane)
Foot bed	Soft polyurethane, covered with a full length cushion of foam polyurethane, topped with a mesh cover	Combination of cellular urethane and PORON® urethane
Sole	Combination of PVC/nitrile rubber and PORON®xRD™ material	Low density polyurethane
Toe cap	Type 1 (heavy work environment) steel	High carbon steel with a latex cap liner
Sizes available	AU 4-13 Wide fit to accommodate broad feet	AU 5-14, 6.5-10.5

[a] Averaged across the five boot sizes (sizes 8–12) used in this study.

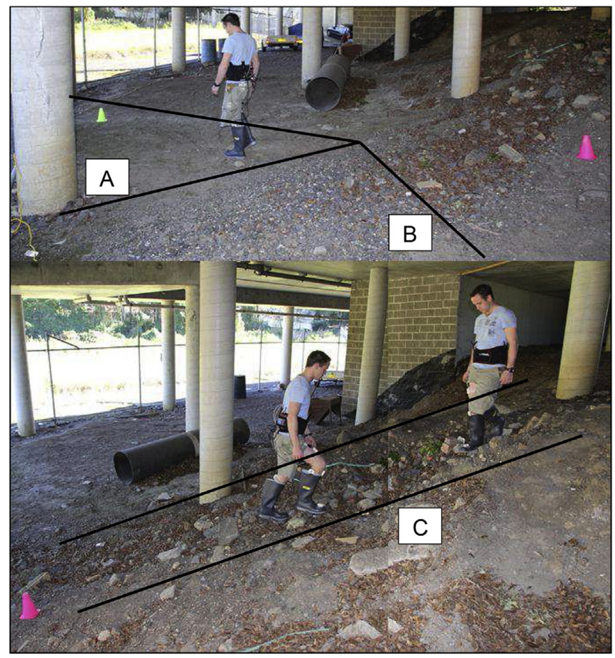

Fig. 2. Test walking circuit. A: Flat hard dirt section, B: Flat gravel section and C: Inclined and declined rocky, gravel sections.

window was then calculated (mV/s) to represent the intensity of muscle activity during these two separate phases of the gait cycle (Nigg et al., 2006). This process was conducted for all five lower limb muscles and initial contact and pre-swing were determined from the in-shoe pressure data (see Section 2.3.1). The literature

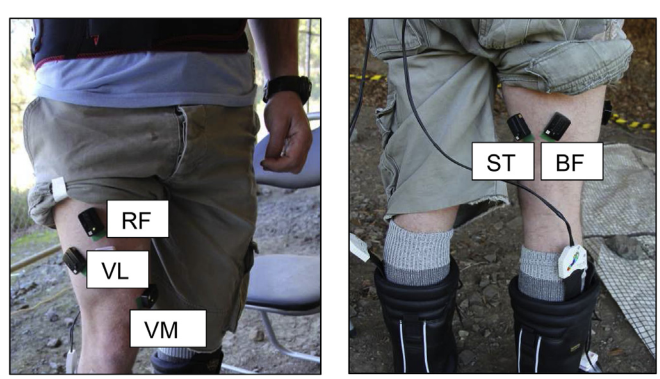

Fig. 3. Participant showing EMG sensor placement for the lower limb. Muscles: quadriceps; rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) and hamstrings; biceps femoris (BF), semitendinosus (ST).

consistently shows that when stability is challenged, muscle activity, expressed in millivolts (mV), consistently increases (Blackburn et al., 2003; Greensword et al., 2012; Mika et al., 2012; Nigg et al., 2006; Romkes et al., 2006). Therefore, the area under the curve (mV/s) was used as a measure of muscle intensity in the present study (Finsterer, 2001; Hamill and Bensel, 1996).

2.3.3. Knee and hip joint angles during walking

A digital video camera (JVC, Japan; 25 Hz), levelled on a tripod approximately 1.5 m above the ground and positioned to minimise errors of perspective, was used to film the sagittal plane motion of the participants walking the circuit. Two-dimensional knee joint (between the thigh and shank segments) and hip joint (between the thigh and trunk segments) angles at the video frames representing initial contact and at pre-swing were measured (LongomatchVersion 0.18.12 software; Creative Commons, USA) directly from the video images. Two-dimensional analyses of joint angles have frequently been used as an accurate measure to represent gait (Whittle, 2007).

2.4. Statistical analysis

Means and standard deviations of the muscle activity and knee and hip joint angles at initial contact and at pre-swing were calculated over the three walking trials per boot condition per surface condition. A two-way repeated measures ANOVA design, with two within factors of boot type (gumboot versus leather lace-up boot) and surface (flat gravel, incline, decline and flat dirt), was then used to determine whether there were any significant main effects or interactions of either boot type or surface on the muscle activity or joint angles displayed by the participants. Wilks' Lambda multivariate test was used to determine significant main effects and interactions. Paired *t*-tests further investigated any significant main boot effects and interactions. An alpha level of $p \leq 0.05$ was used for all statistical comparisons and all tests were conducted using SPSS statistical software (Version 19, SPSS, USA).

3. Results

3.1. Stance and swing gait cycle timing

Spatiotemporal analysis of the in-shoe pressure data revealed that the type of boot worn had no significant effect on the time spent in either phase of the gait cycle.

3.2. Muscle activity during walking

When participants walked across the flat surfaces (gravel and compacted dirt), no significant differences were found between the gumboot and leather lace-up boot conditions in the mean muscle intensity (mV/s) generated during initial contact or during pre-swing ($p \geq 0.05$) for any of the muscles analysed. Furthermore, there was no significant main effect of boot type on the intensity of vastus medialis or semitendinosus during initial contact and pre-swing for any surface type. The inclined and declined walking surfaces, however, revealed significant differences between the gumboot and leather lace-up boot for mean muscle intensities calculated for rectus femoris, vastus lateralis and biceps femoris, as described below.

There was a significant interaction of boot type × surface ($p = 0.029$) for rectus femoris mean muscle intensity during initial contact. Upon further analysis of the interaction, however, no significant results were found. During initial contact, significant main effects of boot type ($p = 0.008$) and surface ($p < 0.001$) and a significant interaction of boot type × surface ($p = 0.017$) on vastus lateralis muscle intensity were present. As shown in Fig. 4, vastus lateralis muscle intensity significantly increased when participants walked down the declined surface while wearing the leather lace-up boot compared to when participants walked down the declined surface wearing the gumboot. However, there were no significant differences between the two boot conditions in vastus lateralis muscle intensity when the participants walked on the two level surfaces (flat gravel and flat dirt) or on the inclined surface. There was no significant boot × surface interaction for vastus lateralis muscle intensity at the time of pre-swing.

There was a significant main effect of both boot type ($p = 0.003$) and surface ($p < 0.001$), on biceps femoris muscle intensity generated while the participants walked around the circuit. When walking up the incline ($p = 0.047$) and down the decline ($p = 0.048$), biceps femoris mean muscle intensity was significantly increased during pre-swing whilst participants wore the leather lace-up boot compared to the gumboot (see Fig. 5). During initial contact, however, there was no significant main effect of boot type on biceps femoris muscle intensity.

3.3. Knee and hip joint angles during walking

Analysis of the video data revealed a significant main effect of surface ($p < 0.001$) and a significant interaction of boot type × surface ($p = 0.024$) on the knee joint angle at initial contact. Upon further investigation of the boot type × surface interaction it was found that when the participants walked up the incline, their knee was in a more extended position at initial contact when wearing the gumboot compared to when wearing the leather lace-up boot (see Fig. 6). No significant main effects of boot type were found on knee angle at pre-swing or the hip angle at initial contact.

4. Discussion

Gumboots and leather lace-up boots are two types of standard safety footwear provided to underground coal mine workers. Any boot structure that requires miners to use additional muscle activity has the potential to change the boot–surface interaction, increasing the risk of incurring a sprain or strain injury. This study aimed to investigate the effects of wearing two structurally different work boots on lower limb muscle activity when participants walked across simulated underground coal mining surfaces. Boot type was found to significantly influence lower limb muscle intensity of the participants while they walked on inclined and declined surfaces and the implications of these findings are discussed below.

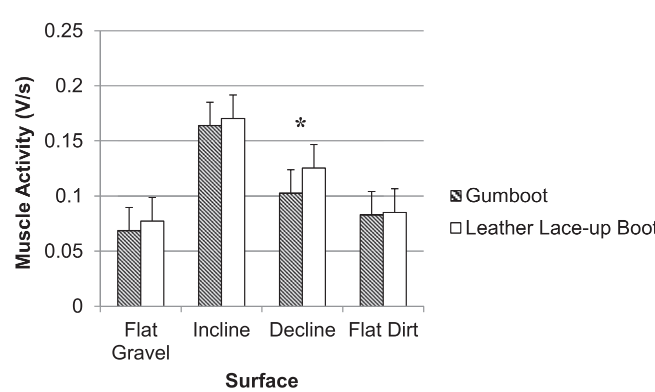

Fig. 4. Mean (+SEM) vastus lateralis muscle activity (V/s) during initial contact while the participants walked in the gumboot and leather lace-up boot on the four different surface conditions. *Indicates a significant interaction of boot type × surface ($p \leq 0.05$).

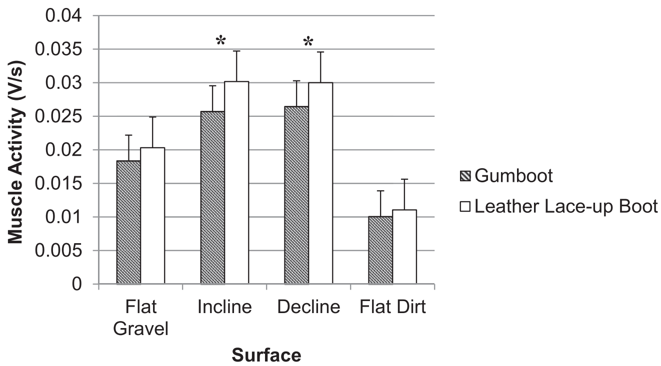

Fig. 5. Mean (+SEM) biceps femoris muscle activity (V/s) during pre-swing while the participants walked in the gumboot and leather lace-up boot on the four different surface conditions. *Indicates a significant difference between the two boot conditions ($p \leq 0.05$).

In contrast to the hypothesis, no significant differences in mean muscle intensity were found between the boot conditions when the participants walked on the level sections of the walking circuit. The demand placed on the lower limb during brief periods of level walking was unlikely to be sufficient to require changes to lower limb muscle activity in response to the structural differences in the two boots. Instead, muscle intensity appears to be more related to the power generation and absorption required to successfully traverse more challenging uneven surfaces, particularly inclines and declines (Franz and Kram, 2012; Lay et al., 2007). In agreement with this notion, the muscle intensities recorded in the present study increased when the participants walked on inclined and declined surfaces compared to level surface walking.

Of the muscles controlling knee joint motion, biceps femoris and vastus lateralis were particularly responsive to changes in surface gradient (Lay et al., 2007). Knee joint muscle intensity also increased significantly when the participants wore the stiffer leather lace-up boots, which provided more shank support, compared to the gumboots. This finding was in contrast to a study by Noé et al. (2009), who found that a stiffer ski boot shaft, which provided more stability for healthy male alpine skiers ($n = 14$, 20 ± 5 years of age) while they performed postural sway tasks, resulted in decreased muscle activity. The authors concluded that muscle activity decreased when sufficient support was provided by an individual's footwear (Noé et al., 2009). We speculate that the between-study difference could be attributed to the influence of boot mass on lower limb motion, irrespective of the changes in boot support (Chiou et al., 2012). It is also possible that regardless of stability, a stiffer boot shaft has more impact when walking on surfaces that already require additional muscular activity and joint motion, such as an incline and decline, compared to static postural sway tasks and level walking.

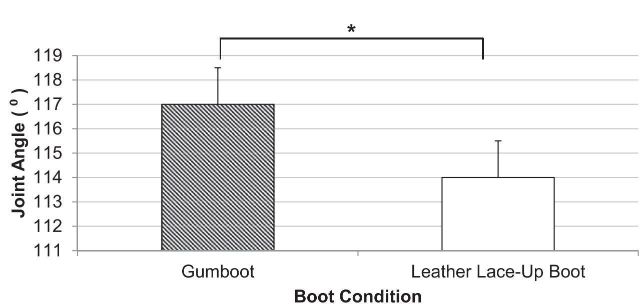

Fig. 6. Mean (+SEM) knee joint angles (°) at initial contact while the participants walked up the incline in the gumboot and leather lace-up boot ($n = 9$). *Indicates a significant difference between the two boot conditions ($p \leq 0.05$).

The leather lace-up boots used in the current study were approximately 0.4 kg heavier than the gumboots. Despite this difference in boot mass, the participants spent the same amount of time in the stance and swing phases of the gait cycle. Therefore, the increased biceps femoris and vastus lateralis muscle intensity when wearing the leather lace-up boot compared to the gumboot might indicate that extra effort was required to walk in a heavier boot. The main objective of pre-swing is to prepare the unloaded limb for successful clearance during swing. As a knee flexor, the role of biceps femoris during pre-swing is to inhibit knee extension and assist the knee in a flexed position ready for swing (Perry, 1992). Immediately after pre-swing, if the limb is not adequately flexed the boot will contact the supporting surface, causing a trip (Austin et al., 1999; Chiou et al., 2012). As heavier boots tend to decrease trailing limb toe clearance (Chiou et al., 2012), the additional biceps femoris muscle activity required in the present study when the participants were wearing the leather lace-up boot compared to the gumboot could be considered a strategy to compensate for the additional boot mass in order to prevent a trip. As there were no significant differences between the knee joint or hip joint angles at pre-swing, it is postulated that the increased muscle activity was successful in maintaining the required limb position when wearing the heavier leather lace-up boots compared to the gumboots.

Increased heel contact velocities have also been documented when wearing heavier boots (Chiou et al., 2012), indicating an additional braking force is required to stabilise the leading limb at initial contact compared to when wearing lighter boots (Lockhart and Kim, 2006). During initial contact vastus lateralis decelerates and controls the leading limb as it contacts the ground (Perry, 1992), particularly when walking down a decline where a larger knee extensor moment is required to control the amount of knee flexion and allow the leading limb to support the body's mass without buckling (Lay et al., 2007). In the present study, increased vastus lateralis muscle intensity at initial contact when walking down the decline suggested that more muscle activity was necessary to decelerate the leading limb when wearing the heavier leather lace-up boot compared to the lighter gumboot. The significant difference in the amount of knee flexion at initial contact between the two boot conditions also supports this notion. The difference in the mean knee angles between the two boot conditions, however, was within the expected range of measurement error (3°) and therefore this result should be interpreted with caution. If the leading limb is not adequately decelerated at initial contact, the shear force of the boot contacting the supporting surface will become greater than the friction opposing the boot's movement, resulting in a slip (Lockhart and Kim, 2006). Slip-related falls are more common on inclined and declined surfaces due to the increased shear ground reaction forces generated at initial contact (Redfern et al., 2001). The observed increase in vastus lateralis muscle intensity when participants wore the heavier leather lace-up boot in the present study, compared to the gumboot, could therefore be a slip prevention strategy by decelerating the leading limb at initial contact. However, further research investigating the relationship between heel contact velocities and vastus lateralis muscle intensity is required to confirm or refute this notion.

The stiffer sole of the leather lace-up boot, compared to the more flexible sole of the gumboot, may also have contributed to the significant increase in biceps femoris mean muscle intensity during pre-swing when the participants walked on both the inclined and declined surfaces. Chiou et al. (2012) found that wearing firefighting boots with a more flexible sole (stiffness index ≤ 15) resulted in larger trailing limb toe clearances when healthy male (n = 14, 28.4 ± 5.5 years of age) and female (n = 15, 33.2 ± 4.4 years of age) fire fighters stepped over obstacles, compared to when these participants wore boots with a stiffer sole (stiffness index > 15; $p = 0.051$). Boot mass and sole flexibility were simultaneously altered in the study by Chiou et al. (2012), such that the test boots with a more flexible sole had a heavier mass and the test boots with a stiffer sole had a lighter mass. Heavier boots significantly reduced toe clearance and lighter boots significantly increased toe clearance (Chiou et al., 2012). It is plausible, therefore, that sole flexibility alone would significantly alter lower limb toe clearance when it is not overridden by the influence of boot mass. The increased biceps femoris muscle intensity displayed by participants wearing the leather lace-up in our study could indicate the stiffer sole of this boot reduced the toe clearance height compared to the more flexible sole of the gumboots. Further research, however, measuring toe clearance when participants wear the different boot types is required to confirm this theory.

The leather lace-up boot used in the present study had both a stiffer sole and heavier mass and the gumboot had a more flexible sole and lighter mass. It is unknown whether the two factors (sole stiffness and boot mass) contributed together or whether boot mass alone caused the observed increase in biceps femoris muscle intensity during pre-swing on both the inclined and declined surfaces when wearing the leather lace-up boot compared to the gumboot. Nigg et al. (2006) found no significant difference in root mean square EMG values when 20 male runners ran on a treadmill in shoes with different levels of sole hardness. Once again, however, the shoes differed in mass and it is unknown whether there were significant differences at specific sub phases in the gait cycle rather than across the whole cycle; in the present study the significant differences were limited to pre-swing. Systematically altering sole flexibility in the same boot and analysing the effects of these structural changes across phases of the gait cycle is recommended to confirm whether boot sole flexibility can significantly influence lower limb muscle activity while walking in underground coal mining work boots.

Increased intensity of vastus lateralis and bicep femoris at both initial contact and pre-swing in the leather lace-up boot compared to the gumboot could also suggest that the stiffer shaft of the leather lace-up boot restricted the participant's ankle joint range of motion. A restricted ankle range of motion can result in more muscle activity at the knee joint in order to compensate for the inability of the ankle to absorb the ground reaction forces generated at initial foot-ground contact (Böhm and Hösl, 2010). Furthermore, compared to level walking, walking on an incline requires additional amounts of ankle motion (McIntosh et al., 2006), such that any restriction may force the knee to compensate and provide additional movement. During the swing phase of the gait cycle, the ankle dorsiflexor muscles become more active as the gradient increases to help prevent the toe from grazing the ground (Patla, 1986). If the ankle is restricted, further dorsiflexion is inhibited and greater flexion at the knee is required during pre-swing to ensure the foot clears the ground. The additional biceps femoris and vastus lateralis muscle activity could therefore have indicated compensation at the knee due to restricted ankle joint motion. Ankle muscle activity and range of motion were not collected in the present study because the boot structure prevented instrumentation being placed on the shank in a way that would allow valid and reliable data. Further research is therefore needed to confirm how variations in boot shaft stiffness affects ankle motion and muscle activity.

Increased muscle activity appears to be facilitating potential boot-related slip and trip prevention strategies. If a muscle is forced to burst at a higher intensity, muscular fatigue commences more rapidly (Allen et al., 2008). If the knee extensor muscles, such as vastus lateralis, and knee flexor muscles, such as biceps femoris, become fatigued, a lack of sufficient limb clearance and limb deceleration could lead to a higher incidence of slips at initial contact and/or trips during pre-swing, respectively. This is particularly the case when walking on surfaces that are already known to be more challenging and require additional muscle activity, such as uneven inclined and declined surfaces, perhaps explaining the high incidence of slip and trip related lower limb injuries sustained by underground coal miners.

Investigation of individual boot features, such as those mentioned in this study (mass, shaft and sole stiffness), appears to be the next step in order to determine why differences in muscle activity occur when participants wear two different underground coal mining work boots. Understanding how individual design features influence lower limb muscle activity creates the potential to manipulate these features in order to design a boot that meets the demands placed on the lower limb while underground coal miners perform working tasks, ultimately reducing the incidence of slip and trip-related lower limb injuries incurred by these workers.

4.1. Limitations

Due to the field nature of this study, inertial sensors were initially used to determine lower limb joint angles. However, excessive drift in the data was evident and the data were subsequently discarded. Two-dimensional joint angle data were therefore derived from video recordings. The shape of a motor unit action potential is influenced by numerous intrinsic factors (number of recruited motor units, size and shape of recruited motor units, firing rates and duration, and recovery time) and extrinsic factors (age, sex, temperature, fitness and fatigue; Finsterer, 2001). Although the utmost care was taken to minimise the influence of these factors, the EMG data must still be interpreted with caution.

5. Conclusions

Walking in a leather lace-up boot compared to a gumboot resulted in increased vastus lateralis and increased biceps femoris muscle activity when participants walked on sloped surfaces. The increased muscle activity appears to be a slip and/or trip prevention strategy in response to challenging surfaces and changing boot features. Whether the increased vastus lateralis and biceps femoris muscle activity is compensating for differences in boot mass, and/or shaft or sole stiffness and whether this is further influenced by prolonged walking, requires further investigation. By understanding the influence that specific boot structures have on lower limb muscle activity of underground coal miners, future work boots can be designed to be more surface and task specific, potentially reducing the high incidence of work-related lower limb injuries in this industry.

Source of funding

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Conflict of interest

None.

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Effects of Wearing Gumboots & Leather Lace-up Boots on Gait & Perceived Comfort when Walking on Simulated Underground Coal Mine Surfaces

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Underground coal mine workers have a high incidence of work-related lower limb injuries with sprains and strains caused by slips, trips and falls being highly prevalent. Inappropriate footwear and walking on uneven surfaces have been cited as likely contributing factors, although no systematic evidence exists as to the effects of mining boot type on gait when walking across uneven surfaces. This study aimed to investigate the effects of wearing mining gumboots and leather lace-up boots on gait and perceived comfort when walking across simulated underground coal mining surfaces. Twenty male participants walked at a self-selected pace around a circuit under two different mining boot conditions (gumboot, leather lace-up boot). The circuit consisted of level, inclined and declined surfaces, which were composed of rocky gravel and hard dirt. Quadriceps and hamstring muscle activity, plantar pressures, knee and hip joint motion and ratings of perceived comfort were recorded. A series of repeated measures ANOVA and t-tests were used to determine whether any of the variables were significantly ($p \leq 0.05$) different between the two boot types and whether walking surface influenced any of these differences. Wearing the leather lace-up boot resulted in increased vastus lateralis activity at initial foot-ground contact and increased biceps femoris activity at pre-swing when walking down the declined surface. Biceps femoris activity was also significantly increased at pre-swing when walking up the inclined surface in the leather lace-up boot. Time spent in the stance and swing phase of the gait cycle was not significantly different between the two boot conditions, nor were perceptions of boot comfort. The gumboot, however, was perceived to be significantly easier to walk in and allowed more ankle and knee range of motion, whereas the leather lace-up boot was perceived to be significantly more stable, relative to one another. Knee joint angles at initial contact and mid-foot peak pressure were significantly increased while wearing the gumboot when walking up the incline. Forefoot pressure-time integrals and forefoot, mid-foot and heel peak pressures also significantly increased when walking down the declined surface while wearing the gumboot compared to the leather lace-up boot. It was concluded that underground coal mining work boot structure significantly influenced gait and perceptions of comfort when walking on surfaces typically encountered by underground coal mine workers. A combination of the preferred features inherent in the two boots may provide an effective boot for walking on underground coal mining surfaces.

THE INFLUENCE OF BOOT AND SURFACE TYPE ON IN-SOLE PRESSURE AND COMFORT WHEN WALKING ON SIMULATED COAL MINING SURFACES

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1. INTRODUCTION

Underground coal mine workers incur a high incidence of work-related lower limb injuries, particularly sprains and strains caused by slips and trips. Anecdotal evidence suggests that uneven surfaces and uncomfortable and poorly fitted boots contribute to these lower limb injuries in coal mining, although this notion has not been systematically investigated. As in-shoe pressure measurements correlate with shoe comfort (Hagen *et al*, 2010; Miller *et al*, 2000), this study aimed to investigate the effects of wearing gumboots and leather lace-up boots on in-shoe pressure and perceived comfort when walking across simulated coal mining surfaces.

2. METHODS

Twenty male participants (age 33.4±12 years) with no lower limb pathology, walked at a self-selected pace around a simulated coal mining circuit. This circuit (≈30 m in length) consisted of level, inclined and declined surfaces, which were composed of rocky gravel and hard dirt. Two boot conditions were included (gumboot, leather lace-up; Fig 1). Plantar pressures and ratings of perceived comfort were recorded using Pedar-X insoles (Novel$_{gmbh}$, Germany) and a Visual Analog Scale. Three-way repeated measures ANOVA and *t*-tests were calculated to determine whether outcome variables were significantly ($p \leq 0.05$) different between the two boot types and whether walking surface and/or area of the foot influenced any of these differences.

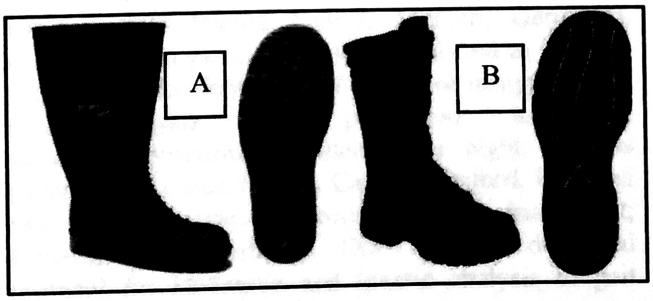

Figure 1: Two underground mining steel-capped work boots. A: Gumboot (Style 015; Blundstone®, Australia) and B: Leather lace-up boot (Style 65-691; Oliver, Australia).

3. RESULTS

The gumboot was perceived to be significantly easier to walk in and allowed more ankle and knee range of motion than the leather lace-up boot. The leather lace-up boot was perceived to be significantly more stable than the gumboot. Mid-foot peak pressure was significantly increased while wearing the gumboot when walking up the incline (Fig 2). Forefoot pressure-time integrals and forefoot, mid-foot and heel peak pressures also significantly increased when walking down the declined surface while wearing the gumboot compared to the leather lace-up boot (Fig 2).

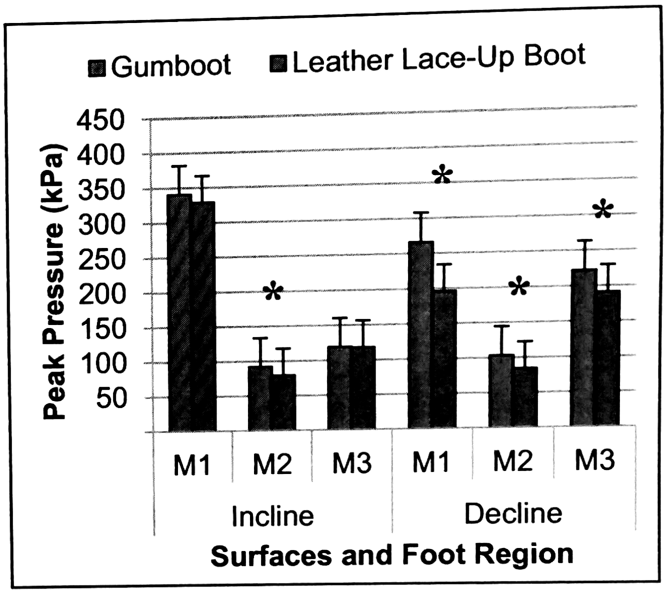

*Figure 2: Mean (+SEM) forefoot (M1), mid-foot (M2) and heel (M3) peak pressure (kPa) while the participants walked up an incline and down a decline in the gumboot and leather lace-up boot (n = 20). *significant difference (p ≤ 0.05).*

4. DISCUSSION

Underground coal mining work boot structure significantly influenced in-shoe pressure and perceptions of comfort when participants walked on sloped surfaces typically encountered by underground coal mine workers. To avoid potential injury, a combination of the preferred features inherent in each boot should be considered for the underground coal mining environment. Further research is warranted, however, to systematically investigate the effects of changes to boot type on underground mining injury rates.

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Review article

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

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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.

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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. Australian/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 (Australian/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 Figs. 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.

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., 2017). 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 Bensel, 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 h walking per shift (Dobson et al., 2017), 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 (Safe Work Australia 2016, personal communication, 5 September).

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 Bensel, 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 Bensel, 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 spare 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.

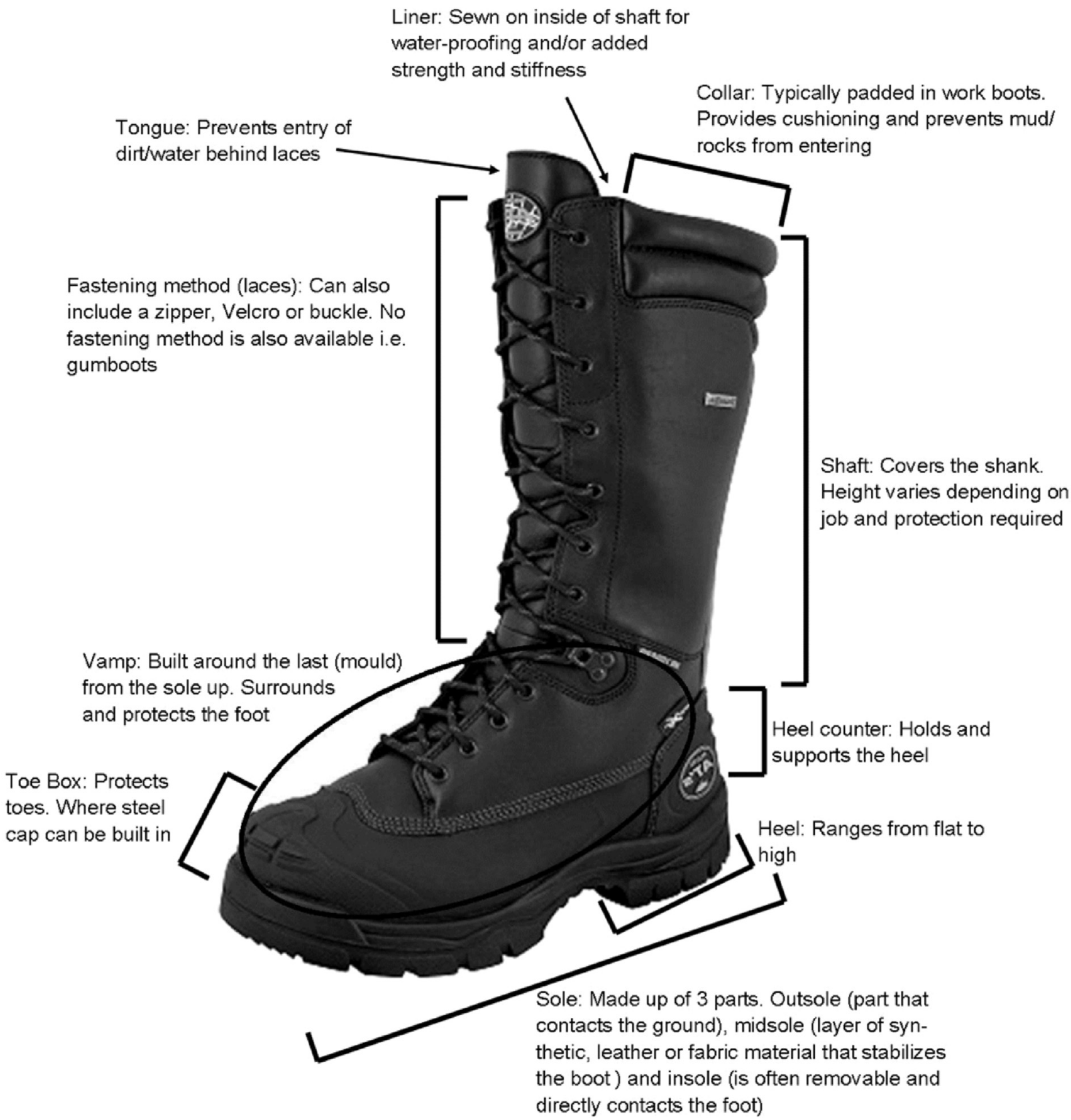

Fig. 1. Distinct design features of work boots (adapted from hotboots. com/bootinfo/terms.html and oliver com.au).

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 Fig. 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.

3. Quality assessment

Methodological quality of the reviewed studies was assessed using the Quality Index (Downs and Black, 1998) and performed by the primary author (see Table 1). The Quality Index is a reliable and

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

validated checklist designed to evaluate randomised and non-randomised studies of health care interventions (Downs and Black, 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 sub-scales. 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).

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 Fig. 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.

4.1. Shaft height

A defining feature of work boot design is the height of the boot shaft (see Fig. 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.

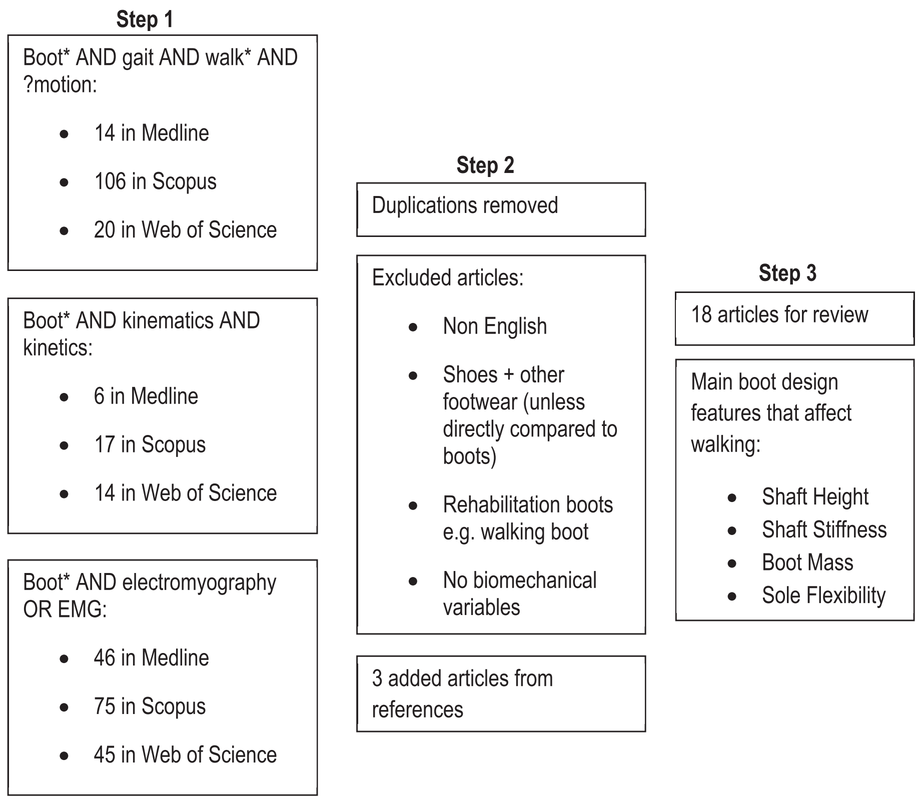

Fig. 3. Literature search strategy.

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 and Hösl (2010)	8	1	5	5	5	24
Chander et al. (2014)	8	0	5	3	5	21
Chiou et al. (2012)	8	1	5	2	5	21
Cikajlo and Matjacić (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 and Bensel (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

Walking in pull-up bunker firefighting boots (see Fig. 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

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 et al. (2012)	Whole gait cycle kinematics (spatio-temporal; toe clearance)	Mass, sole flexibility
Cikajlo and Matjačić (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 Bensel (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

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 Fig. 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 (8329 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 Bensel, 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 Bensel, 1996).

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 min until 240th minute in 3 types of occupational footwear (low-cut shoe, tactical boot, work boot)	Low-cut shoe = ↑ postural sway	Work
Chiou et al. (2012)	Investigate the effect of boot weight and sole flexibility on spatio-temporal characteristics and physiological responses of male and female firefighters in negotiating obstacles	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; 166.6 ± 5.0 cm) firefighters	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
Cikajlo and Matjačić (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 × 3 min simulated firefighter stair climb (60 steps/min) wearing 50 l b 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 Bensel (1996)	Develop a series of recommendations for future military footwear with regard to 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	Reserve Officer Training Corps and university students: 15 men (25.5 ± 5.6 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)	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, Reebok pump, Nike cross-trainer, Rockport hiking boot, Red Wing work boot)	Combat boot, jungle boot and work boot = ↑ metatarsal flexion and limited dorsiflexion during walking, marching and running Reebok pump and Nike cross-trainer = ↑ centre of pressure excursion when marching and running	Military, work, hiking and athletic
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		Cross-over, randomised,		Boot C (with less elasticity and shock absorption) = ↑ GRF and higher discomfort	Clean room

(continued on next page)

Table 3 (*continued*)

Reference	Study Aim	Participants	Study Type	Procedures	Main Outcome	Boot
	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)	controlled comparison	Walking (3.1 km/h) on a 6 m walkway for 5 min (repeated for an hour) in 3 boots with different outsole cushioning	ratings than boot A (greater elasticity and shock absorption)	
Majumdar et al. (2006)	Observe the temporal spatial parameters of gait while walking barefoot, with bathroom slippers and military boots on, respectively and to look into the possible existence of any differences in gait pattern in these three conditions	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 support time	Military
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 to cross-trainer and running shoe conditions using a biomechanical modelling approach.	12 male recreational runners who at least 3 times per week and had a minimum of 3 years running experience (26.3 ± 5.9 yr; 73.9 ± 5.2 kg; 175.6 ± 6.1 cm)	Cross-over, counter-balanced, controlled comparison	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
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

Fig. 4. Summary of the boots tested in the reviewed studies.

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 Fig. 4; Hamill and Bensel, 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 Bensel, 1996). Unfortunately, the authors of the study (Hamill and Bensel, 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 Fig. 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.

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 Matjačić, 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 Fig. 1). Load-deformation curves obtained with equipment such as strain gauges (Arndt et al., 2003), robot manipulators (Cikajlo and Matjačić, 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 Matjačić, 2007), military boots (Hamill and Bensel, 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 Bensel, 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 Fig. 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 Fig. 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 Fig. 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 (Böhm and Hösl, 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 Matjačić, 2007; Hamill and Bensel, 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, 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 Fig. 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 Matjačić, 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 Matjačić, 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 Matjačić (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 Matjačić (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 Matjačić, 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 Matjačić, 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 Fig. 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 Fig. 4) that was almost double the mass of all other test footwear (Schulze et al., 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 Fig. 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 Fig. 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 Fig. 4; Kim et al., 2015). In agreeance 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., (2015) study and almost 3 kg heavier than the combat boot used in Kim et al., (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 Fig. 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 Bensel, 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 Bensel, 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 Bensel (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 Fig. 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 Fig. 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 Fig. 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.

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Conflict of interest

None.

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