The interaction between firefighting boot design and lower body injury risk at work

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INTRODUCTION

When responding to emergency operations, firefighters must wear a range of personal protective clothing (PPC) and equipment (PPE) to maintain their safety. Indeed, in some environments, such as those where high heat and smoke exist self-contained breathing apparatus' (SCBA) and structural clothing ensembles are vital to a firefighters' ability to undertake work. When PPC and PPE are combined, the weight added to the ambulating individual can exceed 23kg in addition to tools or equipment required to complete any given work task. When at work, firefighters are tasked with occupation specific, repetitive movement patterns that can include climbing stairs, alighting from fire appliances and negotiating obstacles. It is therefore likely that, when combined with the requirement to carry significant loads, the repetitive nature may be predisposing firefighters to significant repeated loading, which may lead to increased risk of developing chronic injuries.

For firefighters to work safely in hot and unstable terrain, in addition to firefighting PPE, they wear structural firefighting boots (referred to as Type 2). Boots in this category are required to have protection against penetration and heat, along with toe protection in the form of hard toe caps. These design requirements, while providing necessary thermal and impact protection, add weight while concurrently reducing the flexibility of the boot. Another significant design requirement is that a boot-shaft that terminates above the line of the ankle joint, to increase stability and reduce the incidence of ankle injuries and provide firefighting specific protection. Specifically, boot design standards (ISO) require boots to have a minimum shaft height. For example, for size 45 boots and above, a shaft no shorter than 192mm is needed.

During landing movements, such as alighting from a fire appliance, ground reaction forces (GRFs) are transferred from the distal to the proximal extremities. Specifically during landing, forces are absorbed and dissipated through the ankle, knee and then hip-joint in sequence. This is generally referred to as the kinetic chain and alterations to this will change the body's natural ability to attenuate forces. When landing without restriction to the ankle joint, such as when barefoot, the foot is generally in plantar flexion (toe down). When the ankle is restricted, thus not allowing for plantar flexion on landing, a heel-toe landing (HTL) technique occurs. A HTL landing pattern has been associated with greater vertical GRFs. This then results in increased compressive forces in the soft tissue and joints surrounding the hip and knee joints. It is widely believed that chronic exposure to such forces may lead to lumbar instabilities resulting in lower lumbar and lower body injuries.

Soft tissue injuries, both acute and chronic, in the lower body and lower lumbar region of the spine are reported as being the leading cause of disability and early retirement in firefighters. Thus, it is intuitive to expect that, in addition to work specific movement patterns, an interaction between boot design and injury may be occurring. In research undertaken into non-firefighting boots, such as ski-boots and ice-skates, which share common design features at the ankle joint, reduced range of motion has been observed at both the ankle and the knee joint. As such, we hypothesised that firefighting boots with designs that restrict the ankle joints may elicit similar reductions in range of motion in firefighters when they complete landing tasks. Furthermore, as a consequence, boots may increase the risk of suffering an injury to the lower body or lumbar region as a result of alterations to the kinetic chain.

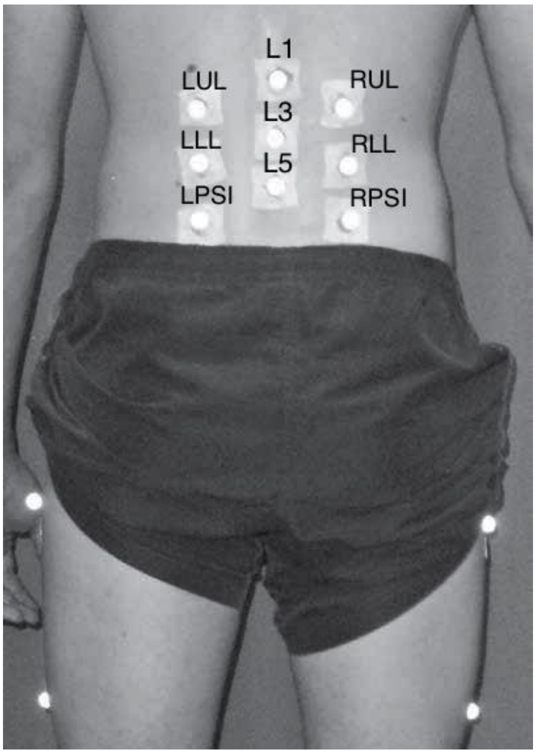
METHODS

Twenty professional male urban firefighters and officers from ACT Fire & Rescue (Mean ± SD; weight 84.4 kg ± 11.6, height 1.81 ± 0.06 m and age 41.3 ± 8.8 years) were recruited to participate in this study. All participants were fully operational at the time of testing and had 13.5 ± 10.9 years of operational service. Participants were excluded if they were injured or currently undertaking any form of lower limb or back rehabilitation. Ethics approval was granted and written informed consent was obtained for each participant before the commencement of the study in accordance with the requirements of the Human Research Ethics Committee at the University of Canberra.

Data collection was conducted in a purpose-built Biomechanics laboratory located at the University of Canberra. Three-dimensional marker trajectories were captured using a 12-camera Vicon motion capture system sampling at 250Hz (Oxford Metrics Ltd., Oxford, UK). GRF data were collected at 1000 Hz using two 400 x 600 mm AMTI Force plates (Advanced Mechanical Technologies, MA, USA). Prior to testing, participants had 37 retro-reflective makers placed on their lumbar and lower body (Figure 1).

Participants were instructed to perform four drop jump landings from a contextually specific height under four randomly assigned conditions (firefighting boots unloaded, firefighting boots loaded, control unloaded and control loaded). Participants used their own athletic footwear for the control condition with a caveat being that they were purchased within the past six months. Brand new Type 2 structural Haix Fire Flash Xtreme (Lexington, Kentucky, USA) boots were used for the boot condition. Loaded conditions composed of participants wearing a firefighting helmet and a 9.5kg backpack to replicate the SCBA. The backpack was located at the thoracic level of the spine to prevent coverage of the lumbar spine markers. A 42cm platform, which replicated the bottom step of an Australian urban fire truck, was placed 10 cm from the edge of two force platforms (Figure

2). Participants were instructed to step off the platform by shifting their weight forward onto their right leg then drop down as vertically as possible to eliminate additional upward motions and reduce horizontal motion from the step off. Participants then simultaneously landed two-footed with one foot on each force plate.



RESULTS

Wearing firefighting boots resulted in significantly increased vGRFs when landing when compared landing in control shoes ($p < 0.05$). The additional load of the stimulated SCBA in loaded conditions (control loaded 2.31 ± 0.65 body weight (BW), boot loaded 2.55 ± 0.53 BW) also showed significant increases ($p < 0.05$) in vGRF, independent of firefighting boots (control unloaded 2.14 ± 0.65 body weight (BW), boot unloaded 2.40 ± 0.58 BW).

A significant loading and footwear effect was found in peak ankle displacement between all conditions during landings ($p < 0.01$). Peak ankle plantar flexion angle for the control loaded conditions were greater in comparison to the control unloaded and boot loaded conditions (-42.05 ± 11.55°, -32.49 ± 9.95°, -28.83 ± 13.12°, $p < 0.01$ respectively).

At initial contact, increased plantar flexion was observed in the control shoe for both the unloaded and loaded conditions compared with the boot (control -36.41 ± 10.43°, boot - 25.59 ± 9.17°, $p < 0.01$ and control -40.73 ± 11.55°, boot -28.31 ± 13.51°, $p < 0.01$).

Landing in firefighting boots under unloaded (222.89 ± 18.47 $deg \cdot s^{-1}$) and loaded (240.91 ± 24.37 $deg \cdot s^{-1}$) conditions showed greater peak lumbo pelvic (LP) flexion angular velocity ($p < 0.05$) when compared to the control unloaded condition (187.56 ± 60.96 $deg \cdot s^{-1}$). Peak LP flexion force was also observed when wearing firefighting boots (unloaded 13.40 ± 1.48 $N \cdot kg^{-1}$, loaded 14.46 ± 1.46 $N \cdot kg^{-1}$) in comparison to the control shoe (unloaded 12.32 ± 5.44 $N \cdot kg^{-1}$, loaded 14.37 ± 6.94 $N \cdot kg^{-1}$). Greater peak lumbar internal rotation angular velocities and moments were also observed when wearing firefighting boots unloaded (111.06 ± 13.07 $deg \cdot s^{-1}$, $p < 0.05$; 3.26 ± 0.34 $Nm \cdot kg^{-1}$, $p < 0.05$ respectively) and loaded (114.49 ± 16.30 $deg \cdot s^{-1}$, $p < 0.05$; 3.81 ± 0.42 $Nm \cdot kg^{-1}$, $p < 0.01$ respectively) in comparison to the unloaded control shoe (80.51 ± 47.23 $deg \cdot s^{-1}$, $p < 0.05$; 2.60 ± 0.78 $Nm \cdot kg^{-1}$, $p < 0.05$ respectively).

Landing in firefighting boots resulted in greater peak LP adduction force when compared to the unloaded control condition (control 19.84 ± 11.44 $N \cdot kg^{-1}$, boot 30.54 ± 19.76 $N \cdot kg^{1}$, $p < 0.01$). These findings were also observed in the peak LP adduction moments (control 2.21 ± 1.01 $Nm \cdot kg^{1}$, boots 3.15 ± 0.50 $Nm \cdot kg^{-1}$, $p < 0.01$).

DISCUSSION

This study aimed to establish a relationship between ankle restricting boot designs and changes to GRFs, and ankle and lumbar biomechanics during a simulated landing task. Our data indicate that the design of a structural firefighting boot increases vGRFs, decreases ankle displacement and increases load to the lumbar region, compared with a control shoe. This study provides novel findings by exploring the influence of ankle restrictive firefighting boots on the kinetics and kinematics of the LP segment during landing.

On landing, we observed reduced ankle plantar flexion in firefighters when they were wearing the firefighting boots. It is likely that these findings resulted from the rigid shaft design, resulting in restricted range of motion (ROM) of the ankle joint. Previous research into landings in military settings, along with sports such as figure skating, basketball and skiing showed similar increases in vGRFs as we observed in this study. By limiting the ROM of the ankle during landing, firefighters adopted a HTL technique, previously observed to lead to reductions in knee flexion and increased hip flexors. Thus, it is likely that the changes to the biomechanics of firefighters during landing tasks observed in this study, has the potential to expose soft tissue and joints in the lumbar region and the lower body to greater compressive forces and other kinematic changes. It must be noted that it is further likely that the reduced range of motion observed may not be solely attributed to shaft inflexibility. Rather, other components such as the rigid sole or the protective steel toe cap may also have played a part due to restrictions to the range of motion in the toes and should be examined in further research.

As demonstrated in this study, the ability of the ankle joint to dissipate forces through the kinetic chain may be being negatively impacted by the current design standards of structural firefighting boots. Thus, based on our findings, it is likely that the design standards required for firefighting boots may be contributing to an increased risk of lower back injuries in firefighters. However, to date there remains limited understanding of the effects of load and lower body biomechanics during landing and walking tasks. As such, we recommend further investigation of the links between boot design and injury rates in firefighters and possibly re-examining the design standards required. At the minimum, consideration for maximising the natural movement of the ankle should occur when designing future firefighting boots.