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Effect of work boot shaft stiffness and sole flexibility on lower limb muscle activity and ankle alignment at initial foot-ground contact when walking on simulated coal mining surfaces: Implications for reducing slip risk

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Conflict of interest

None.

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Abstract

Design features of safety work boots have the potential to influence how underground coal miners' feet interact with the challenging surfaces they walk on and, in turn, their risk of slipping. Despite the importance of work boot design in reducing the risk of miners slipping, limited research has investigated how boot design features, such as shaft stiffness and sole flexibility, affect the way miners walk. Therefore, this study aimed to investigate the effects of systematic variations to boot shaft stiffness and sole flexibility on lower limb muscle activity and ankle motion in preparation for initial foot-ground contact when 20 males walked across two simulated coal mining surfaces under four mining boot conditions. It was concluded that a boot which has different flexibility and stiffness between the shaft and sole is a better design option to reduce underground coal miners' slip risk than a boot that has a stiff shaft and stiff sole or flexible shaft and flexible sole.

Keywords: Boot design, walking, slip risk, gait, coal mining

1. Introduction

The primary requirement for everyday work footwear is to maintain and enhance mobility (1). However, in occupations where a safety work boot is compulsory, the need to maintain and enhance mobility becomes a secondary priority to mandatory safety requirements. For example, mandatory safety toe caps, high boot shafts, and penetration resistant soles are required in safety work boots to protect the lower limb of workers from falling objects, undesirable external stimuli, and puncture wounds. Although providing protection, these work boot safety features often restrict movement of the lower limb while individuals walk (1). The foot's natural motion, particularly during the roll-over process and propulsive phase while walking, can be affected by a safety toe cap and a thick sole, which restricts movement of the foot, and a high boot shaft, which restricts movement of the ankle (2, 3). When the lower limb is unable to move naturally, there is increased reliance on secondary structures, such as the muscles, for support during walking (4). During prolonged walking an increased reliance on the lower limb muscles for support can be problematic because this increases the risk of overuse injuries, sprains and strains (5, 6).

Walking constitutes a large component of the day-to-day activities performed by underground coal miners, with most workers spending 8-12 hours on their feet either standing or walking (7). Underground coal miners also work on challenging surfaces that are often wet, uneven, and unstable (7). Therefore, miners' boots are required to meet safety standards and protect the workers' feet from workplace hazards while simultaneously providing sufficient support and flexibility needed to walk on these challenging surfaces (7). However, the design of current underground coal mining work boots is not meeting these requirements because miners currently experience a high incidence of work-related lower limb injuries, with sprains and strains caused by slipping being highly prevalent (6-8).

A slip is typically initiated by a sudden increase in the horizontal velocity of a shoe as it contacts the supporting surface (9). A dangerous forward slip is most likely to occur less than 70-120 ms after the heel strikes the ground (10). Therefore, initial contact between the foot and ground is considered to be the critical point during the gait cycle when a slip is most likely to occur (11, 12). Immediately after initial foot-ground contact, if the lower limb does not adequately decelerate, or if there is a poor shoe-surface interaction, the shear forces generated by the foot contacting the supporting surface will exceed the frictional forces opposing the foot's movement and a slip will eventuate (11). Higher heel contact velocities at initial foot-ground contact are therefore a primary risk factor for slipping during walking.

A reason for increased or decreased heel contact velocity at initial foot-ground contact is the way an individual recruits his or her lower limb muscles in preparation for initial contact (11). Increased heel contact velocities are thought to result from delayed and reduced activation of the hamstring muscles prior to initial contact (13, 14). Other researchers, however, have speculated that co-contraction of the hamstring and quadriceps muscles, rather than just activation of the hamstring muscles, ultimately controls the speed of the leg as the foot approaches initial contact with the ground (11, 15). Irrespective of which lower limb muscles control heel contact velocity, it is imperative that any changes in work boot design do not impede lower limb muscle co-ordination in a manner that would increase heel contact velocity at initial foot-ground contact.

In addition to heel contact velocity, ankle motion at initial contact influences the shoe-surface interaction. Ideally, at initial contact, the ankle should be in a relatively neutral position in the sagittal plane and slightly adducted and externally rotated to allow the heel to initially contact the ground (16). Activation of the shank muscles is also important in preventing a slip at initial contact by controlling movement of the foot at the ankle joint. For example, individuals will typically increase the peak activity of muscles that control the ankle joint to

keep the foot in a stable position and prevent slipping in anticipation of walking on a slippery surface (15). Healthy individuals are typically able to alter their lower limb muscle activity and ankle motion (15, 17) to correct their balance in response to a slip when walking on a level, even surface (18). Underground mines, however, encompass an unpredictable environment whereby the supporting surface can be both uneven and moveable (19) due to gravel and soft coal dust (personal communication, 12th October 2016). Successfully walking across these types of uneven, moveable surfaces requires constant adjustments of the lower limb muscles to keep the foot contacting the supporting surface in a way that retains an individual's line of gravity within his or her base of support (11, 15, 17, 19) to prevent a slip from occurring.

Lower limb mediated slip alterations, particularly in response to uneven surfaces, appear to depend on the design of the work boots worn (5, 20). When walking on uneven surfaces it is vital that the foot and ankle have enough flexibility to allow adjustments in balance to occur, but not too much flexibility that the ankle rolls (3, 4, 6). The shaft of a boot provides external support for the shank, thereby influencing ankle motion (21). In contrast, the sole of a boot influences how the foot interacts with the surface, which in turn, can change the position of the ankle during walking (22). Changing footwear shaft and sole stiffness also potentially triggers a reorganisation of the muscle activity that is responsible for stabilising the ankle and knee joint (21). Mining work boots of varying shaft stiffness and sole flexibility may therefore influence how an underground coal miner's foot interacts 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. Therefore, shaft stiffness and sole flexibility are important boot design features that appear to interact with one another and affect lower limb muscle activity and ankle motion at initial contact when individuals walk (23).

Despite the importance of work boot design in reducing the risk of miners slipping, only one previous study could be located that investigated boot design features, such as shaft

stiffness and sole flexibility, in a systematic way (23). The test boot conditions in most previous research have differed with respect to several critical design features such as boot mass, shaft height, and midsole hardness, rather than altering just one design feature in isolation. It has therefore been difficult to draw conclusive results from previous studies because any of these boot design features could influence lower limb biomechanics during walking (23). In the one study in which boot design parameters were systematically altered (2), changes to a boot shaft and a boot sole were found to significantly influence boot comfort and the plantar pressures generated when individuals walked on challenging surfaces, such as those experienced by underground coal miners. It remains unknown, however, whether changes to a boot shaft and/or a boot sole can influence lower limb muscle activity or ankle motion, especially in preparation for initial foot-ground contact, in an attempt to reduce the risk of a slip. Therefore, this study aimed to investigate the effects of systematic variations to shaft stiffness and sole flexibility in safety work boots on lower limb muscle activity and ankle motion in preparation for initial foot-ground contact when individuals walked across simulated underground coal mining surfaces. It was hypothesized that boot shaft stiffness and boot sole flexibility would interact to influence lower limb muscle activity and the ankle alignment displayed at initial foot-ground contact during the gait cycle. Specifically, compared to work boots in which both the shaft and the sole were too stiff or too flexible, a boot designed with variable stiffness between the shaft and sole would influence:

- (i) heel contact velocity at initial foot-ground contact by altering the onset of the thigh muscles relative to initial contact, and
- (ii) the position of the foot at the ankle at initial foot-ground contact by altering the activity of the shank muscles.

2. Methods

2.1 Participants

Twenty males who habitually wore steel-capped safety boots (11 underground coal miners; 9 trade workers who wore safety boots; age 36 ± 13.8 years; height 174.8 ± 6.3 cm, body mass 76.9 ± 9.2 kg) volunteered to participate in this study. Participants were excluded from the study if they had lower limb injuries or foot pain/discomfort that impaired their ability to perform the experimental procedures, or habitually wore corrective shoe inserts (such as orthoses). Recruitment involved posting the study details on social media and through South32 (Australia) advertising the study on work noticeboards, work newsletters, and during mine training sessions. The participants' ages, body stature measurements, working roles, working surfaces, and time spent walking during a typical 8-10 hour shift were consistent with those previously reported for underground coal mine workers (7). 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; 5).

2.2 Experimental Procedures

After providing written informed consent each participant completed a survey to confirm they satisfied the inclusion criteria. Height (cm) and body mass (kg) were then recorded and all participants were provided with a new pair of socks (Miners Corp., Essentials Pty Ltd, Australia). Electromyography (EMG) sensors (Delsys Inc., USA), motion capture sensors (Optotrak Certus® Northern Digital Inc., Canada), and an electronic goniometer (Biometrics Ltd, UK) were adhered to specific locations on each participant's dominant lower limb (see Sections 2.3.1 and 2.3.2) and pressure insoles (Pedar-X novel_{gmbh}, Germany) were inserted inside the test boots (2). Before data collection began, participants completed a functional circuit set out in the Biomechanics Research Laboratory at the University of Wollongong (2). This circuit took approximately 10 minutes to complete and was used to recreate some of the common working tasks performed by underground coal miners and familiarize participants with each new boot condition (2). After completing the functional circuit, participants

performed five walking trials on an uneven gravel and a soft surface where lower limb muscle activity (see Section 2.3.1) and ankle motion (see Section 2.3.2) data were collected. The two walking surfaces were designed to replicate the environmental surface conditions underground coal mine workers typically walk on during their daily work tasks (Figure 1). The uneven surface (6 m x 0.8 m) was made of pebbles 10-40 mm in diameter (Tuscan Path, Australia) and was raked after each trial so that the surface remained relatively even. These pebble sizes were selected as they represented coal pieces typically encountered in underground coal mines (personal communication, 12th October 2016). The soft surface (6 m x 0.8 m) was made of underlay foam (Standard Carpetmate, Dunlop, Australia) and was selected to recreate the soft coal dust surface the underground coal miners walk on (personal communication, 12th October 2016). Walking speed was not controlled as we wanted the participants to walk as naturally as possible in the boots.

To ensure order effects did not influence the results, boot condition order and surface condition order were randomized. To minimize 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.

Figure 1: Uneven gravel and soft surfaces used for the walking trials: (A) uneven surface formed by 10-40 mm diameter pebbles, and (B) soft surface formed by underlay foam. These surfaces were designed to simulate the “feel” of underground coal mining surfaces in a laboratory environment.

2.3 Boot Conditions

The four boot conditions included a boot with a stiff shaft + stiff sole (overall stiff boot), a flexible shaft + flexible sole (overall flexible boot), a stiff shaft + flexible sole, and a flexible shaft + stiff sole (Figure 2). The boot design characteristics are described in detail elsewhere (2). In summary, the boot shafts were constructed from a variety of materials to create differences in shaft stiffness (Figure 2). To create the flexible sole conditions, the Chief Investigator (JD) used a razor blade to cut slits across the sole of the boot at the approximate location where the metatarsophalangeal joints flex during walking (Figure 2). The boots were “colour coded” during testing (red, blue, green, and yellow) to blind the participants and researchers to boot condition during testing and analysis. Shaft stiffness and sole flexibility testing were performed 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 two sets of each test boot condition so participants 1-10 wore one set of new boots and participants 11-20 wore the other set of new boots. The full details of this testing procedure are provided elsewhere (2).

Figure 2: The test boots: (A) the stiff shaft condition, (B) flexible shaft condition, and (C) arrow where the 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.

An Optotrak Data Acquisition Unit II (ODAUII; 270 mm x 175 mm x 65 mm; 2 kg) was used to record the lower limb muscle activity data (see Section 2.3.1), which was synchronized with the ankle motion capture data and a trigger switch, which activated the Biometrics DataLOG system (Biometrics Ltd, UK; see Section 2.3.2).

2.3.1 Lower limb muscle activity

The lower limb muscle activity generated during the walking trials were recorded (1000 Hz; bandwidth 20-450 Hz) using a wireless EMG system (Trigno™, Delsys Inc., USA). An EMG sensor (Delsys Adhesive Sensor Interface; Delsys Inc., USA) was attached over the muscle bellies of vastus lateralis (VL), semitendinosus (ST), tibialis anterior (TA), peroneus longus (PL), and gastrocnemius medialis (GM) on each participant's dominant lower limb (Figure 3). Standard EMG sensors (37 mm x 26 mm x 15 mm, < 15 g) were used to monitor the activity

of VL and ST whereas mini EMG sensors (25 mm x 12 mm x 7 mm, 2.1 g) were used for TA, PL, and GM because these muscle bellies were located under the shaft of the boot (Figure 3). Electrode placement sites were identified following recommendations by SENIAM (24) and the guidelines endorsed by the International Society of Electrophysiology and Kinesiology (25). These muscles were selected for analysis due to their superficial location and their role in controlling heel contact velocity and motion of the foot about the ankle joint at initial contact (16). Prior to electrode placement, the skin over each designated muscle belly was shaved, abraded with prep tape, and cleaned with an alcohol swab to ensure optimal readings (26).

A custom MATLAB (R2017b 9.30 713579) script was used to analyse the EMG data. After visual inspection of the data (to ensure no trials were contaminated grossly by movement artefact), the raw EMG signals were filtered using a fourth-order zero-phase-shift Butterworth low pass filter ($f_c = 15$ Hz). The in-shoe pressure data were then used to determine when initial contact occurred (2). The filtered EMG signals representing the muscle bursts immediately before initial contact were visually inspected using a threshold detector of 12% of the maximum burst to determine the timing (ms) of muscle onsets relative to initial contact (whereby a negative value indicated that the muscle onset occurred before initial contact). When the muscle burst onset and offset were confirmed, the software automatically derived the peak value (mV) and duration (ms) of the burst. The mean of five walking trials performed by each participant on each surface, walking in each of the four footwear conditions were analysed. The literature consistently shows that when stability is challenged, muscle activity, expressed in millivolts (mV), consequently increases (27-31). Therefore, the area under the curve (mV/s) was used as a measure of muscle intensity (32, 33).

2.3.2 *Ankle motion*

Each participant's ankle alignment within the boot was captured (100 Hz) using a twin-axis electronic goniometer (29 g; accuracy $\pm 2^\circ$ measured over a range of $\pm 90^\circ$; Biometrics Ltd,

UK). The goniometer was mounted using double-sided adhesive tape (Creative Hair Products, Australia) and positioned across the ankle joint of the participant's dominant limb following the instructions of the manufacturer (Figure 3). The goniometer was attached to a DataLOG (Type No. MWX8 Bluetooth®; 104 x 62 x 22 mm; 129 g) and data were sent to the DataLOG software application in real time via Bluetooth®. A custom MATLAB script was then used to derive the ankle plantar flexion and eversion angles at initial contact. The data were filtered using a zero-phase shift 2nd order Butterworth filter with a cut-off at 12 Hz (MATLAB function `filtfilt`), as recommended by the software manufacturers (MathWorks®, Natick, United States; Biometrics Ltd, UK).

To quantify heel contact velocity, the motion of each participant's dominant lower limb was recorded while he walked in each boot condition using an Optotrak Certus® motion analysis system (Northern Digital Inc., Ontario, Canada). Before each data collection session, a new global coordinate system alignment was performed and the position sensor coordinate system was defined (positive y as upward, positive x as the direction of travel, and positive z as pointing to the right (34)). To track each participant's foot and shank, 11 smart markers (11 mm diameter) were attached over the skin (double-sided toupee tape, Creative Hair Products, Australia) at specific anatomical landmarks (Figure 3). The smart markers were connected to a wireless strober unit (85 mm x 55 mm x 20 mm; 100 g) using flat smart marker interconnect cables (40 mm – 900 mm long) and smart marker hubs (Figure 3). The coordinates were detected by three Certus® Position Sensors (161 mm x 200 mm x 1126 mm; 18 kg), which were factory calibrated with an accuracy of 0.1 mm and a resolution of 0.01 mm. The motion capture data were sampled at 100 Hz across one whole gait cycle using NDI First Principles software (Version 1.2.4, Northern Digital Inc., Canada) and stored for later analysis.

Figure 3: Participant showing: (A) EMG sensor placement for the lower limb. Muscles: vastus lateralis (VL), semitendinosus (ST), tibialis anterior (TA), peroneus longus (PL) and gastrocnemius medialis (GM). (B) Optotrak (Northern Digital Inc., Canada) smart marker positions, the strober unit (1), flat smart marker interconnect cables (2) and smart marker hubs (3). The smart markers were placed on the 1st, 2nd and 5th metatarsal heads (boot), navicular (boot), posterior calcaneus (boot), anterior shank (boot), lateral and medial malleoli (boot), and tibial tuberosity (skin). (C) Electronic goniometer placement (Biometrics Ltd, UK).

The positional data were loaded into Visual 3D (Professional, Version 5.02.27, ATI Technologies Inc., Canada) where it was filtered using a Butterworth low pass ($f_c = 6$ Hz) digital filter (3, 35, 36). From these smoothed positional data, a rigid body model was constructed to derive heel contact velocity, which was defined as the first derivative of the proximal end of the foot segment at initial foot-ground contact. Initial contact was defined using a velocity based algorithm described by C-Motion (Maryland, United States) and based on recommendations by Zeni et al. (37).

2.4 Statistical Analysis

Means and standard deviations for the lower limb muscle activity and ankle alignment data across the five walking trials were calculated per boot condition. A three-way repeated measures ANOVA design, with three within factors of boot shaft type (flexible and stiff), sole

type (flexible and stiff), and surface condition (gravel and soft) was then used to determine whether there were any significant main effects or interactions of either shaft type, sole type, or surface condition on the lower limb muscle activity and lower limb motion data displayed by the participants. Wilks' Lambda multivariate test was used to determine any significant main effects and interactions. Paired *t*-tests further investigated any significant main effects and interactions. This design determined whether any of the data were significantly different between the boot shaft and sole types and whether any of these differences were influenced by which surface the participants were walking on. An alpha level of $p \leq 0.05$ was used for all statistical comparisons and all tests were conducted using SPSS statistical software (Version 21, SPSS, USA).

3. Results

3.1 Effects of Boot and Surface Type on Lower Limb Muscle Activity

3.1.1 Muscle burst onsets

There was a significant main effect of boot shaft type ($p < 0.001$) and surface condition ($p < 0.001$), an interaction of boot sole type x surface condition ($p = 0.003$), and an interaction of boot shaft type x boot sole type x surface condition ($p = 0.002$) on the muscle burst onsets (ms) relative to initial contact (Figures 4A-C, 5A-C). When participants walked on the gravel surface there was a main effect of boot shaft type ($p < 0.001$), a main effect of boot sole type ($p = 0.032$), and a boot shaft type x boot sole type interaction ($p = 0.032$) on the muscle burst onsets (ms) relative to initial contact (Figures 4A, 4C, 5A, 5B). In contrast, when the participants walked on the soft surface, there was a significant main effect of boot sole type ($p < 0.001$) and a boot shaft type x boot sole type interaction ($p = 0.044$) on the muscle burst onset (ms) relative to initial contact (Figures 4B, 5C).

Thigh muscle onsets: When the boot had a stiff sole and the participants walked on a gravel surface, a stiff boot shaft resulted in an earlier VL ($p = 0.047$; Figure 4A) and ST ($p = 0.003$;

Figure 4C) onset relative to initial contact compared to a flexible boot shaft. There was also a difference between sole types when the participants walked on the gravel surface while wearing a boot with a flexible shaft. That is, a flexible sole led to an earlier ST onset ($p = 0.004$) compared to a stiff sole (Figure 4C) when the boot shaft was flexible. Furthermore, when the participants walked on the soft surface while wearing a boot with a flexible shaft + flexible sole, there was earlier VL onset ($p = 0.001$) relative to initial contact compared to when wearing a boot with a flexible shaft + stiff sole (Figure 4B).

Shank muscle onsets: When participants walked on the gravel surface wearing a boot with a stiff sole combined with a stiff shaft, PL was activated significantly earlier ($p = 0.023$; Figure 5B) and GM was activated significantly later ($p = 0.005$; Figure 5D) relative to initial contact compared to when wearing a boot with a stiff sole combined with a flexible shaft. Furthermore, when walking on the gravel surface wearing a boot with a flexible sole, a flexible shaft led to a later TA onset ($p = 0.023$) relative to initial contact compared to a stiff shaft (Figure 5A). On the soft surface, however, when the shaft was stiff, a stiff sole led to an earlier PL onset ($p = 0.005$) relative to initial contact when compared to a flexible sole (Figure 5C).

Figure 4: The significant interactions of boot shaft x sole on the thigh muscle onsets (ms; A-C) and burst peaks (mV; D-E) relative to initial contact when walking on the gravel (G) and soft (S) surface. VL = vastus lateralis and ST = semitendinosus. *indicates a significant difference between boot shaft type or boot sole type ($p < 0.05$).

Figure 5: The significant interactions of boot shaft x sole on the shank muscle onsets (ms; A-D) and burst peaks (mV; E) relative to initial contact when walking on the gravel (G) and soft (S) surface. TA = tibialis anterior, PL = peroneus longus and GM = gastrocnemius medialis. *indicates a significant difference between boot shaft type or boot sole type ($p < 0.05$).

3.1.2 *Peak muscle activity*

The boot sole type ($p = 0.041$) and surface condition ($p < 0.001$) both had a significant main effect on the peak activity of the lower limb muscles at initial foot-ground contact (Figure 6A). There was also a significant interaction of boot shaft type x boot sole type ($p < 0.001$), an interaction of boot shaft type x surface condition ($p = 0.035$), and an interaction of boot sole type x surface condition ($p = 0.002$) on the peak lower limb muscle activity at initial contact (Figures 4D-E, 5E). When the participants walked on the gravel surface there was a significant main effect of boot sole type ($p = 0.029$), and an interaction of boot shaft type x boot sole type ($p < 0.001$) on the peak lower limb muscle activity at initial contact (Figure 4D). In contrast, when the participants walked on the soft surface, there was a significant main effect of boot shaft type ($p = 0.026$), a significant main effect of boot sole type ($p = 0.009$), and an interaction of boot shaft type x boot sole type ($p < 0.001$) on the peak lower limb muscle activity at initial contact (Figures 4E, 5E).

Peak thigh muscle activity: When the participants walked on a gravel surface while wearing a boot with a stiff sole, a stiff boot shaft led to increased peak ST activity ($p = 0.041$) at initial contact compared to a flexible boot shaft (Figure 4D). There was also a difference in peak ST activity between sole types on the gravel surface when participants wore a boot with a stiff shaft, whereby wearing a boot with a stiff sole led to increased ST activity ($p = 0.028$) compared to a flexible sole (Figures 4D, 6A). When the participants walked on the soft surface, peak ST activity was significantly higher ($p < 0.001$) when they wore a boot with a stiff shaft, compared to a boot with a flexible shaft, when the boot sole was stiff (Figures 4E, 6A). In regards to sole flexibility, when the boot had a flexible shaft, a flexible boot sole led to significantly increased peak ST muscle activity ($p < 0.001$) at initial contact compared to a stiff boot sole on the soft surface (Figures 4E, 6A).

Figure 6: Mean ($\pm$ standard deviation) of the peak muscle burst value (A; mV) and muscle burst duration value (B; ms) for the thigh muscles (VL = vastus lateralis, ST = semitendinosus) and shank muscles (TA = tibialis anterior, PL = peroneus longus, GM = gastrocnemius medialis) on the gravel and soft surface. *indicates a significant difference between a stiff and flexible boot shaft when the boot sole is stiff. **indicates a significant difference between a stiff and flexible boot sole when the boot shaft is stiff. ***indicates a significant difference between a stiff and flexible boot sole when the boot shaft is flexible.

Peak shank muscle activity: When the participants walked on the soft surface while wearing a boot that had a flexible sole, there was significantly higher peak GM muscle activity ($p = 0.038$) relative to initial contact in the boot with a flexible shaft compared to a boot with a stiff shaft (Figures 5E, 6A).

3.1.3 Muscle burst duration

There were no significant main effects of either boot shaft or boot sole on the duration of the lower limb muscle bursts at initial contact (Figure 6B). Although there was a significant main effect of surface condition ($p < 0.001$) on lower limb muscle duration, this finding was not explored any further because the main aim of this study was to investigate changes in boot shaft and boot sole type on lower limb muscle activity.

3.2 Effects of Boot and Surface Type on Heel Velocity and Ankle Alignment

3.2.1 Heel contact velocity

There were no significant main effects or interactions of boot shaft type, sole type or surface condition on heel contact velocity displayed at initial foot-ground contact (Figure 7).

Figure 7: Mean ($\pm$ standard deviation) of the ankle motion data when the participants walked on the soft and gravel surfaces: heel contact velocity (A; s) and plantar flexion (PF) and eversion (EV) angle (B; degrees). *indicates a significant difference between a stiff and flexible boot shaft when the boot sole is flexible. **indicates a significant difference between a stiff and flexible boot sole when the boot shaft is stiff.

3.2.1 Ankle alignment at initial contact

There was a significant main effect of boot shaft type ($p = 0.022$), an interaction of boot shaft type x boot sole type ($p = 0.033$), and an interaction of boot shaft type x boot sole type x surface condition ($p = 0.041$) on the ankle alignment displayed by the participants at initial contact. When these results were analysed by surface condition, there was a significant main effect of boot shaft type ($p = 0.010$), a main effect of boot sole type ($p = 0.027$), and a boot shaft type x boot sole type interaction ($p = 0.027$) when the participants walked on the gravel surface. Upon further analysis of the participants walking on gravel, when they wore a boot with a flexible sole, a stiffer boot shaft led to a greater eversion angle at initial contact compared to a flexible shaft ($p < 0.001$; Figure 7B). There was also a difference between sole types at initial contact when the participants walked on the gravel surface. That is, a significantly greater eversion angle ($p = 0.002$) was displayed when the participants wore a boot with a stiff shaft combined with a flexible sole compared to a stiff boot sole (Figure 7B). There were no further significant main effects or interactions of the boot shaft type or boot sole type when the participants walked on the soft surface (Figure 7B). The significant findings for the study are summarized in Table 1.

Boot Shaft	Boot Sole	Gravel	Soft
(A) Stiff vs. flexible	Stiff	earlier onset VL, ST and PL later onset GM ↑ peak activity ST	↑ peak activity ST
	Flexible	earlier onset TA ↑ ankle eversion	↓ peak activity GM

Boot Sole	Boot Shaft	Gravel	Soft
(B) Stiff vs. flexible	Stiff	↑ peak activity ST ↓ ankle eversion	VL later onset earlier onset PL
	Flexible	later onset ST	VL later onset ↓ peak activity ST

Table 1: Summary of the lower limb muscle activity and ankle motion data significant interactions ($p < 0.05$) when the participants walked on the gravel and soft surfaces. (A): Stiff boot shaft compared to a flexible boot shaft when the boot sole was stiff and when the boot sole was flexible. (B): Stiff boot sole compared to a flexible boot sole when the boot shaft was stiff and when the boot shaft was flexible. VL = vastus lateralis, ST = semitendinosus, PL = peroneus longus, GM = gastrocnemius medialis, and TA = tibialis anterior.

4. Discussion

By systematically altering boot shaft stiffness and sole flexibility, we were able to investigate the effects of these specific boot design features on lower limb muscle activity and ankle angle at initial contact during walking. The complexity of work boot design was highlighted by the numerous significant shaft type x sole type x surface type interactions affecting the lower limb muscle activity and ankle angle data at initial contact in the current study. These results are in agreeance with our hypothesis and highlight the notion that boot design features should not be examined in isolation because interactions between the design features and the surfaces walked upon need to be considered when designing future work boots for underground coal miners. Although there were no significant differences in heel contact velocity between the boot conditions, the activity of the thigh and shank muscles and the position of the ankle at initial contact was influenced by the type of boot shaft and sole and the surface walked on.

4.1 Effect of Thigh Muscle Activity on Heel Contact Velocity

In partial contrast to our hypotheses, the boot shaft type and boot sole type did not significantly influence heel velocity at initial foot-ground contact (Figure 7A). However, in agreement with our hypotheses, thigh muscle activity was significantly affected by different combinations of stiffness and flexibility between the shaft and the sole of the work boots (Figure 4). These differences in thigh muscle activity between the test boot conditions appeared to keep heel velocity at initial contact constant, most likely in order to negate any increase in slip risk.

Differences in semitendinosus (ST) activity between the boot conditions could explain why heel contact velocity was not significantly affected by boot conditions in the present study. Increased ST activity would ensure the swing leg was adequately decelerated leading into initial contact, thereby influencing heel contact velocity (16). There was increased peak ST activity when the participants wore the overall stiff boot (stiff shaft + stiff sole) compared to the boots with variable stiffness (flexible shaft + stiff sole and the stiff shaft + flexible sole) when they walked on the gravel and soft surfaces (Figures 4D-E). We speculate that this additional ST activity in the overall stiff boot condition was required to adequately decelerate the swing leg leading into initial contact, possibly due to an inability to make any modifications at the ankle due to the overall increased boot stiffness. Furthermore, when walking on the gravel surface, to achieve the same heel contact velocity, an overall stiff boot required earlier vastus lateralis (VL) and ST onset compared to when wearing a boot with a flexible shaft + stiff sole (Figures 4A, 4C). These earlier thigh muscle onsets further suggest that an overall stiff boot required earlier thigh muscle activation to decelerate and control the swinging leg leading into initial contact (11, 15). It is possible that the overall stiffness of a boot affects the end of the stance phase of gait, leading to a more rapid leg swing that must be controlled prior to initial foot-ground contact. Irrespective of the reasons, an overall stiff boot seemed to require increased thigh muscle activity to decelerate the lower limb during swing and before ground

contact. Interestingly, wearing an overall flexible boot (flexible shaft + flexible sole) also led to increased peak ST activity and an earlier ST onset when participants walked on the gravel surface when wearing a boot with a flexible shaft + stiff sole (Figures 4C-D). Further research examining how boot and sole stiffness influence other phases of the gait cycle and, in turn, acceleration of the lower limb prior to initial contact, are needed to provide further insight into these results.

In contrast to walking on the gravel surface, a boot with a stiff sole, regardless of shaft type, led to a later VL onset when participants walked on the soft surface (Figure 4B). This finding provides further evidence for surface specific designs when developing underground coal mining work boots. To control the amount of knee flexion during the loading response in the gait cycle, VL has a major peak of activity following initial contact (16). An earlier onset of VL at initial contact could therefore be implemented in preparation to control excess knee flexion leading into the loading response. Conversely, a later VL onset at initial contact could indicate that an individual anticipates that the appropriate amount of knee flexion will occur during the loading response. The finding of the present study where a stiff boot sole, regardless of shaft type, led to a later VL onset indicated that when walking on a soft surface, where there is more surface deformation, foot motion might play a larger role in determining how much knee flexion occurs during stance and, therefore, needs to be controlled. However, research investigating knee motion during the entire gait cycle is needed to confirm or refute this notion.

Greater heel contact velocities at initial contact are a primary risk factor for slipping (11). To prevent a slip, the lower limb needs to adequately decelerate in preparation for initial contact (11). In the present study, earlier onsets and increased activity of the thigh muscles occurred during the different boot conditions, most likely as compensatory actions to ensure heel contact velocity remained consistent at initial foot-ground contact. We speculate that any increases in thigh muscle activity could eventually become a slip risk due to earlier muscular

fatigue over a typical 8-12 hour underground coal mining work shift (38). Therefore, a boot that has variable flexibility and stiffness between the shaft and sole of the boot appears to be a better design option in regards to how thigh muscle activity influences slip risk for underground coal miners than a boot that is overall stiff or overall flexible.

4.2 Effect of Shank Muscle Activity on Ankle Alignment

Although there were only minor changes in ankle alignment at initial foot-ground contact in response to the different boot conditions, shank muscle activity was significantly affected by different combinations of stiffness and flexibility between the shaft and the sole of the work boots (Figure 5). When walking on the gravel surface, to achieve a similar ankle alignment, an overall stiff boot (stiff shaft + stiff sole) required earlier peroneus longus (PL; Figure 5B) onset and later gastrocnemius medialis onset (GM; Figure 5D), compared to when wearing a boot with a flexible shaft + stiff sole. These changes in shank muscle onsets suggested that an overall stiff boot might restrict ankle motion compared to a boot with a flexible shaft + stiff sole, requiring different muscle activity to align the ankle correctly to prepare for foot-ground contact. We speculate that earlier PL onset when wearing the overall stiff boot was required to stabilize the ankle against foot inversion and ensure slight eversion at initial contact (16). Earlier PL onset was also evident when the participants walked on the soft surface in the overall stiff boot compared to the boot with the stiff shaft + flexible sole (Figure 5C). This finding again supports the notion that an overall stiff boot restricted ankle motion and required earlier PL activity to properly position the foot leading into initial contact. When comparing the overall stiff boot to the boot with the stiff shaft + flexible sole, although there were no differences in shank muscle activity, there was a reduction in eversion in the overall stiff boot (Figure 7B). However, when the boot sole was flexible, a stiff boot shaft compared to a flexible boot shaft led to increased eversion (Figure 7B) and earlier onset of TA (Figure 5A) when the participants walked on the gravel surface. This finding suggests that it is the combination of a

stiff boot shaft + a stiff boot sole that restricted motion at the ankle, rather than just a stiff shaft in isolation.

Fine tuning of forward leg rotation by the GM is critical to determine the amount of knee flexion leading into the loading response and stance phase of the gait cycle (16). A later GM onset, which occurred when the participants wore the overall stiff boot compared to the boot with a flexible shaft + stiff sole (Figure 5D), helps rotate the leg and increase knee flexion leading into early stance (16). In the current study, this later GM onset was possibly required to overcome restricted leg motion associated with wearing a stiffer boot (16). Increased GM activity, however, can arrest this forward leg rotation from initial contact onwards and result in reduced knee flexion (16). Hence, the increased peak GM activity displayed by the participants when they walked on the soft surface in the overall flexible boot (flexible shaft + flexible sole) compared to the boot with the stiff shaft + flexible sole (Figure 5E) could be detrimental for shock absorption later in the gait cycle due to the lack of knee flexion. Further research examining lower limb motion throughout the stance phase of gait is therefore recommended to confirm or refute this notion.

Immediately after initial foot-ground contact, if there is a poor shoe-surface interaction, a slip will eventuate (11). As ankle alignment at initial contact influences the shoe-surface interaction, activation of the shank muscles is important in preventing a slip at initial contact by controlling movement of the foot at the ankle joint. If the shank muscles are required to be consistently activated earlier or at a higher intensity they can become fatigued (38). Any factor that contributes to earlier onset of fatigue could increase the risk of an underground coal miner slipping because they might not be able to maintain an appropriate foot position in a boot that is overall stiff. However, further research is needed to examine the effects of changes to boot design to lower limb muscle activity over a longer time period to confirm or refute this concept.

4.3 Limitations

As with any biomechanical study we acknowledge the limitations inherently involved when collecting and analysing electromyographic and goniometric data. This study also involved measuring an acute effect of the test boot conditions in simulated coal mining conditions. With underground coal miners working shifts ranging from 8-12 hours it is unknown whether these same results would apply after such a long period of time or within an actual mining environment (7). As this was an exploratory study we believed acute effects in a simulated environment were acceptable to identify directions for future research, which should now involve investigating chronic effects of variations in boot design on slip risk in underground coal mining. In regards to the flexible sole condition, the position of flexibility may have varied from person to person given the variations in foot length ratios among the participants.

5. Conclusions

To prevent a slip, the lower limb needs to be adequately decelerated in preparation for initial foot-ground contact. In the present study, the participants displayed earlier onsets and additional thigh and shank muscle activity when they walked in boots that were overall stiff or overall flexible relative to the other boot conditions. These changes in muscle activity were thought to be compensatory actions in response to the overall boot stiffness/flexibility, most likely to achieve constant heel contact velocity and the correct ankle alignment in preparation for initial contact. However, these earlier onsets and increased thigh and shank muscle activity could become a slip risk due to increased potential for fatigue of the key slip prevention muscles over a typical 8-12 hour underground coal mining work shift. Therefore, a boot that has variable flexibility and stiffness between the shaft and sole of the boot is thought to be a better design option for underground coal miners in regards to slip risk than a boot that is overall stiff or overall flexible.

6. References

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