Applied Ergonomics 49 (2015) 34–40

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

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

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ARTICLE INFO

Article history:
Received 14 May 2014
Accepted 26 January 2015
Available online 17 February 2015

Keywords:
Boots
Mining
Surfaces

ABSTRACT

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

1. Introduction

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

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

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

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

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http://dx.doi.org/10.1016/j.apergo.2015.01.006
0003-6870/

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

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

2. Methods

2.1. Participants

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

2.2. Footwear conditions

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

2.3. Experimental procedures

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

2.3.1. In-shoe pressure data

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

2.3.2. Muscle activity during walking

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