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The three-dimensional shapes of underground coal miners' feet do not match the internal dimensions of their work boots

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Abstract

Mining work boots provide an interface between the foot and the ground, protecting and supporting miners' feet during lengthy coal mining shifts. Although underground coal miners report the fit of their work boots as reasonable to good, they frequently rate their boots as uncomfortable, suggesting that there is a mismatch between the shape of their feet and their boots. This study aimed to identify whether dimensions derived from the three-dimensional scans of 208 underground coal miners' feet (age 38.3 ± 9.8 years) differed from the internal dimensions of their work boots. The results revealed underground coal miners wore boots that were substantially longer than their feet, possibly because boots available in their correct length were too narrow. It is recommended boot manufacturers reassess the algorithms used to create boot lasts, focusing on adjusting boot circumference at the instep and heel relative to increases in foot length. Practitioner Summary: Fit and comfort ratings suggest a mismatch between the shape of underground coal miners' feet and their boots exists. This study examined whether three-dimensional scans of 208 miners' feet differed from their boot internal dimensions. Miners wore boots substantially longer than their feet, possibly due to inadequate width.

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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Mining work boots provide an interface between the foot and the ground, protecting and supporting miners' feet during lengthy coal mining shifts. Although underground coal miners report the fit of their work boots as reasonable to good, they frequently rate their boots as uncomfortable, suggesting that there is a mismatch between the shape of their feet and their boots. This study aimed to identify whether dimensions derived from the three-dimensional scans of 208 underground coal miners' feet (age 38.3 ± 9.8 years) differed from the internal dimensions of their work boots. The results revealed underground coal miners wore boots that were substantially longer than their feet, possibly because boots available in their correct length were too narrow. It is recommended boot manufactures reassess the algorithms used to create boot lasts, focusing on adjusting boot circumference at the instep and heel relative to increases in foot length.

1. Introduction

During a typical 8-12 hour shift, underground coal miners spend most of their time standing and walking (Dobson et al., 2018). Throughout this time their mining work boots are required as an interface between the foot and the ground and provide protection and support to the foot (Doi et al., 2010). Poor fitting footwear can fail to provide support and instead result in clinically-reported foot problems such as blistering, chafing, black toes, bunions, pain and tired feet (Rossi, 2001, Yates and Merriman, 2009).

In a recent survey of 358 underground coal miners (39 ± 11 years of age), over half of the participants (55.3%) reported experiencing foot problems, with calluses being the most common complaint (Dobson et al., 2018). Of those participants who listed foot and/or ankle pain, 62.3% associated this pain with their mining work boots. Less than half of the miners (37.7%) rated their boots as comfortable, with 18.1% rating their mining boots as uncomfortable and 38.5% rating their boot comfort as indifferent (Dobson et al., 2018). How an individual's footwear fits is one of the most important aspects when determining footwear comfort (Miller et al., 2000, Hawes and SOVAK, 1994). Interestingly, despite the poor comfort ratings reported by the miners surveyed, 83.8% reported their mining work boot fit as reasonable to good (Dobson et al., 2018). Therefore, it remains unknown why these underground coal miners found their mining work boots uncomfortable despite perceiving their boots to fit relatively well.

A mismatch between the foot and footwear can affect the mechanical load applied by the footwear to the foot and, in turn, influence overall foot function (Doi et al., 2010, Rossi, 2001). For example, footwear that is too tight restricts foot movement adversely influencing the distribution of the forces generated during walking (Doi et al., 2010, Rossi, 2001). Conversely, footwear that is too loose creates a point of instability leading to unwanted foot slippage (Doi et al., 2010, Rossi, 2001). For footwear to be comfortable and allow natural foot motion, its internal shape must match the shape of the foot as closely as possible (Hawes and SOVAK, 1994). However, matching the exact individual foot shape and dimensions can be problematic in a shoe, as during weight bearing the foot undergoes changes in shape with impact and fluctuations in temperature (Yates and Merriman, 2009). Recommended values to ensure proper footwear fit and allow sufficient room for the foot to move within a shoe are available. A gap of 10-20 mm between the longest toe and the end of a shoe (Rossi, 1988, Barton et al., 2009, Hayashi and Hosoya, 2014) and a snug to 20 mm gap across the foot

breadth (Rossi, 1988) is typically recommended. However, a gold standard value is not available and these values are based on anecdotal evidence rather than any systematic scientific investigation.

This lack of clear parameters for fit has led to three-dimensional foot scanning becoming more frequently used in footwear research to systematically assess footwear fit. Advancements in scanning technology, three-dimensional visualisation methodologies and mathematical modelling techniques have enabled the development of algorithms that can accurately match foot shape to the internal structure of footwear (Witana et al., 2004). Footwear manufacturers typically use such algorithms to develop their footwear, whereby foot shape is characterised using a last, a three-dimensional mould that approximates the shape of the human foot (Nácher et al., 2006). In order to maximise their competitive commercial advantage, footwear manufacturers have developed custom lasts that offer something new to the consumer, such as different fits (i.e. wide fitting), shapes (i.e. wedge heels) and styles (i.e. minimalist shoes; (Nácher et al., 2006, Witana et al., 2004). To ensure shoes cater for foot shape and provide comfort, it is imperative that any such last is based on foot dimensions of individuals who are likely to wear the shoes.

Although a large percentage of underground coal miners have reported the fit of their mining work boots as reasonable to good, they rate the comfort of these boots as indifferent to uncomfortable. This suggests that while an individual miners' feet tend to fit inside their work boots, there is possibly a mismatch between specific areas within the boot with the shape and/or dimensions of the miners' feet. Therefore, this study aimed to identify whether dimensions derived from the three-dimensional scans of mine workers' feet differed from the internal dimensions of their work boots. It was hypothesised:

H1: A 10-20 mm gap in length would be present between the distal end of a miner's longest toe and the end of the toe box of their work boot.

H2: There would be no gap in width, circumference or height between a miner's foot and the edge of their work boot.

H3: Hypothesis 1 and 2 would hold true, irrespective of boot size or work boot type.

2. Methods

2.1 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 (Dobson et al., 2018). 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.

2.2 Foot Scans

Three-dimensional foot scans (INFOOT three-dimensional foot scanner; I-Ware, Japan) of all the participants' left and right feet were collected following the procedures of de Mits et al. (2010). In brief, prior to scanning, 15 felt markers (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 1; 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 for 15 seconds whereby the scanner projected two laser beams across the foot and eight cameras recorded the resulting image. The scanning process was repeated three times per foot. A single foot scan 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).



Figure 1: 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.

2.3 Boot Moulds

The two mandatory safety work boot types provided to underground coal miners at Illawarra Coal were selected as the experimental footwear (Dobson et al., 2018). 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. Further details of the boots are documented elsewhere (Dobson et al., 2017). 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 2). 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). The chief investigator (JD) created all the moulds.

2.4 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 (see Section 4.2.2; I-Ware, Japan). To achieve this, each boot mould was placed one at a time into the scanner, and scanned four times per mould.

Due to the nature of Plaster of Paris, the felt markers 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 2). 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 and Ulbrecht, 1994); see Figure 2).

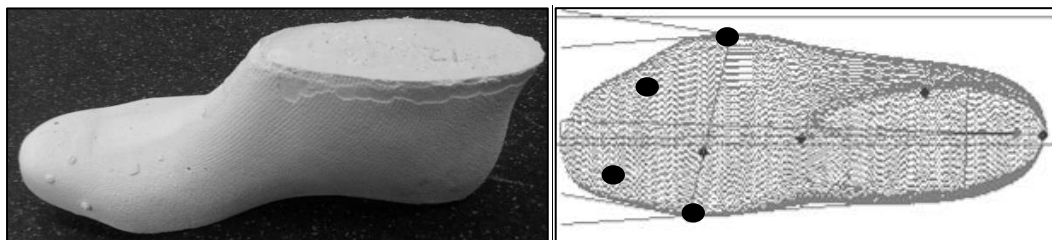


Figure 2: An example mould representing the internal shape of the gumboot and the associated three-dimensional scanned image, showing the four marker locations.

2.5 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 3 and Figure 4). 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, Nacher 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 and Watkins, 1993).

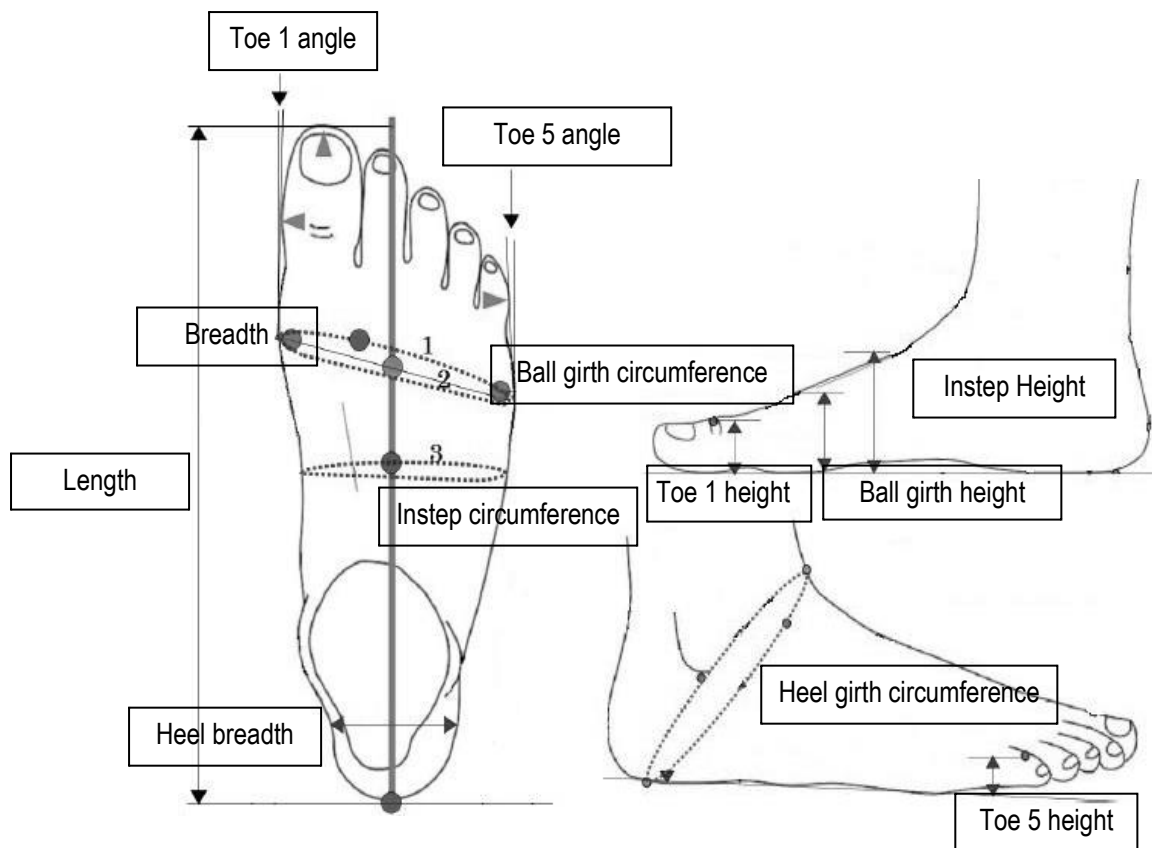


Figure 3: The 12 variables calculated from the participants' feet and the boot moulds based on the marker positions.

2.6 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 was 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.

2.6.1 Comparing the Miners' Feet and their Internal Boot Dimensions

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 their internal work boot structure. 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.

2.6.2 *Boot Type and Boot Size Effect*

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 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.

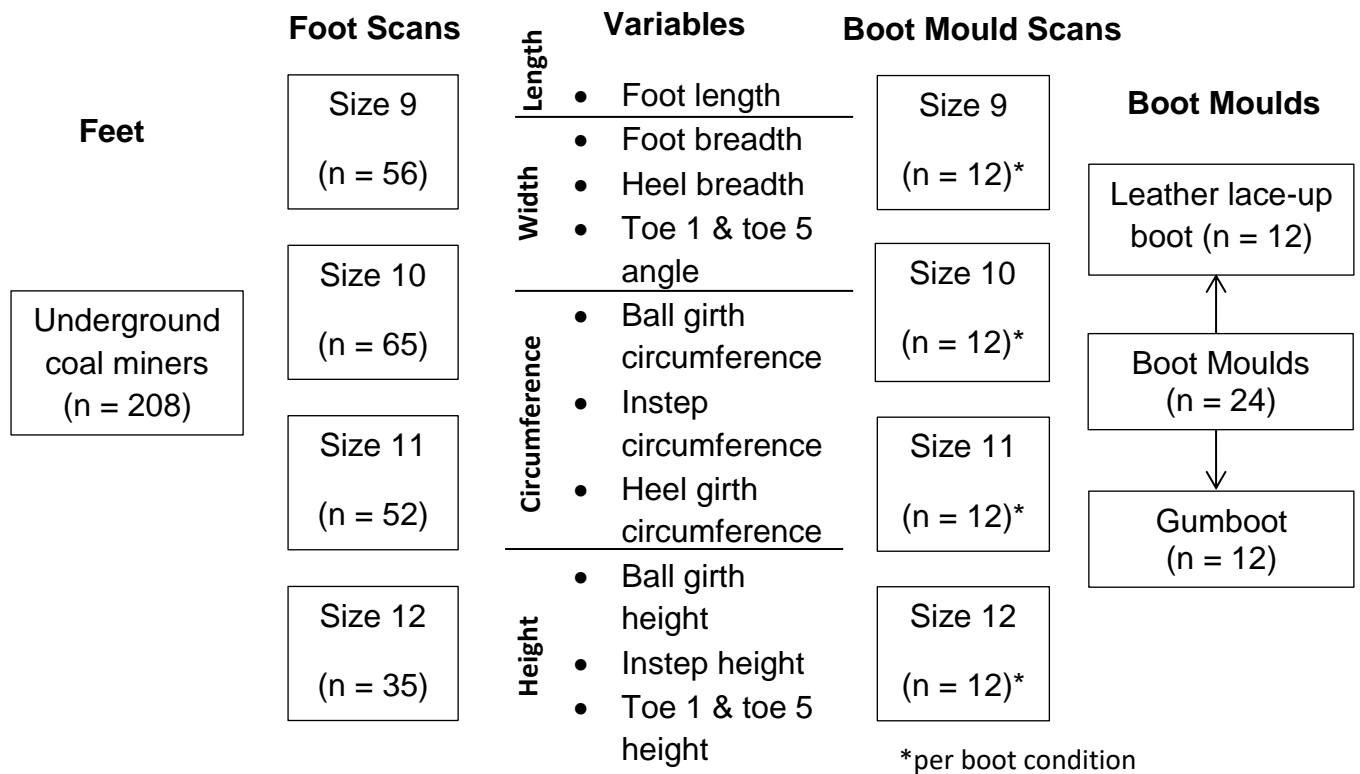


Figure 4: Summary of the experimental protocol: The right feet of 208 underground coal miners were grouped into four sizes while three moulds per boot condition per boot size (9, 10, 11, and 12) were created and scanned four times. The length, width, circumference and height variables were calculated for both the foot scans and boot mould scans.

3. Results

3.1 Comparing the Miners' Feet and their Internal Boot Dimensions

Means (\pm 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 **Error!**

Reference source not found. All variables derived from the scans of the miners' feet were significantly different from 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 5 (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).

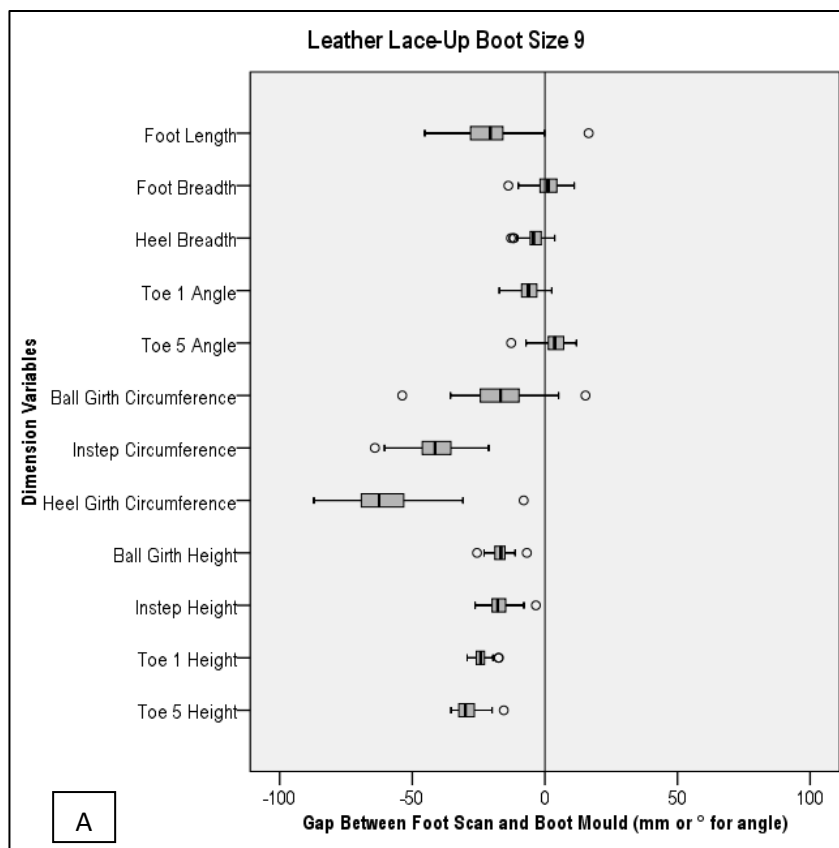
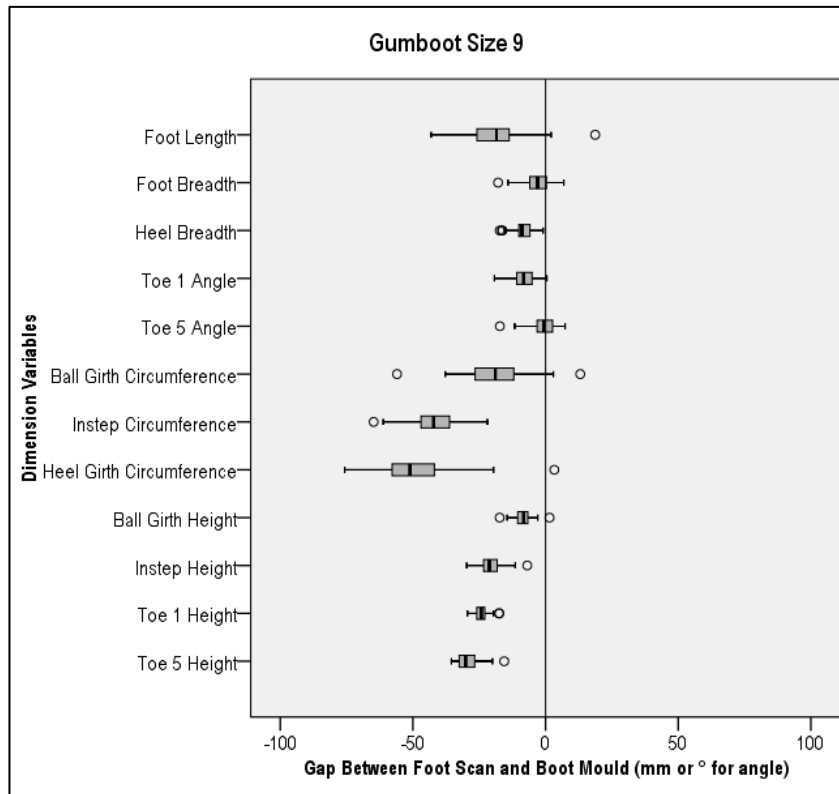
These outliers highlight the broad range of feet displayed by underground coal miners. Foot breadth, heel breadth and toe 5 angle were regions where the miners' feet were larger than their work boots.

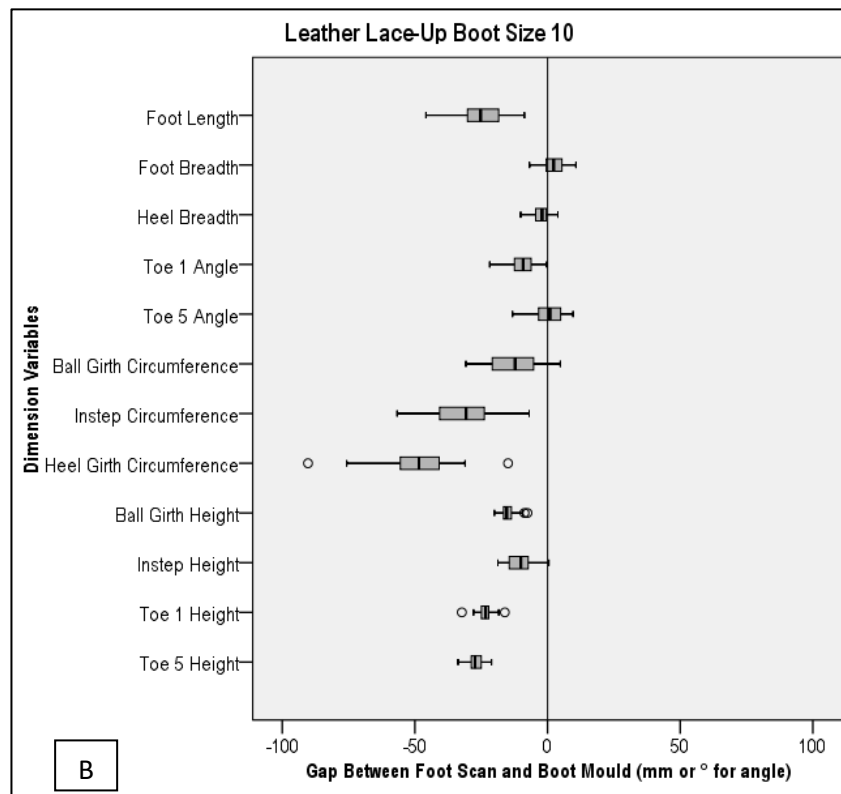
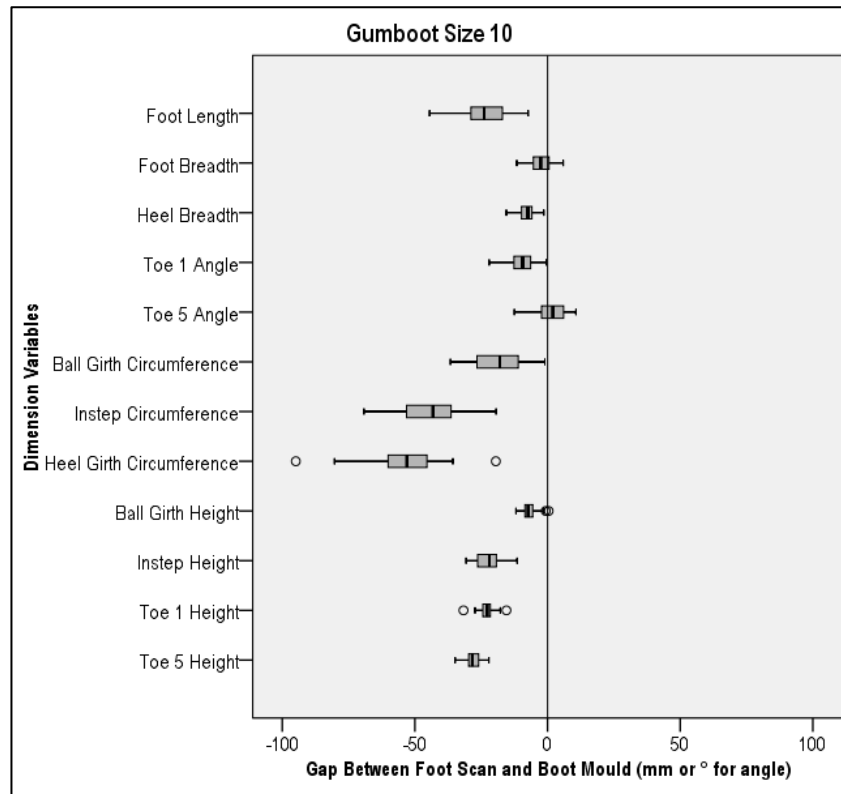
Table 1: Means (\pm standard deviations) of the gumboot and leather lace-up boot moulds and the miners' foot scans for each of the 12 variables (mm or degrees for angle). Independent samples *t*-test results comparing the gumboot and leather lace-up boot mould scans to the miners' feet are also presented.

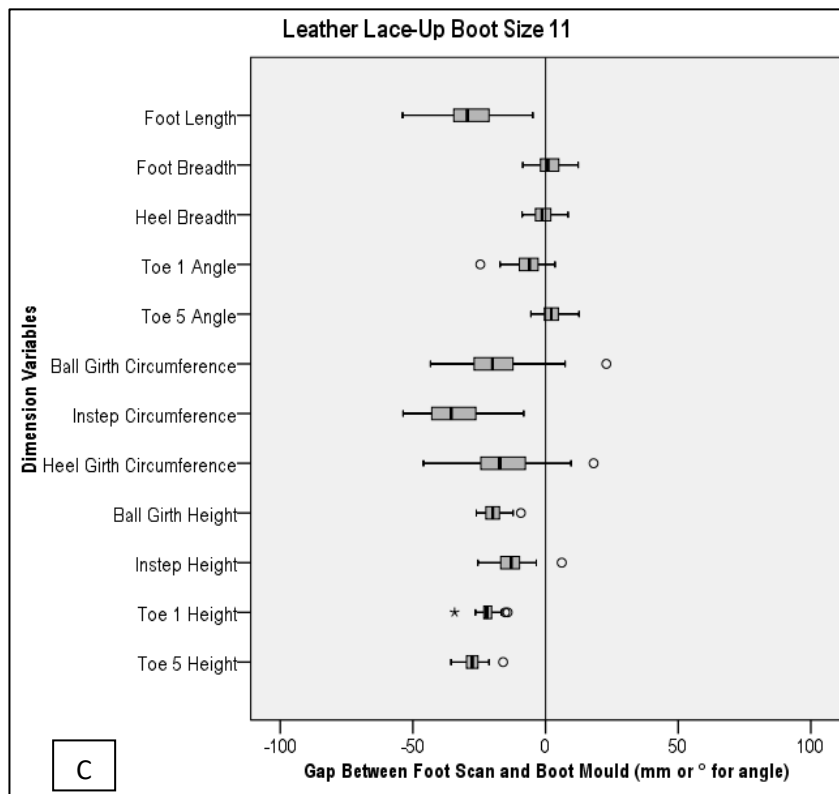
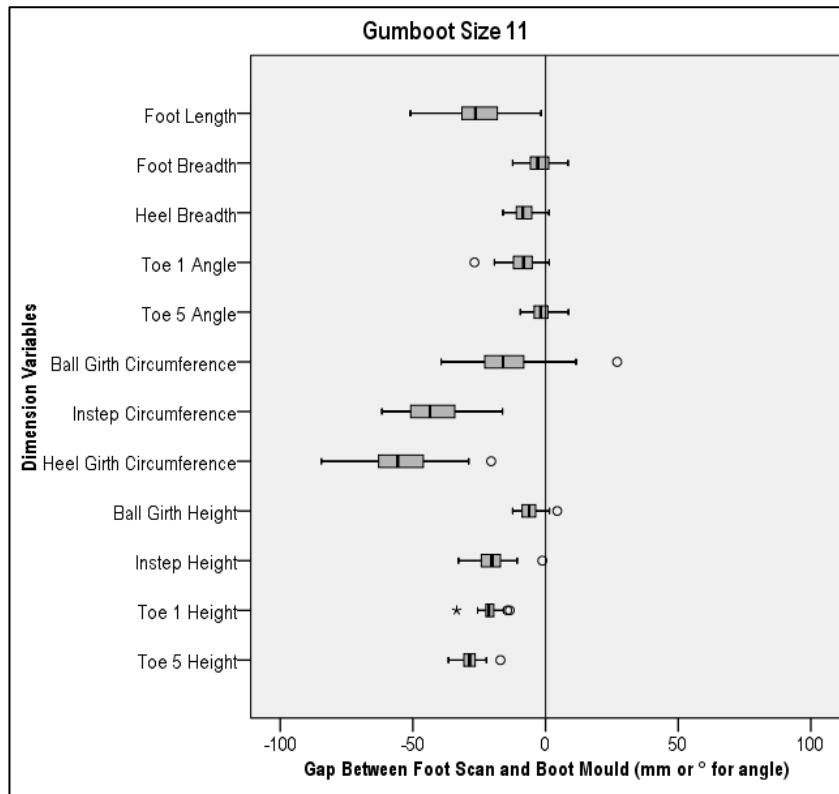
	Variable	<i>p</i> -value	Gumboot Mould	Miners' Feet	Lace-Up Boot Mould	<i>p</i> -value
Length	Foot Length (mm)	< 0.001 ^a	298.5 \pm 10.6	273.3 \pm 11.2	300.7 \pm 11	< 0.001 ^b
	Foot Breadth (mm)	0.002 ^a	111.9 \pm 2.4	109.3 \pm 5.5	107.7 \pm 2.8	.065
Width	Heel Breadth (mm)	< 0.001 ^a	77.9 \pm 2.8	70.1 \pm 4.1	72.8 \pm 1.9	< 0.001 ^b
	Toe 1 Angle (°)	< 0.001 ^a	14.9 \pm 1.6	5.8 \pm 5.3	13.7 \pm 2.9	< 0.001 ^b
Circumference	Toe 5 Angle (°)	.859	14.3 \pm 1.8	13.9 \pm 5.2	11.4 \pm 2.4	< 0.001
	Ball Girth Circumference (mm)	< 0.001 ^a	283.2 \pm 6.1	265.9 \pm 14.7	282.3 \pm 8.1	< 0.001 ^b
Height	Instep Circumference (mm)	< 0.001 ^a	309.1 \pm 9.9	266.1 \pm 12.5	299.5 \pm 5.2	< 0.001 ^b
	Heel Girth Circumference (mm)	< 0.001 ^a	409.4 \pm 12.8	356.1 \pm 18.4	398.6 \pm 11.8	< 0.001 ^b
	Ball Girth Height (mm)	< 0.001 ^a	53.6 \pm 1.8	45.8 \pm 3.7	63.4 \pm 3.6	< 0.001 ^b
	Instep Height (mm)	< 0.001 ^a	95.5 \pm 4.8	73.9 \pm 5.0	85.3 \pm 3.8	< 0.001 ^b
	Toe 1 Height (mm)	< 0.001 ^a	49.6 \pm 2.2	26.1 \pm 3.6	50.1 \pm 3.2	< 0.001 ^b
	Toe 5 Height (mm)	< 0.001 ^a	48.6 \pm 2.1	19.2 \pm 3.6	47.5 \pm 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 ($p \leq 0.05$)







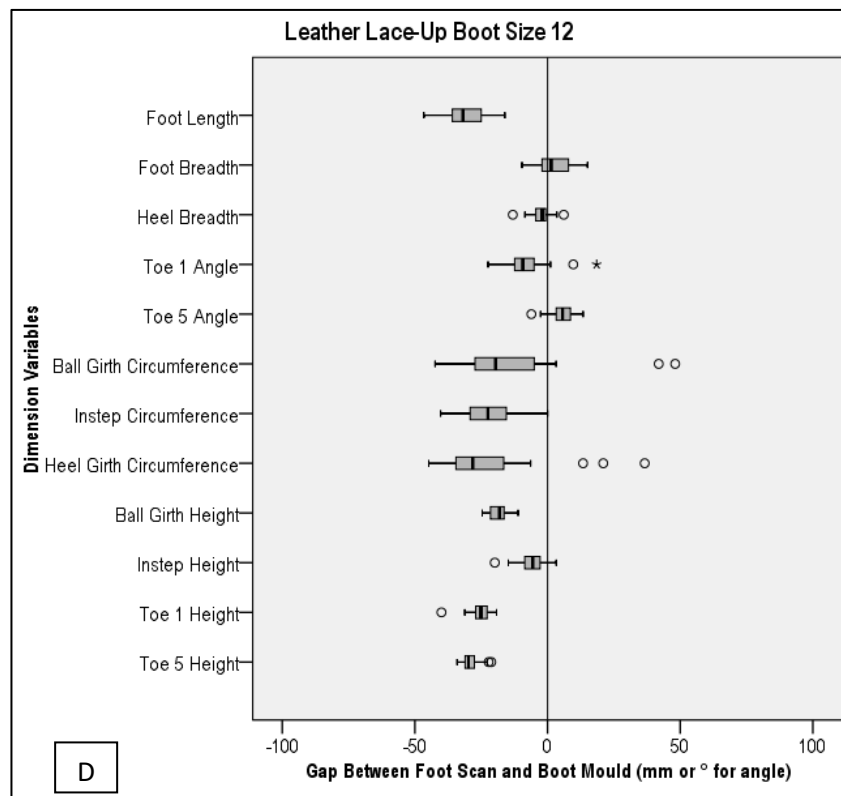
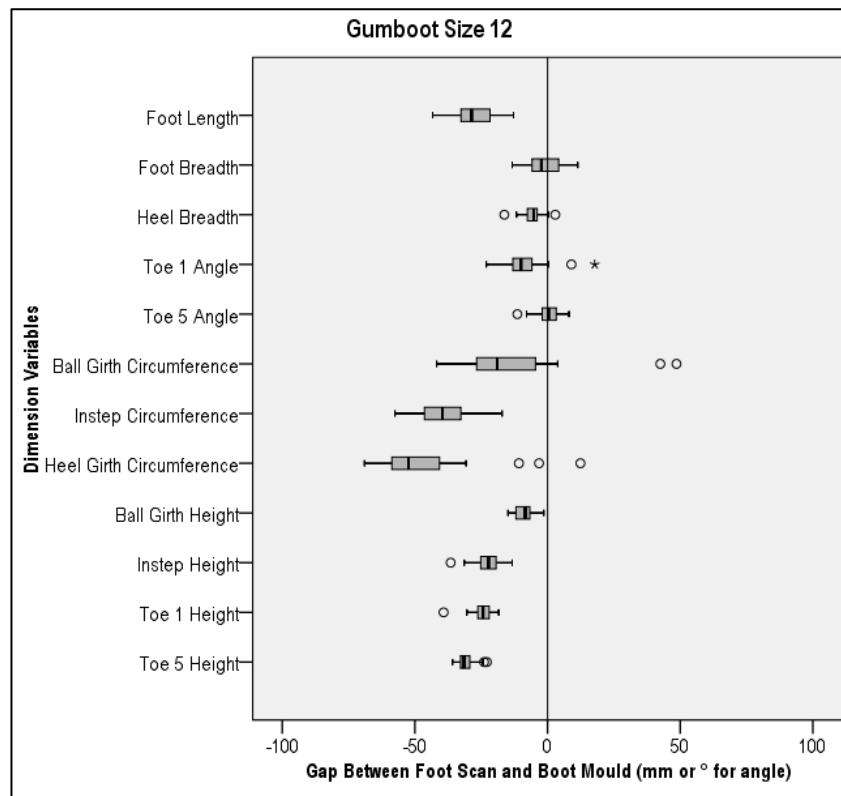
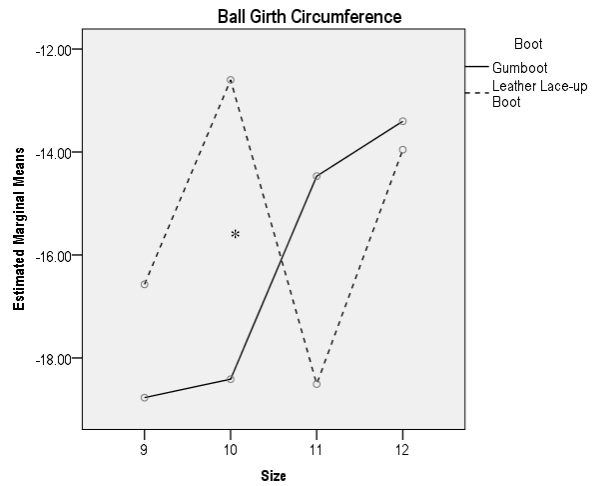
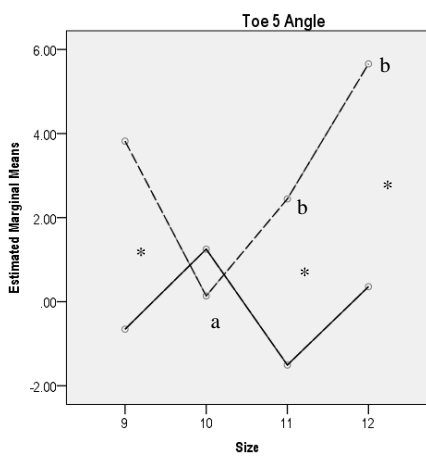
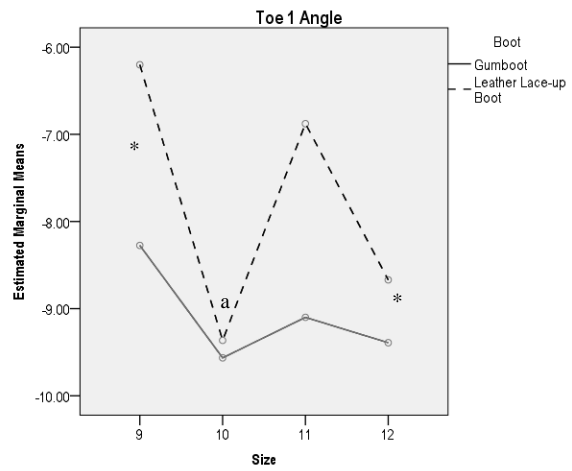
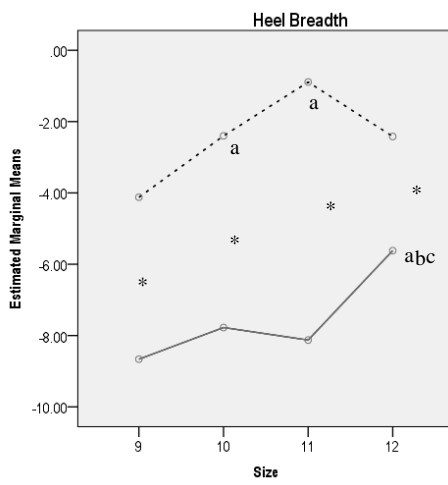
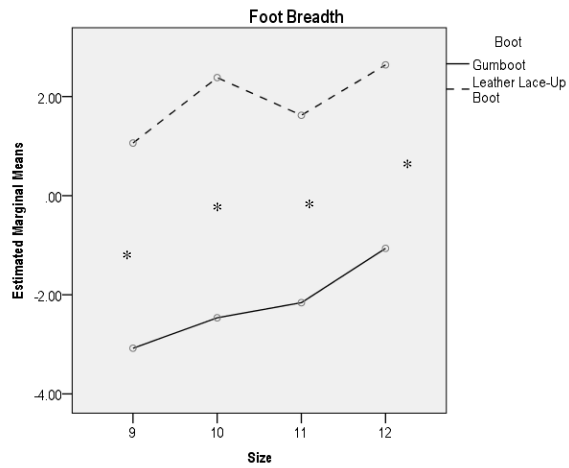
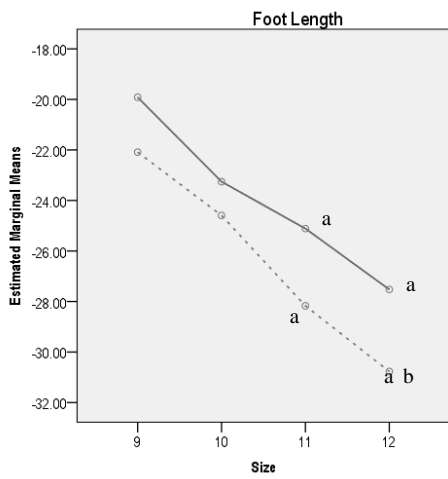
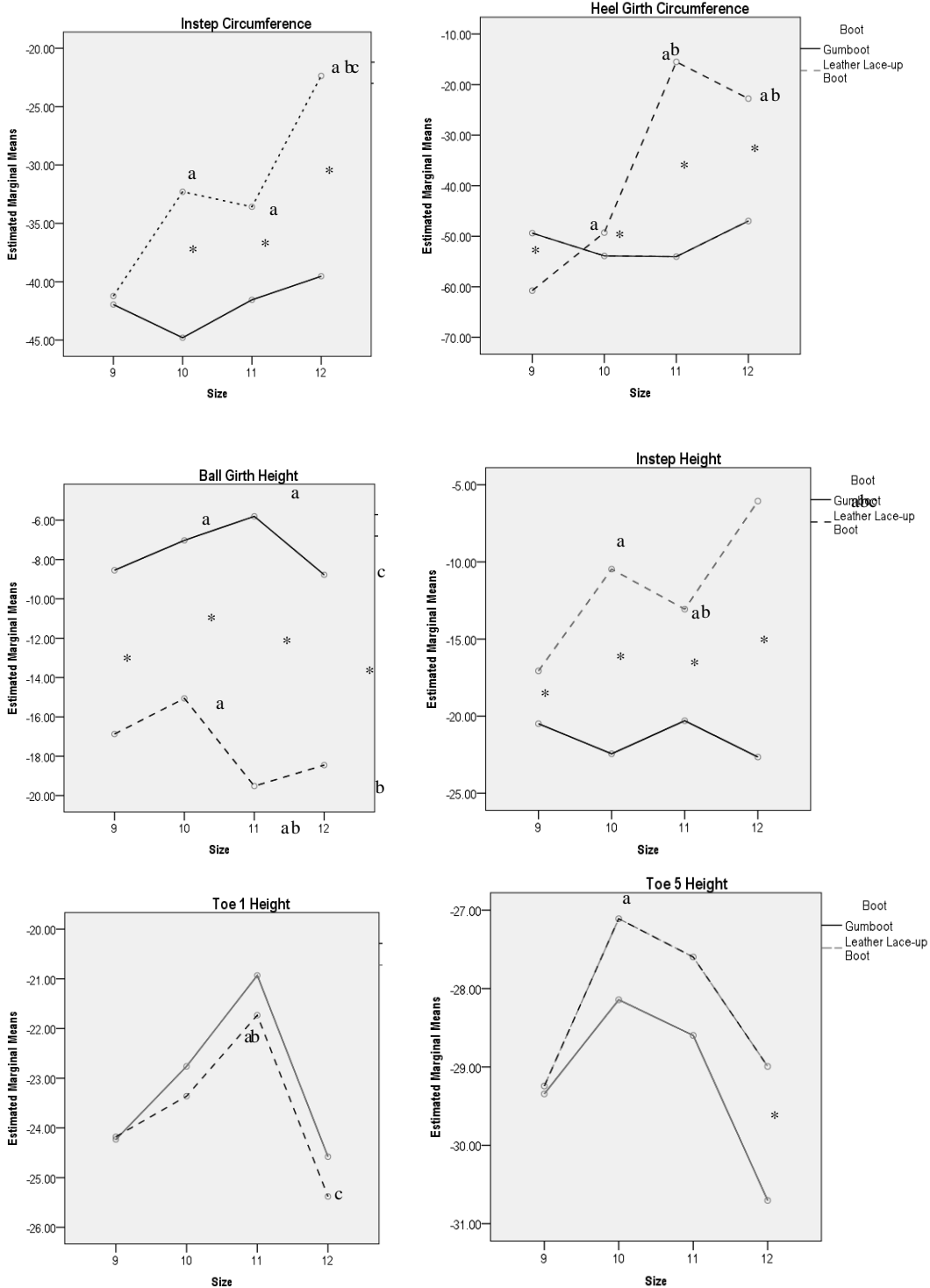


Figure 5: The gap between a miner's foot and their internal boot dimensions for boot sizes: (A) 9, (B) 10, (C) 11 and (D) 12 represented by a box-and-whisker plot. Values to the left of the 0 line indicate the miners' feet were smaller than their boots and values to the right of the 0 line indicate their feet were larger than their boots. Circled values represent outliers.

3.2 Boot Type and Boot Size Effect

There was a significant main effect of boot type ($p < 0.001$) and boot size ($p < 0.001$) and a significant interaction of boot type x boot size ($p < 0.001$) 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 6). 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 6). 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 6). 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.





- 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 6: Boot type x boot size interactions for the 12 variables of 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 were smaller than their boots and positive values indicate their feet were larger than their boots.

4. Discussion

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 have revealed that 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. The implications of these findings are discussed below.

A work boot should be slightly longer than the foot to compensate for elongation that occurs when standing and walking (Menz et al., 2014, Grau and Barisch-Fritz, 2017, Hawes and SOVAK, 1994). Unfortunately, what the gap between the longest toe and the end of a boot should be has not been systematically investigated. Values in the literature currently range from 10-20 mm or a thumbs width (Rossi, 1988, Barton et al., 2009, Hayashi and Hosoya, 2014). It should be noted that it is not possible to use the "thumb width rule" when fitting work boots because of the inability to palpate the longest toe beneath the mandatory steel cap. In support of our first hypothesis (H1), the underground coal miners' feet in the current study were shorter in length than their work boots. On average, however, the gap between the longest toe and the end of the work boots was greater than the gap recommended in the literature. Furthermore, in contrast to our third hypothesis (H3), the size of this gap increased as boot size increased, whereby there was a 20-30 mm gap between the end of the miners' feet and their work boots in the largest boot sizes (see Figure 6). We speculate that this larger gap at the end of the miners' boots was likely to be related to insufficient boot

width. Shoe width does not always incrementally increase with shoe length and, to obtain adequate width, people with wide feet often choose shoes much longer than their feet (Yates and Merriman, 2009). This finding is supported in other study populations, for example older adults (227 women, 172 men; 60-90 years of age) who wore shoes much longer than their feet had wider feet, suggesting foot width determines shoe size selection (de Castro et al., 2010). Infantry recruits with wider feet also compensated for a lack of available shoe width by choosing larger shoe sizes (Finestone et al., 1992). In the current study, the miners' feet were closer to the end of the gumboot, which has a wider forefoot design compared to the narrower leather lace-up boot. This result further supports the relationship between foot width and boot size selection, and is consistent with previous research where gumboot wearers were more likely to select a work boot that was smaller than their everyday shoe size compared to leather lace-up boot wearers who were more likely to select a work boot larger than their everyday shoe (Dobson et al., 2017).

Discomfort can result from selecting a work boot that is larger than the foot. In this case, the position of the metatarsophalangeal joint is the main contributing factor to this discomfort. In a boot that is too long relative to foot length, the metatarsophalangeal joint sits further back than where it would normally sit in proper fitting footwear. For the foot to move naturally in this position the boot must now flex in a different location than how it was designed (Yates and Merriman, 2009). If the boot is unable to flex in this more distal location discomfort results because the metatarsophalangeal joint is unable to flex while walking, thus inhibiting natural rollover and push-off via the toes. This could explain why underground coal miners find their work boots uncomfortable despite no reported issues with fit (Yates and Merriman, 2009, Hawes and SOVAK, 1994, Dobson et al., 2018).

In contrast to our second hypothesis (H2), a mismatch between the miners' feet and the internal dimensions of their boots for the variables of foot breadth and heel breadth was

found. The foot and heel breadth dimensions of the participants were either similar in size or larger than the internal dimensions of their work boots leading to a compression of the miners' forefoot and heel to fit inside their work boots (see Figure 5). In fact, across all boot sizes there was less than a 4 mm gap between the miner's foot breadth and the internal edge of the boot in the gumboot, whereas in the leather lace-up boot, the miners' feet were wider than their internal boot structure (see Figure 6). Gaps less than 5 mm between the feet and the internal edge of a shoe have been linked to discomfort (Pavlackova et al., 2015), again explaining why underground coal miners rate their work boots as uncomfortable (Dobson et al., 2018).

The toe 5 angle, a width dimension, of the miners feet was also greater than the boot moulds, highlighting that the miners' 5th toes would likely be compressed to fit inside their work boots (see Figure 5 and Figure 6), particularly when wearing leather lace-up boots (see Figure 6). Constantly compressing the 5th toes against the internal edge of their work boot throughout a typical 8 hour shift will increase the likelihood of developing corns and/or calluses (Dobson et al., 2018, Grouios, 2004). However, these results need to be interpreted with caution because the position of toe 5 on the boot moulds had to be approximated.

For the variables of instep height, instep circumference and heel girth circumference in the leather lace-up boot and heel breadth in the gumboot, the miners' feet were closer to the internal edge of their work boot in the larger boot sizes compared to the smallest boot size (see Figure 6). This finding is in contrast to H3 where we hypothesised that the gap between the miners' feet and their boots would remain constant across sizes and boots. This result also implies that boot designers are not increasing the boot circumference at the instep and heel sufficiently in the larger boot sizes. Work boots that are too tight would not only be uncomfortable and lead to foot pain but could impair foot function leading to further lower limb discomfort (Luximon et al., 2003, Rossi, 2001). We recommend boot manufacturers

reassess the algorithms used to create boot lasts, particularly focusing on adjusting boot circumferences at the instep and heel relative to increases in foot length.

In contrast to our second hypothesis (H2), there was a substantial 20-30 mm gap between the dorsal surface of the miners' toes and the boot toe box, and this gap was evident across both boots and all sizes (see Figure 6). This result suggests that the foot discomfort reported by miners is more likely to be associated with inadequate boot width rather than insufficient toe box height.

The boot type x boot size interactions identified in the present study are also in contrast to H3 but support the need to update the current underground coal mining work boot last algorithms. Differences between dimensions representing the miners' feet and the internal work boot structure were not consistent across boot sizes or boot types. To improve work boot fit and comfort of all underground coal miners, the gap between a miners' foot and their internal work boot structure needs to be consistent regardless of the boot type or boot size. Exactly what is an ideal foot-boot gap is currently subjective and vaguely quantified. Gap values in the literature range from 'snug' to a 20 mm gap across the foot breadth with no other width or height gap values reported (Rossi, 1988, Menz et al., 2014, Miller et al., 2000, Witana et al., 2004, Goonetilleke et al., 2000). If a work boot is either too broad or too small, the foot is unable to be stabilised within the boot and this lack of stabilisation can create high pressure points, which can lead to foot problems such as calluses (Marr, 1999). Underground coal miners who had calluses were more likely to rate their work boot fit as 'poor' and boot comfort as 'uncomfortable' than those who did not report calluses (Dobson et al., 2018). Future studies are therefore needed to investigate self-reported comfort and fit ratings and link them to quantitative width fit measurements to create specific numerical boot width fitting guidelines that can be used across different boot types and sizes.

Foot pain is also a consequence of work boots that are too tight or too broad (Rossi, 2001). On average, in the current study, the miners' foot dimensions were smaller than the gumboot internal dimensions but were similar or larger than the leather lace-up boot internal dimensions. Foot breadth, heel breadth, heel circumference, toe 5 angle, instep height and instep circumference are variables where the leather lace-up boot was narrower than the gumboot across all boot sizes (see Figure 6). Corns, bunions and foot problems that result from increased pressure on the foot are more common in wearers of the narrower leather lace-up boot compared to gumboot wearers (Dobson et al., 2017, Grouios, 2004). Leather lace-up boot wearers were also more likely to report navicular and cuboid pain (Dobson et al., 2017), suggesting the narrower foot breadth and instep in the leather lace-up boot is problematic.

Gumboot wearers, on the other hand, are more likely to have pain around the ball of their foot, compared to leather lace-up boot wearers (Dobson et al., 2017). Dobson et al. (2017) suggested that this pain was likely because gumboots allowed too much movement around this region of the foot. However, in the present study the leather lace-up boot had a significantly greater ball girth height than the gumboot, although the gumboot appeared to allow adequate room across the ball girth circumference and was not significantly different from the leather lace-up boot with respect to this variable (see Figure 6). We therefore speculate that the ball of foot pain experienced by gumboot wearers is likely due to additional movement at the forefoot in the gumboot placing extra pressure at the top of the ball of the foot, where there is less room. Further research is recommended to investigate different boot shapes relative to underground miners' foot shapes to identify how much room is required between the foot and work boot at different locations in order to minimise foot pain while optimising foot comfort and movement.

Although enhancing boot design is important, it is vital to develop boot-fitting guidelines to ensure that miners can select work boot to suit their individual foot shape. Furthermore, it is likely to be too difficult to create a boot that adequately fits all workers while still accommodating for the outliers. As such, miners who fall into the extremes of fitting guidelines should be provided with custom boots as a more viable option than trying to fit them into a generic boot shape.

4.1 Limitations

Plaster of Paris creates a hard rigid shape that unlike the foot is unable to be deformed. Hence, during real wear, once a shoe is ‘broken in’ the dimensions and shape of the shoe can be different from the original structure (Rossi, 1988). Therefore, the mismatching points between the feet and the boot moulds identified in the current study may not be as noticeable after a miner has worn their boots in. However, this is also dependent on the material of the boot upper with leather, for example, tending to have minimal give, especially when compared to rubber (Rossi, 1988). Wear testing of boots during real underground mining conditions is vital in future research to confirm how footwear deforms due to wear and whether this is affected by boot material.

Due to the nature of the Plaster of Paris moulds, the positions of toe 1 and toe 5 had to be approximated and, although the utmost care was taken to make these positions as accurate as possible, the results still need to be interpreted with caution.

5. Conclusions

Underground coal miners wore boots that were substantially longer than their feet, most likely because boots available in their correct length were too narrow. Work boots that do not fit properly are not only uncomfortable but can lead to foot pain while working. It is

recommended boot manufactures reassess the algorithms used to create boot lasts, 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. It is therefore vital future studies investigate self-reported comfort and fit ratings and link them to quantitative fit measurements to develop boot-fitting guidelines that ensure miners can select a work boot that suits their individual foot shape.

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