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Abstract

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Effect of shaft stiffness and sole flexibility on perceived comfort and the plantar pressures generated when walking on a simulated underground coal mining surface

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Conflict of interest

None

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July, 2019

Abstract

The structural features of work boots worn by underground coal miners affect comfort, foot motion and, in turn, loading of the plantar surface of miners' feet. Although shaft stiffness and sole flexibility appear to be boot design features that could influence perceived comfort and plantar pressures, no study has systematically altered these boot design features to truly understand how they affect these parameters. This study aimed to systematically investigate the effect of changes to shaft stiffness and sole flexibility on perceived comfort and plantar pressures when 20 males walked on a simulated gravel coal mining surface under four different work boot conditions. There were no significant effects of shaft stiffness or sole flexibility on perceived comfort. However, shaft stiffness and sole flexibility each significantly affected the plantar pressures generated under the medial midfoot, heel, middle metatarsals and hallux and, in combination, affected plantar pressures generated beneath the lateral midfoot, medial and lateral metatarsals and lesser toes. Participants preferred a boot with a flexible shaft combined with a stiff sole, citing properties such as fit, moveability, walking effort and support to explain why they perceived one boot as more comfortable than another. We therefore recommend that underground coal mining work boots should be designed to incorporate different flexibility and stiffness between the shaft and sole of the boot to optimise foot movement and, consecutively, walking efficiency.

1. Introduction

Footwear construction can influence the distribution of loading across the anatomical structures of the foot, including the foot's plantar surface, as well as affect the way individuals move (Hennig and Milani, 1995, Hennig et al., 1996, Dixon et al., 2017). Proper loading of the foot while walking leads to adequate shock absorption, confidence in mobility and enhanced perceptions of comfort (de Castro et al., 2010, Witana et al., 2009). Abnormal loading, on the other hand, creates instability leading to reliance on secondary structures such as the muscles and ligaments for support during walking (Smith et al., 1999). Abnormal loading of the foot can also create areas of high pressure on the plantar surface of the foot, which can lead to soft tissue injuries, such as ulcers and calluses, and make footwear uncomfortable (de Castro et al., 2014, Schwarzkopf et al., 2011, Au & Goonetilleke, 2007, Marr, 1999). For underground coal miners, uncomfortable work boots that alter the foot's natural movement can lead to incorrect foot placements when the miners walk on uneven moveable surfaces (Neely, 1998, Dobson et al., 2015). As a consequence, the risk of incurring a sprain or strain injury, via slipping and tripping, can increase if miners wear unsupportive and uncomfortable work boots when walking on these challenging surfaces (Neely, 1998, Liu et al., 2012, Smith et al., 1999). It is therefore imperative that factors affecting the functionality and comfort of work boots designed for underground coal miners are properly understood.

Despite the importance of comfortable work boots, underground coal miners have historically reported their work boots to be uncomfortable. In 1994-95, 56.5% of 589 underground coal miners, who had recently (within 12 months), experienced a below the hip injury, were dissatisfied with their work boots (Smith et al., 1999). More specifically, 53.3% reported their boots contributed to their injury and 71.4% wanted their boots changed (Smith et al., 1999). In 1999, 77% of 400 underground coal miners (randomly selected from mine sites in New South Wales, Australia) still rated their work gumboots as hot, sweaty and

uncomfortable (Wood et al., 1999). A lack of adequate support from their work boots was also revealed whereby 41.3% of the surveyed miners reported slipping inside their boots and 40.2% stated their boots did not fit (Marr, 1999).

Over the last decade advances in materials have resulted in structurally different underground coal mining work boot construction in regards to boot mass, shaft stiffness, shaft height and sole flexibility (Dobson et al., 2017a). These are all boot design features that have previously been shown to alter movement of the foot and, consequently, the way boot wearers walk (Dobson et al., 2017b). However, despite these advances, in a recent survey of 358 underground coal miners, less than half of the study participants (37.7%) rated their boots as comfortable, with 18.1% rating their mining work boots as uncomfortable and 38.5% rating their boot comfort as indifferent (Dobson et al., 2018a). Furthermore, over half of the participants (55.3%) reported experiencing foot problems, with calluses being the most common complaint. Of those miners who listed foot and/or ankle pain, 62.3% associated this pain with their mining work boots (Dobson et al., 2018a). High plantar pressures generated during walking have been associated with the development of lower limb pain (Aliberti et al., 2011, Willems et al., 2006) and linked to a greater risk of developing uncomfortable pressure sores, such as ulcers, and overuse injuries such as stress fractures (Arndt et al., 2003, Mohamed et al., 2005). Therefore, it is likely that this foot discomfort and pain reported by underground coal miners is at least partially associated with high plantar pressures being generated when the miners walk in their work boots.

Previous research examining mining, military, hiking and casual boots has shown that altered foot mechanics due to different boot designs can lead to changes in loading of the plantar surface of the foot during walking (Hamill and Bense, 1996, Nunns et al., 2012, Arndt et al., 2003, Sinclair and Taylor, 2014, Dobson et al., 2018c). Shaft stiffness and sole flexibility appear to be key boot design features that affect foot motion and, in turn, the plantar pressures

generated during gait (Dobson et al., 2017b). For example, when 20 male participants (33 ± 12 years, 84.8 ± 10 kg, 1.8 ± 0.7 m) walked in a safety gumboot, which had a relatively unstructured shaft and flexible sole, they displayed significantly increased peak pressures and pressure-time integrals under the heel and forefoot compared to when they walked in a leather lace-up boot, which had a much more structured and stiff shaft and sole (Dobson et al., 2018c). The researchers of this study speculated that the participants' ankles and feet moved more inside the less structured gumboot, requiring the miners to push off more from the forefoot when walking in the gumboot compared to the structured leather boot, causing these higher gumboot-related plantar pressures (Dobson et al., 2018c). Similarly, an army boot with a more flexible sole increased dorsal tension under the second metatarsal when two participants walked on a treadmill (Arndt et al., 2003). Increased plantar pressures under the forefoot, particularly around the second metatarsal, are concerning as they are a risk factor for stress fractures (Arndt et al., 2003, Nunns et al., 2012). Shaft stiffness and sole flexibility, however, are not the only boot design features likely to cause increased plantar pressures under the forefoot. For example, when compared to a low-cut gym trainer, a stiff high-shafted combat assault boot led to significantly higher peak pressures under metatarsals 2-5 when seven injury free active males (18.3 ± 0.4 years, 81.1 ± 8.2 kg) ran on a treadmill. These plantar pressure changes were attributed to a significant reduction and earlier occurrence of ankle dorsiflexion and greater ankle stiffness during stance due to the additional shank support provided by the combat assault boot (Nunns et al., 2012). The combat assault boot, however, was three times heavier than the gym trainer and had almost double the midsole hardness, making it challenging to directly compare the effects of shaft stiffness between the two footwear conditions. Therefore, the true effects of shaft stiffness and sole flexibility are difficult to derive when other boot design features such as mass, midsole hardness and shaft height, vary between the test boot conditions.

To truly understand the effects of shaft stiffness, or any other boot design feature, on walking performance it is imperative that researchers systematically alter the boot design feature of interest while controlling for other boot features, such as boot mass, midsole hardness and shaft height, which can confound any observed results (Dobson et al., 2017b). Unfortunately no published studies could be located which have systematically altered work boot design features. Therefore, the effect of changes to features such as shaft stiffness and sole flexibility on work boot comfort and the plantar pressures generated during gait, and the degree to which they interact, remains unknown. If structural features of work boots worn by underground coal miners affect comfort, foot motion and, in turn, loading of the plantar surface of the miners' feet, certain boot designs could predispose miners to foot discomfort and pain, as well as be a risk factor for developing lower limb injuries. Therefore, the aim of this study was to systematically investigate the effects of changes to shaft stiffness and sole flexibility on perceived comfort and plantar pressure generated when walking on a simulated gravel coal mining surface. It was hypothesised that:

- H1: A boot where the shaft and sole were either both stiff or both flexible would be the most uncomfortable boot conditions.
- H2: A boot with a stiff shaft would result in increased plantar pressures under the second metatarsal when compared to a boot with a flexible shaft, irrespective of sole flexibility.
- H3: A boot with a flexible sole would lead to increased contact area and plantar pressures under the forefoot when compared to a boot with a stiff sole, irrespective of shaft type.
- H4: The plantar pressures generated during walking would be affected by how the boot shaft stiffness and boot sole flexibility interacted.

2. Methods

2.1 Participants

Twenty males who habitually wore steel-capped safety boots (11 underground coal miners, 9 trades workers; age 36 ± 13.8 years; height 174.8 ± 6.3 cm, body mass 76.9 ± 9.2 kg; foot length 23.8 ± 0.6 cm; foot width 9.2 ± 0.4 cm) volunteered to participate in this study. As the prototype boots used in the study were only constructed in one size, only participants who wore a shoe size AU/UK 8 or EUR 42 could be recruited. Exclusion criteria included lower limb injuries, foot deformities or foot pain/discomfort that impaired an individual's ability to perform the experimental procedures, or habitual wearing of corrective shoe inserts, such as orthoses. Participants were recruited through advertising the study on social media platforms and through South32 (Australia) advertising the study on their work noticeboards, work newsletters and during mine training sessions. *A priori* analysis of the peak pressure data confirmed that a cohort of 20 participants would be sufficient to demonstrate a significant difference between the boot conditions with a power of 95% ($p < 0.05$; Dobson et al., 2018c).

2.2 Experimental Procedures

After providing written informed consent each participant completed a survey to confirm they satisfied the inclusion criteria and to characterise their normal work footwear patterns.

Measurements of height (cm) and body mass (kg) were then recorded and all participants were provided with a new pair of standardised socks (Miners Corp. Essentials Pty Ltd, Australia). To ensure an appropriate shoe fit, each participant's static weight-bearing foot length and width was assessed using a pedograph (Productos Suavepie, Argentina) following the procedures outlined by Riddiford-Hardland et al. (2000). The participants then completed a functional circuit and gait trials in the Biomechanics Research Laboratory at the University of Wollongong under four different work boot conditions (see Section 2.3). The four different boot conditions were allocated in a random order to prevent any order effects. The

functional circuit (see Figure 1) was designed to replicate common working tasks performed by underground coal miners (personal communication with industry, October 2016; Dobson et al., 2018a) and to familiarise the participants with each new boot condition. The circuit took approximately 10 minutes to complete.

Figure 1: Simulated working task circuit, which required the participants to step up onto a box, carry a pipe, drive a pole overhead and crouch down.

After completing the functional circuit, participants performed five walking trials on an uneven surface during which time in-shoe pressure data were collected (see Figure 2; see Section 2.3.3). At the end of each trial participants were required to fill out a Visual Analogue Scale (VAS) pertaining to their perceptions of boot comfort (Lesage et al., 2012;

see Section 2.3.2). The walking surface was designed to replicate the gravel surface conditions underground coal miners typically walk over during their daily work tasks. The uneven surface (6 m x 0.8 m) was made of 10-40 mm diameter pebbles (Tuscan Path, Australia) and was raked after each trial to avoid the surface developing ruts or concavities. Pebble size was selected to replicate coal pieces and gravel underground coal miners walk over (personal communication, 12th October 2016; see Figure 2). To minimise fatigue, participants rested after completing the functional circuit and before each walking trial. Following each boot condition a post-testing questionnaire was conducted to determine each participant's boot preferences (see Section 2.3.2). The University of Wollongong Human Research Ethics Committee (HE14/396) approved all study procedures.

Figure 2: Uneven surface used for the walking trials. This surface, consisting of 10-40 mm diameter pebbles (Tuscan Path, Australia), was designed to simulate the “feel” of a typical underground coal mining surface in a laboratory environment.

2.3 Work Boot Conditions

The four work boot conditions included boots with: (i) a flexible shaft + stiff sole, (ii) a stiff shaft + stiff sole, (iii) a stiff shaft + flexible sole and (iv) a flexible shaft + flexible sole (see Figure 3 and Table 1). These boot conditions were selected as shaft stiffness and sole flexibility are key boot design features that affect foot movement during walking and appear to interact with one another to alter perceived comfort and plantar pressures (Dobson et al., 2017b). Differences in the materials the boot shafts were constructed from created the desired differences in shaft stiffness (see Figure 3 and Table 1). To create the flexible sole conditions, the Chief Investigator (JD) used a razor blade to create slits across the sole of the boot at the approximate point where the metatarsophalangeal joint flexes during walking (see Figure 3). Participants were blinded to the test boot conditions to prevent bias in their comfort scores. The boots were also “colour coded” during testing to blind the researchers during testing and analysis to the specific boot condition.

Figure 3: The test boots: (A) the stiff shaft condition, (B) the flexible shaft condition, and (C) line where sole was cut to create the flexible sole condition. The boots were custom made for the study by Mack Boots, Bunzl Brands and Operations, Erskine Park, NSW, Australia.

In order to systematically test the effects of shaft stiffness and sole flexibility on the outcome variables, the boot prototypes were constructed specifically for the study so that all other boot design features (e.g. boot mass, shaft height) were kept as similar as possible. Because the boot with a flexible shaft was 40 g lighter, small fishing sinkers (Size 1, Rogue, Australia) were attached across the boots with a flexible shaft to ensure the boots had the same overall mass. All the boots were made to be wider across the forefoot and heel relative to current commercially-available safety work boots to account for the wide shape of coal miner's feet (Dobson et al., 2017a, Dobson et al., 2017b, Dobson et al., 2018b, Dobson et al., 2018d).

2.3.1 Shaft stiffness and sole flexibility testing

Passive shaft stiffness and sole flexibility were measured with a strain gauge (LC 1205-K200, Litra Co., LTD, Japan) attached to a prosthetic shank and foot inserted inside the boot (see Figure 4). The prosthetic shank and foot could flex at the ankle and metatarsophalangeal joint to simulate the mobility of a real foot and ankle. The midsole section of the boot was secured in a vice (Craftright, Australia; see Figure 4). Shaft stiffness was defined as the force (N) required to pull the shaft forward 25° from the vertical (Böhm and Hösl, 2010, Cikajlo and Matjacić, 2007). This value was selected because the ankle moves through approximately 15- 25° range of motion (ROM) during gait when individuals walk wearing high shafted boots (Cikajlo and Matjacić, 2007, Fraser et al., 2014, Nunns et al., 2012). To measure sole flexibility, the forefoot section of the boot was clamped in the vice (Craftright, Australia) and a force of 30 ± 0.5 N was applied normal to the plane of the clamped boot. The degree to which the sole of the boot flexed forward was recorded (Standard, 2010, Standard, 2004; see Figure 2). Each test was performed three times for the left and right boot for all boot conditions and the average of the three trials was recorded. Testing was also repeated after participant 5, 10, 15 and 20 completed their trials to ensure the boots maintained the same amount of shaft

stiffness and sole flexibility across all participants. There were eight pairs of test boots (two pairs for each of the four boot conditions) and each boot was worn by 10 participants. The shaft stiffness and sole flexibility testing showed no significant differences ($p > 0.05$) across the testing sessions throughout the study.

Variable	Boot Design Characteristics Specific to each of the Four Boot Types			
	Flexible Shaft + Stiff Sole	Flexible Shaft + Flexible Sole	Stiff Shaft + Stiff Sole	Stiff Shaft + Flexible Sole
Mass (kg)	0.94	0.94	0.98	0.98
Shaft Height (cm)	29.5	29.5	30	30
Shaft Stiffness (N)*	1.1	1.1	1.7	1.7
Shaft Material	Nappa leather + nylon: elasticised material between each eyelet to allow expansion and contraction		Nappa leather: full leather with reinforced sections around ankle	
Sole Flexibility (°)**	20.3	30.2	20.3	30.2

* Force to flex shaft to 25°

** Flex angle achieved when 30 N of force applied

Variable		Boot Design Characteristics Common Across the Four Boot Types	
Fit	Wide	Heel Height (cm)	4
Midsole Hardness (Shore)	58	Heel Sole Width (cm)	10
Midsole Material	Phylon	Forefoot Sole Width (cm)	13
Outsole Hardness (Shore)	68	External Waterproofing	Waterproof
Outsole Material	Nitrile rubber (resistant to 300°C)	Toe Cap	Composite steel
Insole Material	Woven polyester (penetration resistant)	Metatarsal Guard	Poron XRD
Footbed Material	Breathable PU sole response foam	Safety Standards	Penetration resistant, metatarsal guard, antistatic, water resistant, slip resistant C
Fastening Method	Laces – Flat waxed 5 mm extra-long (270 mm; TZ Laces Ltd, Australia)		

Table 1: Boot design characteristics (Mack Boots, Bunzl Brands and Operations Pty Ltd, NSW, Australia). The boots were designed to meet relevant safety requirements, which dictated the need for a high shaft and steel toe cap to protect the leg and foot from external material.

Figure 4: Boot shaft stiffness and sole flexibility testing set up where a prosthetic shank and foot was inserted inside the test boot and the boot clamped at the middle (A) and forefoot (B) in a vice. (A) The amount of force (N) required to flex the shaft of the boot forward 25° . (B) The amount the sole flexed ($^{\circ}$) when 30 ± 0.5 N was applied.

2.3.2 Perceived comfort

After each boot condition participants completed a 120 mm visual analogue scale (VAS; Lesage et al., 2012) to rate their perceptions of boot comfort; boot stability; freedom of foot, ankle and knee movement; difficulty of walking; shaft tightness and ankle support. The participants indicated their perceptions by placing a mark on the line between anchors such as

0 = 'very uncomfortable' and 12 = 'very comfortable'. Although perceptions of footwear comfort can be difficult to quantify, visual analogue scales have been shown to be a reliable measure of footwear comfort (Mündermann et al., 2001). Following testing, participants were required to complete a post-testing questionnaire, where they were asked to select their preferred boot, least preferred boot and comment on why these choices were made. Participants were also asked to choose whether they liked their preferred test boot more or less than their current work boot and why they made this choice.

2.3.3 Plantar pressures

The plantar pressures generated inside the boot during the walking trials were measured (100 Hz) using Pedar-X (novel_{gmbh}, Germany) insoles. Each insole (99 sensors) was attached to the Pedar-X box, which was secured to the participant's waist. Before data collection began, the insoles were calibrated and both insoles were zeroed each time they were placed inside a new boot condition, as per the manufacturer's instructions (novel_{gmbh}, Germany). Pedar-X data acquisition software (Version 23.3.4; novel_{gmbh}, Germany) was used to collect and filter the plantar pressure data of each participant's right and left feet during four consecutive steps in the mid-phase of their gait across the gravel surface. Novel Projects combined with Multimask evaluation (Version 13.3.42; novel_{gmbh}, Germany) software was used to derive the variables of contact area (cm²), contact time (ms), peak pressure (kPa) and pressure-time integral (kPa's) across nine masks of each participant's feet during the middle stride of each walking trial (see Figure 5). The variables of interest for each masked area of the foot were calculated using the mean value across the five trials.

Figure 5: Insole mask (Creation of any masks; Version 13.3.42; novel_{gmbh}, Germany) showing the divisions of the 99 sensors into the nine regions of the foot. The masks were created as a percentage of the length (L) and width (W) of the insole.

2.4 Statistical Analysis

Means and standard deviations of the VAS scores and in-shoe pressure values were calculated over the five walking trials per boot condition. A series of paired *t*-tests were then

used to compare the plantar pressure data derived for the cohort's dominant and non-dominant foot. As there were no significant differences between the dominant and non-dominant foot, further analyses were restricted to the dominant foot of each participant. The dominant foot was identified as the foot each participant used to step up onto the box when completing the functional circuit.

Responses to the closed-ended items of the post-testing questionnaire were coded and counted to define 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. Chi-squared tests were applied to the data pertaining to which boot participants selected as the most preferred and least preferred boot to determine whether the frequency of responses differed significantly ($p < 0.05$) based on shaft type, sole type or boot type (i.e. shaft + sole combination).

A two-way repeated measures ANOVA design, with two within factors of shaft type (flexible and stiff) and sole type (flexible and stiff), was then used to determine whether there were any significant main effects or interactions of either shaft type or sole type on the comfort ratings. A three-way repeated measures ANOVA design, with three within factors of shaft type (flexible and stiff), sole type (flexible and stiff) and foot region (M1-M9) was used to analyse the plantar pressure data. Wilks' Lambda multivariate test was used to find any significant main effects and interactions. Paired *t*-tests were used to further investigate any significant main effects and interactions. The purpose of this statistical design was to determine whether any of the data were significantly different based on boot shaft type, sole type or an interaction of shaft x sole. This design also helped determine whether the plantar pressure results were specific to a certain region of the foot. Although multiple comparisons were made, no adjustment to the alpha level was deemed necessary given the exploratory

nature of the present study, the low cost associated with any error and because such adjustments can increase the likelihood of Type II errors.

3. Results

3.1 Perceived Comfort

The participants' perceptions, on average, of boot comfort, stability, walking effort, shaft tightness, ankle support and foot, ankle and knee range of motion in each boot condition are illustrated in Figure 6. There was a significant main effect of boot shaft type on perceptions of foot ROM ($p = 0.025$) and ankle ROM ($p = 0.048$), and a significant main effect of boot sole type on perceptions of ankle support ($p = 0.020$). However, further *post-hoc* analysis of the data failed to identify significant differences between the boot conditions.

No significant associations were identified between which boot condition participants selected as the most preferred ("best boot") and/or least preferred ("worst boot") and boot shaft type or sole type. However, there was a significant association ($\chi^2 = 11.8$; $p = 0.008$) between overall boot type and which boot condition was selected by participants as the "best boot", whereby the boot with the flexible shaft + stiff sole was the preferred boot condition and the boot with the stiff shaft + stiff sole was least likely to be selected as the preferred option (see Figure 7). Participants reported that they chose the flexible shaft + stiff sole boot as the "best boot" because of the perceived fit and ankle support, and because it was perceived to be comfortable and easy to walk in (see Figure 8). When compared to their current work boot, 85% of participants ($n = 17$) preferred their "best test boot" better, 10% ($n = 2$) preferred their current boot and best test boot equally, and 1% ($n = 1$) preferred their current work boot more than the test boots. The main reason participants preferred the test boots to their current work boot was that their preferred test boot was perceived to provide more support, particularly to the foot and ankle and, overall, was more comfortable.

Figure 6: Visual analogue scale (VAS) scores of the participants' perceptions of boot comfort; stability; walking effort; foot, ankle and knee range of motion; shaft tightness and ankle support grouped by boot condition (flexible shaft + stiff sole, stiff shaft + flexible sole, flexible shaft + flexible sole and stiff shaft + stiff sole), represented by box and whisker plots (inferior box end = first quartile, superior box end = third quartile, dark line = median, left whisker = minimum value, right whisker = maximum value and circles = outliers). 0 = Very comfortable, very stable, very easy to walk in, very moveable, very loose and very unsupportive. 120 = Very uncomfortable, very unstable, very hard, very restricted, very tight, very supportive.

Figure 7: Post-testing questionnaire results displaying the number of participants who reported which boot they thought was the “best boot” and which boot they thought was the “worst boot” (n = 19). *Indicates significantly more likely ($p < 0.05$) to be selected as the “best boot” compared to the other boot types. **Indicates significantly less likely ($p < 0.05$) to be selected as the “best boot” compared to the other boot types.

Figure 8: Post-testing questionnaire results displaying which features participants liked about the boot they selected as the “best boot” (n = 19).

3.2 Plantar Pressure

Analysis of the plantar pressure variables across the nine masks of the foot revealed a significant main effect of boot shaft type ($p = 0.043$), boot sole type ($p = 0.002$) and foot region ($p < 0.001$) on the contact area, contact time, peak pressure and pressure-time integral variables. There were also significant interactions of boot shaft type x boot sole type ($p = 0.049$), boot shaft type x foot region ($p < 0.001$), boot sole type x foot region ($p < 0.001$) and boot shaft type x boot sole type x foot region ($p < 0.001$) with respect to the plantar pressure variables. Further investigations of the significant results, including the *post-hoc* analyses, are discussed below.

3.2.1 Shaft main effects

There was a significant main effect of boot shaft type on the plantar pressures generated under the medial heel (M01; $p < 0.001$), medial midfoot (M03; $p = 0.015$), middle metatarsals (M06; $p = 0.016$) and hallux (M08; $p = 0.015$). Compared to when the participants walked in a boot with a flexible shaft, walking in a boot with a stiffer shaft resulted in a significantly greater contact area and contact time under the medial heel, a significantly greater pressure-time integral and smaller contact area under the medial midfoot and a significantly greater contact time and peak pressure under the middle metatarsals (see Table 2). The effects of boot shaft stiffness on the plantar pressures generated under the hallux were not found to be significant in the *post-hoc* analyses.

Foot Region	Stiff Shaft	Flexible Shaft	p-value
Medial heel (M01)	↑ Contact area		0.038
	↑ Contact time		< 0.001
Medial midfoot (M03)	↑ Pressure-time integral	↑ Contact area	0.025; 0.011
Middle metatarsals (M06)	↑ Contact time		0.039
	↑ Peak pressure		0.021

Table 2: Results of the paired samples *post-hoc t*-test results to identify where the main effects of boot shafts on the plantar pressure variables derived for the nine masked areas of the foot, while the participants walked across the simulated coal mining surface, were significant.

3.2.1 Sole main effects

There was a main effect of boot sole type on the plantar pressures generated under the medial heel (M01; $p < 0.001$), lateral heel (M02; $p = 0.003$) and hallux (M08; $p = 0.004$). Wearing the flexible boot sole resulted in a greater peak pressure and pressure-time integral under the heel and a reduced pressure-time integral under the hallux when compared to wearing the stiff boot sole (see Table 3).

Foot Region	Stiff Sole	Flexible Sole	p-value
Medial heel (M01)		↑ Peak pressure	< 0.001
		↑ Pressure-time integral	0.036
Hallux (M08)	↑ Pressure -time integral		< 0.001

Table 3: Results of the paired samples *post-hoc t*-test to identify where the main effects of boot sole on the plantar pressure variables derived for the nine masked areas of the foot, while the participants walked across the simulated coal mining surface, were significant.

3.2.2 *Shaft x sole interactions*

An interaction of boot shaft type x boot sole type on the plantar pressures generated under the lateral midfoot (M04; $p < 0.001$), medial metatarsals (M05; $p = 0.038$), lateral metatarsals (M07; $p = 0.009$) and lesser toes (M09; $p < 0.001$) was found when looking at the foot regions individually (see Figure 9). When the boot sole was stiff, a flexible boot shaft resulted in significantly increased contact area under the lateral midfoot and decreased peak pressure and pressure-time integral under the medial metatarsals. A stiff boot shaft had increased contact time under the lateral midfoot compared to a flexible boot shaft when the boot sole was flexible. A stiff shaft + flexible sole boot, compared to a flexible shaft + stiff sole boot, had decreased peak pressure under the lateral midfoot and lateral metatarsals and increased peak pressure under the lesser toes. When the boot shaft was stiff, a flexible boot sole led to increased contact area and peak pressure under the lateral midfoot when compared to a stiff boot sole. In contrast, a flexible boot sole compared to a stiff boot sole led to a greater peak pressure under the medial metatarsals when the boot shaft was flexible.

Figure 9: The plantar pressure variables and area of the foot (M04 - lateral midfoot, M05 - medial metatarsals, M07 - lateral metatarsals and M09 - lesser toes) that had a significant interaction of boot shaft x sole. * indicates a significant difference between boot shaft type or boot sole type ($p < 0.05$).

4. Discussion

By systematically altering boot shaft stiffness and sole flexibility we were able to investigate the effect of these boot design features on perceived comfort and plantar pressures generated when participants walked on a simulated underground coal mine surface. Although there were no significant effects of boot shaft stiffness and sole flexibility on perceived comfort, the boot shaft and sole independently affected the plantar pressures generated under the medial midfoot, heel, middle metatarsals and hallux plantar pressures and, in combination, influenced the plantar pressures generated under the lateral midfoot, medial and lateral metatarsals and lesser toes. The implications of these results are discussed below.

4.1 Perceived Comfort

In agreement with our first hypothesis (H1), participants in the current study preferred a boot with a flexible shaft combined with a stiff sole. This choice was based on the participants perceiving the boot with a flexible shaft + stiff sole to fit well (both in length and width), provide good ankle support, feel comfortable and feel easy to walk in. Overall, most participants liked the test boot conditions better than their current work boots, despite having limited time to become accustomed to the test boots or to “wear the boots in”. The participants reported they preferred the test boots compared to their current boots because they provided improved support, particularly to the foot and ankle, and improved comfort. The two types of work boots provided to underground coal miners in our local region at the time of this study were a gumboot, which has a flexible shaft + flexible sole, and a leather lace-up boot, which has a stiff shaft + stiff sole (Dobson et al., 2018a). In the current study, a stiff shaft + stiff sole boot was the least preferred choice and a boot with a flexible shaft + flexible sole was also rated relatively poorly. It is therefore not surprising why, in general, a high percentage of underground coal miners rate their current work boots as uncomfortable (Dobson et al., 2018a). Manufacturers of underground coal mining footwear should therefore

ensure that the stiffness/flexibility of the shaft and sole of future work boot designs are optimised to maximise boot comfort for workers in this profession.

Although, in general, the participants preferred a boot with a flexible shaft combined with a stiff sole, there was large variability in the participants' perceptions of comfort and there was no significant effect of boot type on boot comfort. This variability was reflected by the large spread of VAS scores recorded for the participants when examining the effects of shaft stiffness and sole flexibility on perceived foot and ankle ROM, shaft tightness and ankle support. Therefore, personal preferences will influence an individual's perceptions of how differences in shaft stiffness and sole flexibility of a work boot influence their comfort such that there will not be one work boot design solution to optimise the comfort of all workers.

Consistent with the results of the current study, Dobson et al. (2013) also found no significant differences in participants' (20 male;s 33 ± 12 years of age, 84.8 ± 10 kg body mas, 1.8 ± 0.7 m height) perceptions of boot comfort when they walked on simulated underground coal mine surfaces in flexible gumboots compared to relatively stiff leather lace-up work boots. Furthermore, participants in the Dobson et al. (2013) study based their most preferred boot condition on perceived fit, support and walking effort, rather than overall comfort. We therefore recommend that future studies assessing boot comfort should incorporate questions relating to properties such as fit, moveability, walking effort and support rather than just comfort because these variables appear to explain why a participant perceives one boot as more comfortable than another.

4.2 Plantar Pressures

4.2.1 Shaft and sole main effects

When the participants walked in a boot with a stiff shaft, compared to a flexible shaft, there was a greater contact area and contact time under the medial heel and, in agreement with our second hypothesis (H2), a greater contact time and increased peak pressures under the middle

metatarsals, irrespective of sole type. We speculate that the stiffer shaft could have restricted movement of the participants' shanks during walking, which therefore required additional movement of the foot to compensate and allow stable walking on the uneven surface (Böhm and Hösl, 2010). This notion is supported by a study where a significant reduction and earlier occurrence of ankle dorsiflexion and greater ankle stiffness during stance occurred when participants wore a combat assault boot that provided support above the ankle (Nunns et al., 2012). This additional shank support was linked to increased plantar pressures under metatarsals 2-5 when compared to a low-cut gym trainer (Nunns et al., 2012). Therefore, it appears that when additional support is provided to the shank, movement of the foot is altered to compensate. Increased peak pressures under the middle metatarsals could, over the longer term, become problematic because increased plantar pressures under the metatarsals have previously been linked to the development of stress fractures (Arndt et al., 2003, Nunns et al., 2012). This notion of altered foot and shank movement, however, is purely speculative in regards to underground coal mining work boots and further kinematic data is needed to confirm or refute this theory.

In contrast to our third hypothesis (H3), irrespective of shaft type, wearing a boot with a flexible sole led to greater peak pressures and pressure-time integrals being generated under the medial heel but reduced pressure-time integrals under the hallux when compared to a stiff sole. This result indicated the participants relied more on contacting with the medial heel rather than rolling the foot forward putting pressure on the hallux during stance. Pressure-time integrals are defined as the area under the peak pressure time curve and are considered a more relevant parameter than peak pressure as this variable incorporates pressure as well as time factors, which are potentially important in ulcer formation (Bus and Waaijman, 2013). The between-boot differences in the pressure-time-integral values suggest that for a given time higher pressures are being generated under the medial heel in a flexible sole compared

to a stiffer sole. This is concerning for two reasons. Firstly, laterally distributed plantar pressures during heel contact allow a more rigid lever, and in turn a more stable foot, to be created when walking (Aliberti et al., 2011). Therefore, if walking in a flexible sole relies more on the medial foot rather than the lateral foot it could predispose miners to a risk of developing lower limb injuries that are associated with foot instability, such as patellofemoral pain syndrome (Aliberti et al., 2011, Willems et al., 2006). Secondly, repeated higher plantar pressures under the heel over long time periods are a risk factor for the development of painful sores such as ulcers (Bus and Waaijman, 2013). Underground coal miners are already more likely to report heel pain when working on hard surfaces (Dobson et al., 2018a). Therefore, we recommend that work boots with a flexible sole should be avoided by coal miners who predominantly work on hard surfaces.

4.2.2 Shaft x sole interactions

The shaft x sole interaction results highlight the complexity of work boot design and confirm our fourth hypothesis (H4) that the shaft and sole of a work boot interact to influence the plantar pressures generated when walking. These findings confirm the notion that boot design features cannot be examined solely in isolation. As this was the first study to systematically alter both shaft stiffness and sole flexibility of a work boot it was difficult to compare our results to previous studies where other boot design features, such as boot mass and shaft height, were not held constant. The following results are therefore discussed with respect to the implications the current findings have for future underground coal mining work boot design.

When the boot sole was stiff, a flexible shaft led to increased contact area under the lateral midfoot and decreased peak pressure and pressure-time integrals being generated under the medial metatarsals compared to a stiff shaft. In contrast, when the boot sole was flexible, a stiff shaft led to an increased contact time under the lateral midfoot compared to a

flexible shaft. As discussed previously, laterally distributed plantar pressures during the earlier phases of the gait cycle are preferable compared to medially distributed plantar pressures because lateral plantar pressures allow a more rigid lever, and in turn a more stable foot, to be created when walking (Aliberti et al., 2011). Interestingly, in the boot that had a combination of a flexible shaft + stiff sole not only was there more contact area in the lateral midfoot but the peak pressure and pressure-time integrals under the medial metatarsals were reduced. Therefore, it is possible that the flexible shaft + stiff sole boot design is more effective at allowing the foot to naturally roll-over laterally during stance and, in turn, taking pressure off the metatarsals when the participants walked across a gravel surface. Indeed, when comparing the boot with a flexible shaft + stiff sole to the boot with a stiff shaft + flexible sole there was increased peak pressure under the lateral midfoot and lateral metatarsals, further supporting a more lateral roll of the foot in the flexible shaft + stiff sole boot condition. However, this result was combined with an increased peak pressure under the lesser toes, implying that the foot is not able to cross over medially to be able to push-off via the hallux as required at the end of stance (Winter, 2009). By altering normal foot motion, the joints of the lower limb are forced to rely on secondary structures, such as the muscles and ligaments, for support during walking (Neely, 1998). This is particularly problematic for underground coal miners walking on uneven and unstable surfaces (Gates et al., 2012) because the demand placed on the lower limb to stabilise and maintain dynamic equilibrium while walking on such challenging surfaces is already heightened (Menz et al., 2003). Therefore, a boot with a flexible shaft combined with a sole that is stiff along the midfoot and heel but provides some flex around the metatarsal and toe areas may be ideal to encourage the foot's natural movement when walking on an uneven surface. Alternatively, it might be feasible to design an insert that goes inside the boot or design the shape of the forefoot of the boot to encourage optimal foot movement. More detailed kinematic data, however, is

required to provide further insight into the results of the current study and confirm whether this concept of a boot with a flexible shaft + partially flexible sole could enhance movement of the foot when walking on a gravel surfaces. These results also need to be examined when miners walk on surfaces other than gravel to see whether the results are consistent or whether more surface-specific recommendations are needed.

4.4 Limitations

This study involved measuring an acute effect of the test boot conditions on the outcome variables. Underground coal miners, however, work long shifts that range from 8-12 hours (Dobson et al., 2018a). It is unknown whether the results found in the current study would apply after such a long period of time. We therefore recommend that further research is warranted to assess whether the acute effects of changes to shaft stiffness and sole flexibility of coal mining work boot are evident over longer working shifts. Furthermore, the boot prototypes used in the current study were made by the one work boot manufacturer and only in one boot size. Future research using different manufactured boots in different sizes is needed to confirm or refute the exploratory results of the current study.

5. Conclusions

Underground coal mining work boot shaft stiffness and sole flexibility influenced the plantar pressures generated, in isolation and in combination, when individuals walked on a simulated underground coal mine surface, highlighting the complexity of work boot design. Participants preferred a boot with a flexible shaft combined with a stiff sole, with properties such as fit, moveability, walking effort and support explaining why a participant perceived one boot as more comfortable than another. The least preferred boots incorporated a stiff shaft combined with a stiff sole or a flexible shaft combined with a flexible sole. We therefore recommend that underground coal mining work boots should be designed to

incorporate different flexibility and stiffness between the shaft and sole of the boot to optimise foot movement and, in turn, walking efficiency.

6. References

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