

Potential mechanisms for the occurrence of tibial stress fractures, metatarsal stress fractures and ankle inversion injuries in Royal Marine recruits

Submitted by Hannah Margaret Rice to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Sport and Health Sciences (January 2015).

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ABSTRACT

Lower limb injury incidence is high amongst Royal Marine recruits. Tibial and metatarsal stress fractures are particularly problematic. The regular load carriage activities undertaken throughout training have been implicated, but mechanisms by which these injuries develop are poorly understood. The aim of this thesis was to improve understanding of the mechanisms by which the most prevalent Royal Marine training injuries develop.

The first experimental chapter was a prospective study of 1065 Royal Marine recruits. Anthropometric and dynamic biomechanical variables (during barefoot running at $3.6 \text{ m}\cdot\text{s}^{-1}$) were recorded at the start of training. A smaller calf girth and bimalleolar breadth were found to predispose recruits to tibial stress fractures and ankle inversion injuries. Recruits who sustained tibial stress fractures demonstrated greater heel loading than those who remained injury-free. Recruits who sustained metatarsal stress fractures demonstrated later peak metatarsal pressures than those who remained injury-free.

A review of the 32-week Royal Marine recruit training programme found an association between prolonged load carriage activities and injury occurrence. The second experimental study identified gait changes following a prolonged load carriage activity (12.8 km, 35.5 kg load). Biomechanical variables were recorded during barefoot running ($3.6 \text{ m}\cdot\text{s}^{-1}$) in 32 recruits pre- and post-activity. Recruits demonstrated increased rearfoot loading, and later peak metatarsal pressures post-activity, indicative of a reduced ability to push-off.

The final study examined the influence of the same load carriage activity on gait changes during walking ($1.4 \text{ m}\cdot\text{s}^{-1}$) in 32 recruits, allowing assessment of the independent influence of load carriage. Kinetic and electromyographic variables provided further explanation of changes observed in the previous study. During load carriage there were increased plantar flexor and knee extensor moments and corresponding increases in muscle activity. There were reduced knee extensor moments, and evidence of plantar flexor muscle fatigue post-activity. A reduced ability to push off during stance due to muscular fatigue was suggested as a key contributor to tibial and metatarsal stress fracture development. This may explain the association between a smaller calf girth and tibial stress fracture development.

DEDICATION

Although she would cringe at the idea, I dedicate this thesis to my Mum.

ACKNOWLEDGEMENTS

I am extremely grateful for the help I have received throughout the process of completing this thesis. I would firstly like to thank my two supervisors, Dr Sharon Dixon and Dr Jo Fallowfield, for their guidance throughout. Sharon has been an inspiration to me as a biomechanist and scientist, demonstrating integrity and thoroughness in everything that she does. Jo has been extremely supportive, and evidently cares greatly about the work. I have enjoyed working with both Sharon and Jo on a personal level.

I would like to thank a number of people from the University of Exeter. Michael Nunns has encouraged, advised and amused me throughout the entirety of this process. Many difficult times have been shared with Michael, and these have all been resolved with laughter. Loic Damm has provided me with invaluable Matlab support and Vicky Stiles ensured that my PhD did not take over my life. Jo Bowtell has also been generous with her time, introducing me to EMG.

I am indebted to Trish Davey for her organisational skills and her willingness to be involved. I will never forget our 4 am data collection in the middle of winter! I would also like to thank all of the staff from the Institute of Naval Medicine who helped with data collection, particularly Sophie Britland who showed dedication to all that she was involved with.

This work was only possible thanks to the staff at the Commando Training Centre Royal Marines, Lympstone. In particular, physiotherapist Richard Hales gave up numerous hours for the benefit of this work. The greatest thanks of all must go to the Royal Marine recruits who volunteered to participate in the studies in this thesis.

Finally, I would like to thank my Dad, and my brothers Joe and George, who have kept a healthy distance from this work. During difficult times they are either pragmatic or hilarious, and both approaches help. I swear by my Dad's advice: "Focus on what matters".

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DEFINITIONS

CTCRM	Commando Training Centre Royal Marines: training centre for recruit training in Lympstone, Devon
MODREC	Ministry of Defence Research Ethics Committee
Recruit	A male, aged 16-33 years who is undertaking the 32-week Royal Marine training programme, in order to become a trained Royal Marine
Troop	A group of approximately 40 – 60 recruits who complete the recruit training programme together
Bergen	A large rucksack worn by recruits during many training activities (Figure 6.1, p.103)
Webbing	A carrying device worn like a belt by recruits during many training activities (Figure 6.1, p.103)
HX	Hallux
T2-5	Second to fifth toes
M1-M5	First to fifth metatarsals
MF	Midfoot
HM	Medial heel
HL	Lateral heel
ROM	Range of motion
VL	Vastus lateralis muscle
BF	Biceps femoris muscle
GL	Gastrocnemius lateralis muscle
PL	Peroneus longus muscle
TA	Tibialis anterior muscle

DECLARATION, PUBLICATIONS AND COMMUNICATIONS

Declaration

The material contained within this thesis is original work conducted by the author. The following communications and publications are a direct consequence of this work.

Publications

- Rice, H., Nunns, M., House, C., Fallowfield, J., Allsopp, A., & Dixon, S. (2013). High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. *Gait & posture*, 38(4), 614-618.
- Nunns, M., Rice, H., House, C., Fallowfield, J., Allsopp, A., & Dixon, S. (2013). A prospective study identifying risk factors for tibial stress fracture in Royal Marine recruits: initial findings. *Footwear Science*, 5(1), S123-S124.
- Dixon, S., Nunns, M., House, C., Rice, H., Stiles, V. (2013). Ankle joint kinematics influence risk of third metatarsal stress fracture in military recruits. *Footwear Science*, 5(1), S122-S123.
- Rice, H., Davey, T., Dixon, S., Fallowfield, J.L. (2012). *A review of the 32-week (RS 10) Royal Marines recruit training programme and the association with injury occurrence* Institute of Naval Medicine Report No. 2012.037.
- Rice, H., Nunns, M., Fallowfield, J.L., Allsopp, A., Dixon, S. (2013). *The Royal Marines Biomechanics Project – II: Prospectively identified biomechanical and anthropometric risk factors for ankle inversion injury*. Institute of Naval Medicine Report No. 2013.039.
- Rice, H., Fallowfield, J.L., Davey, T. Allsopp, A.J. Dixon, S. (2014). *Altered loading under the foot following a military training activity as a potential mechanism for metatarsal stress fracture development*. Institute of Naval Medicine Report No. 2014.029.
- Rice, H., Fallowfield, J.L., Davey, T. Allsopp, A.J. Dixon, S. (2014). *Influence of a prolonged load carriage activity on lower limb gait mechanics and muscle activity*. Institute of Naval Medicine Report No. 2015.007.

Communications

BASES Biomechanics Interest Group, April 2012, University of Ulster.
High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. Oral presentation.

BASES Conference, September 2013, UCLA.
Prospectively identified biomechanical and anthropometric risk factors for ankle inversion injury. Oral presentation.

CHAPTER 1: Introduction

Lower limb injuries are a major burden in military populations (Almeida et al., 1999; Chan et al., 1993; Heir & Glomsaker, 1996; Jones et al., 1993b; Wood et al., 2014) comprising over three-quarters of all training injuries (Almeida, et al., 1999; Jones, 1993). The majority of lower limb injuries sustained during military training have been attributed to running (Jones, et al., 1993b; Neely, 1998). A high injury occurrence of 16-33% has been reported during the Royal Marines (UK) recruit training programme (Munnoch, 2008; Munnoch & Bridger, 2007; Ross & Allsopp, 2002), with the majority of these being lower limb injuries (Munnoch, 2008). The Royal Marines are the Royal Navy's all-male amphibious infantry, and their 32-week recruit training programme is recognised as one of the longest and most arduous military training programmes in the world (Munnoch, 2008). The Ministry of Defence have a duty of care to minimise the risk of injury during training. Injuries are an inevitable part of a physical training programme which must necessarily be demanding in order to prepare a recruit to the required physical and psychological standard for duty. An improved understanding of the mechanisms by which the most prevalent lower limb injuries occur is required in order to minimise injury risk.

Injury occurrence amongst Royal Marine recruits has considerable financial implications. The training officer at the Commando Training Centre Royal Marines, has estimated that the cost per recruit for each week spent in rehabilitation from a training injury is £1600 (Major D. Phillips, personal communication, 24 Nov, 2009). In 2011 for example, 252 recruits were admitted into the Royal Marines remedial troop with lower limb injuries. This resulted in a total of 5586 weeks of lost training time, which would equate to an estimated cost to the Ministry of Defence of £8.9 million in that year, (based on the approximation of £1600 per recruit per week). Thus the necessity of reducing the occurrence of lower limb injuries within the Royal Marine recruit population is indisputable.

Stress fractures are notoriously problematic in military populations, and have been the subject of research for a number of decades. Despite this, a high stress fracture rate remains a considerable problem in these otherwise healthy, active populations. Stress fractures are the most prevalent injury amongst Royal Marine

recruits (28.9% of all injuries (Munnoch, 2008)), with 3.8% - 6% of recruits reportedly sustaining a lower limb stress fracture (House et al., 2013; Munnoch, 2008; Ross & Allsopp, 2002). The metatarsals and the tibia are the most common site of stress fracture in this population, comprising 11.4% and 8.3% of all injuries respectively (Munnoch, 2008). Stress fractures within the Royal Marine recruit population are reportedly the most important cause of lost training days (Ross & Allsopp, 2002), and are particularly burdensome due to the difficulty in diagnosis (Ross & Allsopp, 2002), and the lengthy recovery times (median 23 weeks for tibial stress fracture, and 32.5 weeks for metatarsal stress fracture (Munnoch, 2008)). There is also a high incidence of knee and ankle injuries (15.7% and 7.4% of all injuries respectively (Munnoch, 2008)). Ankle inversion injuries also require a lengthy recovery time (median 19 weeks (Munnoch, 2008)) and may be particularly problematic due to the increased risk of recurrence of this injury, following initial injury (Surve et al., 1994; Yeung et al., 1994).

Load carriage activities during military training have long been associated with the high injury occurrence (Birrell et al., 2007; Knapik et al., 1992; Orr et al., 2014), and particularly the high stress fracture occurrence (Knapik et al., 2004; Orr, et al., 2014) in these populations. This thesis focuses on tibial stress fractures, metatarsal stress fractures and ankle inversion injuries. There is a clear rationale for focusing on tibial and metatarsal stress fractures as they are so problematic specifically within this population. Ankle inversion injuries are considered in addition due to their high reported incidence in the Royal Marine recruit population and the high risk of recurrence following an initial inversion injury (Surve, et al., 1994; Yeung, et al., 1994). Knee injuries were not investigated despite a high incidence amongst Royal Marine recruits, as a range of different specific knee injuries were collated to determine this incidence. Different knee injuries (including anterior cruciate ligament injuries, patellofemoral pain and meniscus injuries) are likely to result from distinct mechanisms and as such require independent investigation.

Previous research has been conducted in an attempt to understand mechanisms and risk factors for lower limb injury occurrence (Beynon et al., 2002; Dixon et al.,

2006; Giladi et al., 1985; Kaufman et al., 1999; Korpelainen et al., 2001; Milgrom et al., 1991; Simkin et al., 1989; Warden et al., 2006; Willems et al., 2005; Willems et al., 2006; Willems et al., 2007). However, despite some improvements in the understanding of mechanisms for such injuries in recent decades, there has been no consistent indication of a reduced injury occurrence within the Royal Marine recruit population. In order to reduce injury occurrence through intervention, identification of variables associated with increased injury risk, as well as an improved understanding of the mechanisms by which these injuries develop is required. To address this proposition, this thesis includes three experimental chapters, as well as an observational review of the Royal Marine recruit training programme.

The first experimental chapter discusses a large prospective study that identified biomechanical and anthropometric variables at the start of recruit training, which were associated with tibial stress fracture, metatarsal stress fracture or ankle inversion injury occurrence during training. The chapter which follows evaluates the recruit training programme, which was systematically reviewed to identify training variables and activities associated with injury occurrence. An example of one such activity was then selected as the protocol for the final two experimental chapters. These final chapters discuss the influence of completing such an activity on running and walking gait respectively, in a pre-post study design. Gait changes as a result of completing this activity provide insight into the mechanisms by which tibial and metatarsal stress fractures develop, through associations with findings from the first experimental chapter. The findings also identify mechanisms that may explain the occurrence of ankle inversion injuries.

Injuries are undoubtedly a multifactorial problem, influenced by intrinsic and extrinsic variables (Murphy et al., 2003). Royal Marine recruits are selected for recruit training based on specified anthropometric characteristics and fitness requirements, resulting in a relatively homogenous population. Additionally, all recruits are required to complete the same training programme within a highly controlled environment, which means that many of the variables that may influence

injury risk are controlled in this population. The Royal Marine recruit population therefore provided an excellent opportunity to identify characteristics associated with the most prevalent training injuries, and to further understand mechanisms for their development. Such findings would benefit the Royal Marine recruit population, wider military populations and even active populations who are at risk of tibial stress fracture, metatarsal stress fracture or ankle inversion injury. An improved understanding of the mechanisms by which injuries occur would guide future intervention studies with the intention of reducing injury occurrence.

The purpose of this thesis was to identify anthropometric and biomechanical variables associated with tibial stress fractures, metatarsal stress fractures, and ankle inversion injuries in Royal Marine recruits, and to improve understanding of the mechanisms by which these injuries occur.

CHAPTER 2: Literature Review

The following literature review evaluates research that has identified anthropometric and biomechanical characteristics associated with the occurrence of tibial stress fractures, metatarsal stress fractures and ankle inversion injuries. The influence of completing military training activities, including the influence of load carriage on lower limb gait is also considered.

2.1 Stress fracture development

The physiological response of bone to loading is well understood but mechanisms for stress fracture development remain unclear. Healthy bone undergoes a remodelling process following optimal levels of loading (Beck, 2000), with prolonged bone strain making the bone stiffer and more dense, and consequently stronger (Cowin & Hegedus, 1976). When bone is loaded, electrical signals activate osteoclasts and osteoblasts. These are cells within bone tissue, each with a specific role in bone remodelling. Osteoclasts break down damaged bone which can then be removed, whilst osteoblasts deposit new bone (Bennell et al., 1996). This remodelling process occurs according to Wolff's Law (Frost, 1994), which states that with increased loading, the bone remodels over time in order to be able to withstand that greater level of loading in the future.

It is well-established that bone atrophy occurs following prolonged periods of bed rest (Bloomfield, 1997), and this is the result of insufficient bone loading. Loading of the bones is therefore essential in order to elicit beneficial remodelling. However, it is consistently reported that repeated bone strain at a level below the failure threshold may result in microdamage development (Brukner et al., 1999; Schaffler et al., 1989). Bone is more porous during the remodelling process, making it more susceptible to stress fracture (Beck, 2000). Accumulated microdamage as a result of repetitive loading, with insufficient opportunity for remodelling, will eventually result in bone failure (Kenny & Campbell, 1968). This may explain the association between prolonged military load carriage activities and metatarsal and tibial stress fracture incidence (Knapik, et al., 1992; Orr, et al., 2014). Such activities are likely to occur on consecutive days, with limited recovery time during military training.

This is an essential part of military training that is designed to simulate potential real-life military activities, where recovery time may be limited. A number of factors influence microdamage progression including high stress magnitude, high strain rates, high number of loading cycles and frequency, and low bone density (Bennell, et al., 1996). Although the physiological and mechanical influences of bone material failure are understood, it is unclear what predisposes certain individuals to a stress fracture, and how gait characteristics may influence stress fracture development.

2.2 Anthropometric and lower limb biomechanical variables

Anthropometric measures have previously been widely assessed with regard to risk of tibial stress fracture, metatarsal stress fracture and ankle inversion injury in military populations (Beck et al., 1996; Blacker et al., 2008; Davey, 2013; Davey et al., 2011; Giladi, Milgrom, & Stein, 1985; Jones et al., 1993a; Kaufman, et al., 1999; Korpelainen, et al., 2001; Simkin, et al., 1989; Warden, Burr, & Brukner, 2006). Dynamic kinematic and plantar pressure gait characteristics have also been associated with occurrence of these injuries (Dixon, Creaby, & Allsopp, 2006; Willems, et al., 2005; Willems, et al., 2006; Willems, et al., 2007), although there is less military-specific evidence. A large proportion of existing studies researching this area have used retrospective or cross-sectional study designs, meaning that causality cannot be determined. Additionally, existing studies have often considered a range of injuries, rather than focusing on one individual injury, which impairs the understanding of injury-specific mechanisms. This is particularly the case in the study of metatarsal stress fractures, where all metatarsal stress fractures are considered as one injury, rather than isolating each of the five metatarsals independently (Dixon et al., 2006). Anthropometric variables which are consistently associated with military training injuries may be useful in informing entry criteria for intake of recruits to military training programmes. The same can be said for biomechanical variables, although they are more difficult to measure. An understanding of biomechanical variables associated with injury development can provide insight into the mechanisms by which these injuries occur (Bahr & Krosshaug, 2005). Any variables associated with injury occurrence can be used to

identify recruits who may benefit most from intervention strategies. The following sections evaluate literature which has identified anthropometric or biomechanical variables associated with tibial stress fracture, metatarsal stress fracture or ankle inversion injury.

As discussed, it is important to consider injury sites independently in order to identify mechanisms for their development. However, as much of the existing literature has identified variables associated with overall lower limb injury occurrence or overall lower limb stress fracture occurrence, these have been included in this review of the literature. A low body mass index (BMI) has been associated with overall injury risk in three different military populations, with increased risk reported in recruits with a BMI below values of 23 kg.m^{-2} (Blacker, et al., 2008), 22.1 kg.m^{-2} (Jones, et al., 1993a) and 21 kg.m^{-2} (Davey, et al., 2011), with the latter reported from a population of Royal Marine recruits. Two of these studies (Davey, et al., 2011; Jones, et al., 1993a) also identified a high BMI (above 28 kg.m^{-2} (Davey, et al., 2011)) and 26.5 kg.m^{-2} (Jones, et al., 1993a)) as risk factors for injury. A low body mass ($< 65 \text{ kg}$) has been identified as a risk factor for lower limb stress fractures in a prospective study of 545 Royal Marine recruits (Davey, 2013). Similarly, a prospective study of 626 United States Marine Corps reported a lower body mass in recruits who sustained stress fractures (67.3 kg) compared with those who remained injury-free (75.4 kg , (Beck, et al., 1996)). Both studies reported a stress fracture incidence of approximately 4-5%. A low BMI and body mass are thought to be associated with increased injury risk in military populations due to the frequent load carriage activities which take place throughout military training programmes (Beck, et al., 1996; Blacker, et al., 2008). These load carriage activities typically require a pre-determined, absolute load to be carried, rather than a load relative to body mass. Recruits with a smaller body mass will be under greater physical stress when carrying a given load than those with a greater body mass. Increased training demand has previously been associated with increased injury risk (Jones et al., 1994). A smaller thigh girth has been identified in recruits who sustain a lower limb stress fracture compared with those who remain injury-free in these same prospective studies (Beck, et al., 1996; Davey, 2013),

with a small calf girth additionally identified amongst the United States Marine Corps.

Arch height has been investigated in the assessment of risk factors for stress fracture (Warden, Burr, & Brukner, 2006). Currently, evidence is limited and conflicting, with both a high arch (Giladi, Milgrom, & Stein, 1985; Kaufman, et al., 1999; Korpelainen, et al., 2001), and a low arch (Kaufman, et al., 1999) cited as risk factors for lower limb stress fracture. Few studies have considered arch height in relation to site-specific stress fractures which may explain these conflicting findings. It is likely that mechanisms for the development of tibial stress fractures differ from those for metatarsal stress fractures. Forefoot varus, which is a structural foot abnormality in which the forefoot is inverted relative to the rearfoot, has been associated with lower limb stress fracture (Hughes, 1985; Korpelainen, et al., 2001). However, these studies considered non-military, athletic populations and did not focus on individual injuries.

2.2.1 Tibial stress fractures

Limited research has focused on variables associated exclusively with tibial stress fractures. In a prospective study of 295 military recruits, a smaller medio-lateral tibia width was reported in those who sustained tibial stress fractures than those who remained injury-free (Giladi et al., 1987). There was no difference in antero-posterior tibia width between groups. This study had an unusually high stress fracture incidence of 31% which was likely influenced by the method of diagnosis. All volunteer recruits in this study were interviewed about lower leg pain prior to examination by radiograph or scintigram, increasing the likelihood of diagnosis. It was also likely influenced by the fact that the data are from a national service military population, and as such selection criteria may differ from many other military populations.

Willems et al, (2006; 2007) in prospective studies of 400 physically active adults, reported that lower fifth metatarsal loading and greater rotation of the tibia relative to the foot during barefoot and shod running stance were associated with increased risk of overuse shin injuries. Additionally, later peak eversion and lower

impulse under the lateral heel were observed during shod running (Willems, et al., 2007) and greater peak eversion, eversion range of motion, and eversion velocity were observed during barefoot running (Willems, et al., 2006) in those who went on to sustain overuse shin injuries compared with those who remained injury-free. The mechanisms for development of overuse shin injuries are believed to be similar to the mechanisms by which tibial stress fractures develop, as bone stress reportedly develops gradually on a continuum that can result in stress fracture (Roub et al., 1979). Willems et al. (2006) suggested that as the foot everts, the tibia internally rotates at the knee, increasing tibial torsion. Bones are reportedly more susceptible to fatigue failure under torsion compared with compression (Taylor et al., 2003) and high torsional stress has previously been associated with military stress fracture, although this was not measured directly, or related to incidence (Beck et al., 2000). Therefore greater eversion and tibial rotation may increase risk of this injury. However, an alternative theory is that excessive eversion may increase internal inversion moments, which may increase tibial traction, as the major invertor muscles originate on the tibia (Willems, et al., 2006). This could result in shin pain which is not a bone stress injury. This is the only known prospective study to identify dynamic, biomechanical variables associated with overuse shin injury, and it is not clear whether these characteristics are also associated with tibial stress fracture development.

2.2.2 Metatarsal stress fractures

As with tibial stress fractures, there is limited evidence evaluating characteristics associated with metatarsal stress fractures, independent of other lower limb injuries. Both a high arch and a low arch have been identified as risk factors for lower limb stress fracture as discussed, but these studies grouped lower limb stress fractures together. However, a low arch was associated with metatarsal stress fracture, in a prospective study which considered this injury independently (Simkin, et al., 1989). A lower-arched foot is reportedly more flexible than a higher-arched foot, resulting in absorption of stress by the musculoskeletal structures in the foot (Warden, Burr, & Brukner, 2006). This may make it more susceptible to

fatigue than a higher-arched foot as it is less stable during stance, and greater muscular activity may be required, particularly at push-off (Bennell et al., 1999).

A retrospective study of ten Royal Marine recruits who had sustained a third metatarsal stress fracture during training, and ten injury-free recruits matched for body-mass and time spent in recruit training reported no association between forefoot varus angle and third metatarsal stress fracture occurrence (Dixon et al., 2006). This was in contrast to existing findings associating forefoot varus with lower limb stress fracture occurrence (Hughes, 1985; Korpelainen, et al., 2001). The retrospective study of Royal Marine recruits also considered dynamic biomechanical variables in association with metatarsal stress fractures. Kinematic variables were assessed during barefoot running and running in military boots at $3.6 \text{ m}\cdot\text{s}^{-1}$. Dynamic ankle dorsi-plantar flexion and subtalar eversion variables were compared between groups. Those who had previously sustained a metatarsal stress fracture demonstrated an earlier peak eversion during both shod and barefoot running. It was suggested that this was evidence of a greater time spent in the propulsion phase of stance, during which time the metatarsal heads are loaded. This is the only known study to have assessed dynamic, biomechanical gait characteristics associated with metatarsal stress fracture. However, the retrospective study design means that causality cannot be determined and these differences in gait characteristics may be the result of having previously sustained a metatarsal stress fracture.

2.2.3 Ankle inversion injuries

Certain anthropometric characteristics have been associated with ankle inversion injury. A larger calf girth as well as a greater body mass were associated with this injury in a study of 390 male Israeli military recruits (Milgrom, et al., 1991). However, corrected calf girth was not considered, and calf girth may have been associated with body mass. A greater foot width has previously been associated with increased risk of ankle inversion injury in athletic populations (Beynnon, Murphy, & Alosa, 2002). It remains unclear why greater anthropometric characteristics may be associated with ankle inversion injury. The study of Israeli military recruits reported an ankle inversion injury incidence of 18% during training

(Milgrom, et al., 1991), considerably higher than the 7.4% reported during Royal Marine recruit training (Munnock, 2008)). The 18% incidence was also reported from a national service military population, and the difference in incidence of this injury between this population and the Royal Marine recruit population highlights the need for population-specific research.

Dynamic biomechanical assessment has also identified variables associated with ankle inversion injuries in a non-military, active population. Willems et al. (2005) conducted a prospective study of 223 physically active adults in order to identify plantar pressure and kinematic variables during barefoot running, associated with ankle inversion injury. Twenty-one participants sustained this injury and these participants displayed a longer ground contact time, greater absolute impulse under the first metatarsal, and lower relative impulse under the fifth metatarsal than those who remained injury-free. There were no significant differences in subtalar joint kinematic variables between groups although greater eversion excursion ($p = 0.063$) and later peak eversion ($p = 0.054$) were reported in those who sustained an ankle inversion injury.

2.2.4 Challenges of injury-related research

The success of using plantar pressure and three-dimensional (3D) kinematic data to identify risk factors for injuries is questionable. Barefoot plantar pressure measurements have been successfully used to categorise military recruits as being at high, medium or low risk of sustaining an overuse injury at the start of training (Franklyn-Miller et al., 2014). Those who had been identified as being at high risk were more likely to sustain an injury than those in the medium or low risk groups. However, mechanisms for injury development remain unclear, making it difficult to intervene. The problem remains that large participant numbers are required in prospective studies to ensure that sufficient injuries occur to be able to identify characteristic differences. This is influenced by the requirement to assess different injuries independently. There are few existing prospective studies which have collected kinematic data from large populations, which may be partly due to the time-consuming process of collecting such data, and the expertise and expensive

equipment required. Plantar pressure data are relatively time-efficient to collect and analyse in comparison to kinematic data, allowing for large numbers of participants to be included in studies. However, plantar pressure systems do not measure movement, and there is a tendency to infer information about movement from the reported data which may be misleading. In order to identify biomechanical risk factors for individual injuries, large prospective studies involving synchronised plantar pressure and 3D kinematic data collection would be beneficial.

2.3 Military training

It is well established that military training programmes have high rates of lower limb injury occurrence (Almeida, et al., 1999; Chan, et al., 1993; Heir & Glomsaker, 1996; Jones, et al., 1993b; Wood, et al., 2014), and this is likely related to the nature of military training. Training must be designed to elicit beneficial adaptations, which can be achieved through physiological stress above normal levels, according to the overload principle (Dick, 2007; Steinhaus, 1933). In order to physiologically stress the body, training variables such as intensity, frequency and duration can be increased (Clark, 2009). However, an increase in any of these variables has been independently and directly associated with increased risk of injury (Jones, Cowan, & Knapik, 1994). Within Royal Marine recruit training, the physical demands of the training can be influenced by altering activity duration, distance covered, time permitted to cover a distance, total load carried, training frequency, recovery time, or by combining a number of these factors. High volumes of weight-bearing activity (Almeida, et al., 1999; Pope, 1999) and sudden increases in training volume (Bullock et al., 2010) have been associated with increased injury risk in military populations. Insufficient recovery time has also been implicated (Kibler et al., 1992). Within the Royal Marine recruit population, training variables, as well as numerous other extrinsic variables, such as footwear and diet, are kept relatively constant between recruits. This suggests that other differences which predispose to injury development may exist between recruits. Gait changes during or following a training activity may differ between recruits, and this may be a mechanism for injury development. There exists a wealth of evidence outlining known walking gait changes as an acute effect of carrying load (Harman, 2000;

Kinoshita, 1985; Quesada et al., 2000; Wang et al., 2013) but minimal evidence identifying gait changes as a result of the degrading effects of completing a prolonged load carriage activity. These are independently evaluated in the following two sections.

2.3.1 Influence of additional load

Load carriage activities are a key component of the Royal Marine recruit training programme, as the ability to complete these activities is fundamental to a deployed Royal Marine. Load carriage activities have previously been associated with lower limb injury occurrence in military populations (Birrell, Hooper, & Haslam, 2007; Knapik, et al., 1992; Orr, et al., 2014). Mechanisms which may explain these associations have been investigated (Harman, 2000; Kinoshita, 1985; Quesada, et al., 2000; Wang, et al., 2013). Harman (2000) found that during walking ($1.1 \text{ m}\cdot\text{s}^{-1}$ - $1.5 \text{ m}\cdot\text{s}^{-1}$), with increasing backpack loads (6 kg, 20 kg, 33 kg and 47 kg), US Army members demonstrated a lowering of their body centre of mass, through increased knee flexion during initial stance. Similarly, in non-military populations walking with additional load elicited an increase in ankle dorsiflexion (Kinoshita, 1985) and knee flexion angle (Kinoshita, 1985; Wang, et al., 2013). During forward locomotion, the ankle plantar flexor and knee extensor muscles are key contributors to sagittal plane motion (Kepple et al., 1997). This may partly explain why increased internal plantar flexor, knee extensor and hip flexor moments have been observed during load carriage activity in military populations (Harman, 2000; Quesada, et al., 2000). Muscles are important contributors of force to joint moments (Robertson et al., 2013) and this may explain the increased quadriceps and gastrocnemius muscle activity observed with increased load (Harman, 2000).

Carrying increasing loads of military equipment (up to 21.1 kg) during treadmill walking has been reported to result in increased electromyographic (EMG) activity of the tibialis anterior, peroneus longus, medial and lateral gastrocnemius, biceps femoris and rectus femoris muscles (Lindner et al., 2012). These increases were observed when carrying up to 17.5 kg in a backpack, with negligible further increase reported with additional load beyond 17.5 kg. The techniques used to measure muscle activity may have been insufficiently sensitive to identify further

changes. Increased muscle activity indicates that walking whilst carrying a load is more physically demanding than unloaded walking and this may increase injury risk. This study did not examine the influence of completing a prolonged weight-bearing activity whilst carrying these loads on muscle activity.

An in vivo study of metatarsal strain during load carriage, and following a load carriage activity, provides a useful understanding of why such activities may increase metatarsal stress fracture risk (Arndt et al., 2002). A strain-gauge staple technique was used in this study of eight male participants, which found increased peak compression in the second metatarsal when carrying a 20 kg backpack compared with no additional load. Increased second metatarsal compression was also reported following a load carriage treadmill walking activity (maximum of one hour) at 3.0 km.h^{-1} (0.8 m.s^{-1}), compared with pre-activity. These latter compression measurements were recorded during walking without the backpack, indicating that the increases in compression were the effects of completing the load carriage activity, independent of the changes observed when carrying the load.

Fatigue damage is known to accumulate more rapidly when bone is under compression than under tension (Carter et al., 1981). Although this is a clear mechanism for the development of a metatarsal stress fracture, it does not explain why many military recruits complete a training programme injury-free, whilst others develop metatarsal stress fractures. By identifying biomechanical changes that occur during load carriage and following a load carriage activity, understanding of the mechanisms for injury development may be improved. This information could help to identify recruits at greater risk of injury, ultimately allowing effective interventions to be developed.

In summary, gait changes during walking with additional load compared with unloaded walking have been identified but it remains unclear how gait changes which result from the completion of prolonged load carriage activities influence lower limb injury risk. There is strong evidence to suggest altered sagittal plane mechanics when carrying load. Further understanding of biomechanical changes as a result of completing a prolonged load carriage activity may provide an insight

into the mechanical degradation that occurs, and this may help to explain mechanisms for injury development.

2.3.2 Influence of completing a prolonged weight-bearing activity

Altered plantar loading following prolonged weight-bearing activities has been widely assessed, predominantly in populations with relatively high metatarsal stress fracture occurrence. Five studies reported reduced vertical loading under the toes following prolonged walking or running (Bisiaux & Moretto, 2008; Escamilla-Martínez et al., 2013; Nagel et al., 2008; Stolwijk et al., 2010; Willems et al., 2012). Increased loading under the metatarsals was reported following an exhaustive run above anaerobic threshold (Weist et al., 2004), a 60-minute run at $3.3 \text{ m}\cdot\text{s}^{-1}$ (Escamilla-Martínez, et al., 2013), a 20 km run (Willems, De Ridder, & Roosen, 2012), and a marathon (Nagel, et al., 2008). Increased loading under the medial heel was additionally observed in three of these studies (those of shortest duration) (Escamilla-Martínez, et al., 2013; Weist, Eils, & Rosenbaum, 2004; Willems, De Ridder, & Roosen, 2012). Stolwijk et al (2010) assessed the influence of five consecutive days of walking (total distance - females: 161.5 km; males: 199.8 km) on plantar loading in 54 participants. Following one day of walking (40-50km) there was increased metatarsal and heel loading, consistent with the previously discussed evidence (Escamilla-Martínez, et al., 2013; Weist, Eils, & Rosenbaum, 2004; Willems, De Ridder, & Roosen, 2012). After four more consecutive days of walking there was a further increase in heel loading, but a reduction in loading under the metatarsals. 88% of participants reported foot pain, 26% of which was blister-related pain, and 22% forefoot pain. Shifting the load to the heel may therefore be a mechanism of pain avoidance. This prolonged, repeated walking activity may be more relevant to the Royal Marine recruit population than activities of shorter duration. The fact that both an increase and a decrease in loading under the metatarsals have been reported following prolonged, weight-bearing activity reinforces the need for the assessment of gait changes as a result of Royal Marine-specific activities. Plantar pressure changes following completion of a prolonged weight-bearing activity in which load is carried have not been assessed.

Although the influence of carrying load on kinematics and kinetics has been investigated, the fatiguing effects of completing a military load carriage activity on lower limb mechanics remain unclear. A reduction in internal knee extensor moments has been reported following 40 minutes of treadmill marching whilst carrying load (Quesada, et al., 2000). Royal Marine recruits complete regular load carriage activities of considerably greater duration than this. This mechanism is therefore likely to be relevant to Royal Marine recruits, and requires further investigation in relation to injury. Plantar flexor (gastrocnemius lateralis and peroneus longus) muscle fatigue has been reported following marching for 2 km without additional load (Gefen, 2002). Plantar flexor muscle fatigue may result in a reduced ability of the muscles to minimise tensile bone strain (Milgrom et al., 2007), increasing the risk of tibial and metatarsal stress fracture (Arndt, et al., 2002; Milgrom, et al., 2007; Sharkey et al., 1995) . Furthermore, the peroneus longus muscle is both a plantar flexor and subtalar evertor, thus as an evertor it plays a role in preventing ankle inversion injuries (Gefen, 2002), which are prevalent amongst Royal Marine recruits (Munnoch, 2008). The ability to prevent this injury may be reduced with fatigue. The existing evidence suggests that gait changes are likely to occur amongst military recruits following a prolonged load carriage activity. Such changes may be influential in injury development.

2.4 Summary of literature review

In order to reduce injury incidence, an understanding of firstly the risk factors and secondly the mechanisms for each individual injury must be established. A major limitation of the assessment of variables associated with injury risk in existing literature is the use of retrospective and cross-sectional study design. Prospective study is required to determine causality, enabling identification of risk factors for injury.

Although there exists evidence to explain the influence of load carriage and of prolonged weight-bearing activity on gait, their association with injury development remains unclear. Furthermore, there is only limited understanding of the mechanical changes which result following completion of a prolonged load carriage activity. Identification of mechanical changes following a real-life training activity

would improve the understanding of mechanisms for injury development by helping to explain why certain characteristics predispose an individual to injury occurrence. If such characteristics are identified and mechanisms understood, interventions to reduce injury occurrence can be introduced.

2.5 Aims

The aims of this thesis which are outlined in Figure 2.1 were to:

- 1) Prospectively identify biomechanical and anthropometric risk factors for tibial stress fractures, metatarsal stress fractures, and ankle inversion injuries within Royal Marine recruits.
- 2) Conduct a review of the Royal Marine recruit training programme in order to identify training variables and activities associated with injury occurrence.
- 3) Assess the influence of a Royal Marine recruit training activity on lower limb mechanics in order to further understand mechanisms for injury.

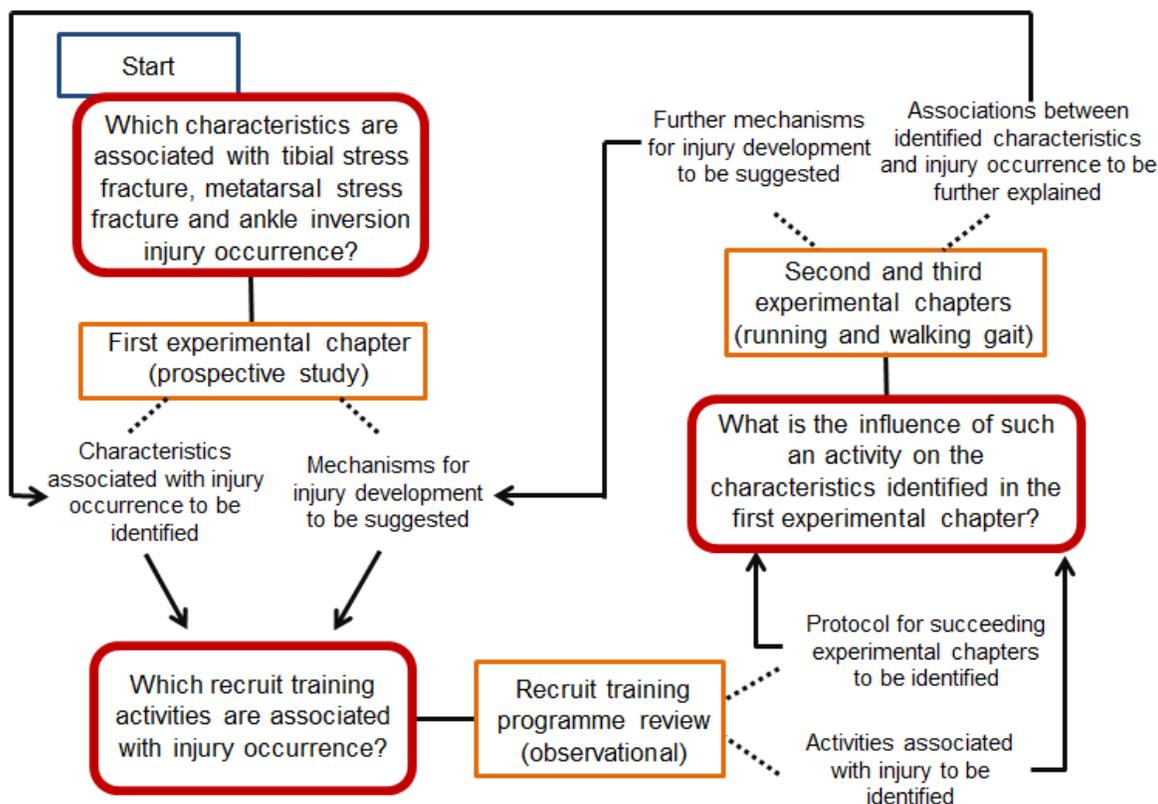


Figure 2.1: Schematic of the research questions addressed in this thesis

CHAPTER 3: General Methods

The methods used to collect data for the three experimental studies (Chapters 4, 6 and 7) are described in detail in this section. A brief overview of the methods in context is also provided within each chapter reporting the experimental studies.

3.1 Participants

This thesis includes three experimental chapters (Chapters 4, 6 and 7) that involved a total of 1137 volunteer Royal Marine recruits. Data collection took place between September 2010 and December 2013 inclusive. All experimental investigations were approved by the Ministry of Defence Research Ethics Committee (MODREC) (Appendices A and B). Recruits were briefed prior to volunteering to participate in a study, and it was emphasised that participation was entirely voluntary. All volunteer recruits provided informed consent prior to commencing the study. Only those investigators named on the MODREC approved protocol and involved in data collection had access to recruit data, which were anonymised. Additional consent was received from a number of recruits allowing photographs to be taken during data collection. All recruit photographs used throughout this thesis have been taken with the consent of those involved.

As a consequence of evidence-based Royal Marine selection procedures, all Royal Marine recruits are aged 16-33 years, height > 151.5 cm, body mass > 65 kg, and must have completed a number of fitness tests prior to entry, including aerobic running tests. Chapter 4 involved recruits who were in their second week of the 32-week recruit training programme and Chapters 6 and 7 involved recruits in week-21 of the programme. All recruits were injury-free at the time of data collection and had not been removed from training for any reason prior to data collection. A number of recruits are excluded from training as a result of injury or for other medical or professional reasons throughout the programme. Although this limited the number of recruits available for data collection, very few had been excluded for the study in Chapter 4, as it occurred in week-2 of training. It is unknown how many recruits had been excluded from training at the time of data collection for Chapters 6 and 7 (week-21) of training. Eight recruits were requested from each troop for

these studies, and only recruits who had not been removed from training were invited. It was also requested that recruits had not sustained a major lower limb injury in the previous five years, but this was self-declared. Recruits for the study in Chapter 4 were asked to complete a Health History Questionnaire (Appendix C), including detail about previous lower limb injuries. Recruits were familiarised with all biomechanical procedures prior to data collection, in a relaxed environment, with no limit to the number of familiarisation trials permitted per recruit.

3.2 Injury data

Chapter 4 identified anthropometric and biomechanical gait characteristics that differed between recruits who sustained a particular injury, and those who completed training injury-free. This required prospective follow-up to allow the collection of injury data throughout the 32-week training programme. The injuries included were those that were sustained during training, which required a recruit to be removed from the training programme to undergo rehabilitation. Each case was examined and diagnosed initially by the Commando Training Centre Medical Centre and then by the Physiotherapy Department, who were able to provide investigators with anonymised, detailed information about lower limb injuries sustained by any recruit who had consented to participate in the study in Chapter 4. The information obtained included the injury site, week of training in which it occurred, the activity during which it occurred (where applicable), and whether it was a recurrence of a previous injury.

3.3 Anthropometric data

Height and body mass were recorded in all three experimental studies, and further anthropometric measures were required for Chapter 4. All anthropometric measures were taken by a trained investigator following procedures outlined by the International Society for the Advancement of Kinanthropometry (Olds et al., 2006). Anthropometric measures were taken with recruits wearing shorts and t-shirt, without footwear. Body mass (kg) was recorded using scales (Sartorius AG, Goettingen, Germany) and reported to the nearest 0.1 kg. Height (cm) was measured using a stadiometer (Seca 202, Seca, Hamburg, Germany) to the

nearest centimetre. Body mass index (BMI, $\text{kg}\cdot\text{m}^{-2}$) was calculated by dividing body mass (kg) by height (m) squared. Calf girth (cm) was measured at the site of maximum circumference using a retractable tape measure (Rabone, Chesterman, England) to the nearest 1 mm. Calf skinfold (mm) was taken from the height of maximum calf circumference at the medial aspect of the calf (Figure 3.1) using Harpenden callipers (BodyCare, UK) and measured to the nearest 0.2 mm. Three skinfold measurements were taken per leg, with sufficient time between to allow adipose tissue to return to its natural state (Olds, et al., 2006). The mean skinfold value was reported. Corrected calf girth (mm) was the calf skinfold value subtracted from the calf girth value, to provide an indication of calf muscle mass (Martin et al., 1990). Bimalleolar breadth (cm) was the distance between the lateral and medial ankle malleoli, measured using a Holtain small sliding breadth calliper (Holtain Ltd, Crymych, UK) to the nearest millimetre. Lower limb anthropometric measures were taken from both the left and right legs for Chapter 4. Where possible, the same investigator recorded anthropometric measures, but there were exceptions due to the large number of recruits involved in Chapter 4. Existing literature has reported suitable intra- and inter-observer reliability for body mass (McDowell, 2008), height (McDowell, 2008), bimalleolar breadth (Ahmed, 2013) calf girth (Haniff et al., 2008; McDowell, 2008), and calf skinfold (Knechtle et al., 2014). Coefficients of variation indicated that anthropometric standard deviations were within 10% of the mean (Appendix D).



Figure 3.1: Calf skinfold measurement

3.4 Biomechanical data

The equipment used to collect dynamic data throughout this thesis is outlined in this section. Dynamic variables included plantar pressure, kinematic, kinetic and electromyographic (EMG) data. Reliability has been assessed throughout with intraclass correlation coefficients (ICC) calculated using a single measures, two-way random effects model. Values were classified as fair ($0.4 < ICC \leq 0.6$), good ($0.6 < ICC \leq 0.8$), or excellent ($0.8 < ICC \leq 1$) (Landis & Koch, 1977) .

3.4.1 Running protocol

The studies in chapters 4 and 6 involved barefoot running at $3.6 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$), the speed which best represents recruits' training speed (Creaby & Dixon, 2008). This speed has previously been used to successfully identify kinematic differences between Royal Marine recruits who sustained third metatarsal stress fractures and those with no history of stress fracture (Dixon et al., 2006). Speed was monitored using timing gates (Chapter 4: system created by Len Maurer, University of Exeter, UK, Chapters 6 and 7: Brower, Utah, USA). Barefoot rather than shod running trials were conducted as the study aimed to identify gait characteristics of each recruit, and footwear may have a confounding effect on these characteristics (McNair & Marshall, 1994). Data for the prospective study (Chapter 4) were collected at the start of training where recruits may have been unaccustomed to the military footwear provided. On the other hand, the effects of military footwear on gait may play an important role in injury development (Sinclair & Taylor, 2014). Due to the time constraints and demand on recruits, it was not possible to collect both shod and barefoot data in any of the three experimental studies. It has been reported that variables associated with lower limb injury can be identified using both barefoot and shod protocols, but with characteristics more pronounced during barefoot conditions (Willems, et al., 2007). This supports the use of barefoot rather than shod running trials to identify gait characteristics. Synchronised plantar pressure and kinematic data were collected during running trials.

3.4.2 Walking protocol

Chapter 7 assessed walking at $1.4 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$). This speed represented the speed of the prolonged load carriage activity undertaken by the recruits, which was the exercise protocol for this study. Recruits wore military boots during this training activity, therefore boots were also worn during walking trials to simulate conditions of the activity. Synchronised kinematic, kinetic and EMG data were collected during walking trials.

3.4.3 Plantar pressure data

Pressure data were collected in Chapters 4 and 6 using a 2 m pressure plate (RSscan International, Belgium, 4 x 0.5 m x 0.4 m, 4096 sensors) positioned and marked in the middle of a 10 m EVA runway. EVA material was selected for the runway as it is often used in the midsole of footwear (Wang et al., 2012). Data for Chapter 4 were collected at 200 Hz, and for Chapter 6 at 125 Hz following assessment of the data quality in Chapter 4.

3.4.4 Plantar pressure analysis

The Footscan (RSscan International, Version 7) pressure software divides the foot automatically into zones that represent the hallux, lesser toes, five metatarsals, midfoot and the medial and lateral heel (Figure 3.2). The software additionally divides the foot into rearfoot, midfoot and forefoot regions to provide values of contact percentage and impulse relative to those of the entire foot. The rearfoot region includes the medial and lateral heel zones, the midfoot region is the area under the midfoot zone, and the forefoot regions include the hallux, lesser toe and metatarsal zones. Peak pressure, impulse and time of peak pressure can be obtained for each zone and region. Ground contact time and time of heel-off (when the heel zones first lose contact with the ground) can also be obtained. Due to the association between ground reaction force and body weight (Mullineaux et al., 2006), and reported associations between increased body mass and peak pressures (Arnold et al., 2010), pressure variables were correlated with recruit body weight throughout this thesis, in order to determine whether any association existed. Bivariate correlation analyses were conducted between peak pressure and

impulse for each zone, and body weight. Where an association existed ($r > 0.5$) this variable would be normalised to body weight, whereas absolute pressure values were used where there was no association. The mean relative variability of the selected pressure variables was 28%, which is considerably higher than the mean relative variability of the anthropometric measures (6%) but similar to the relative variability of other dynamic measures used in this thesis (Appendix D). The relative variability values of peak pressures under the first and third metatarsal, and lateral heel were 36%, 29% and 31% respectively. A similar value of 34% was reported for peak pressure under the first metatarsal using an in-shoe pressure system during walking (Bisiaux & Moretto, 2008), whereas lower values were reported under the third metatarsal (11%) and lateral heel (12%) using the in-shoe system. These differences may be influenced by the different systems used. Temporal variables demonstrated the least variability.

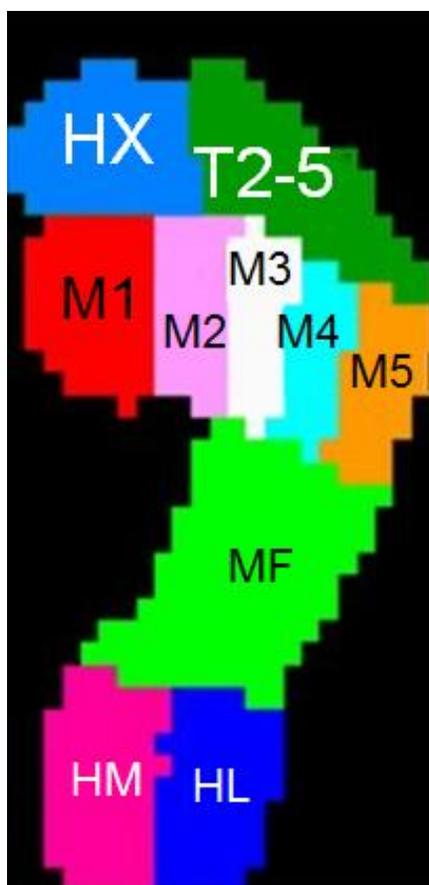


Figure 3.2: Automatically identified zones in RSscan software
HX: hallux; T2-5: less toes; M1-M5: metatarsals 1-5; HM: medial heel; HL: lateral heel

3.4.5 Reliability of pressure data

Throughout this thesis, all zones were manually adjusted by either one (Chapter 6) or two investigators (Chapter 4) to represent each foot zone. The manual adjustments were made in order to ensure that the zones represented the corresponding areas of the foot based on comparisons with the pressure image displayed. The criteria used to adjust the trials are presented in Appendix E. The inter- and intra-observer reliability values of this process for the two investigators involved in manual adjustment for this thesis are presented in Appendix E. There was excellent reliability ($ICC \geq 0.99$) for intra- and inter-observer values of peak pressure and impulse.

Within-recruit reliability of pressure measurements was assessed using five barefoot running trials ($3.6 \text{ m}\cdot\text{s}^{-1}$) from 12 recruits (Appendix F). Reliability of peak pressures ranged from poor (first metatarsal) to excellent (lateral heel). Impulse variables were more reliable than peak pressure variables. Temporal variables demonstrated good or excellent data reliability ($ICC > 0.68$). Contact area and impulse under the rearfoot and forefoot demonstrated excellent reliability ($ICC \geq 0.90$). These differences in reliability across zones/regions are likely to be influenced by the size of the zone/region, where smaller zones are likely to cover a smaller proportion of the area they are purported to represent than the larger zones. Greater reliability ($ICC \geq 0.95$) than presented here has previously been reported during walking using pressure insoles (Godi et al., 2014). However, the reliability was only reported for the whole foot, rather than individual zones, thus this supports the previous suggestion that plantar pressure reliability is likely to be greater when a larger area is being considered. It may be that insole pressure systems provide more repeatable measures than pressure plates, but this cannot be confirmed.

3.4.6 Kinematic data

Kinematic data were collected at 200 Hz using two Coda mpx30 units (CodaMotion, Charnwood Dynamics, UK) and eleven active markers per leg. Bilateral kinematic data were collected in Chapters 4 and 6. Data from only the left

leg were collected for Chapter 7. Unilateral data were collected in Chapter 7 in order to minimise recovery time (by minimising time spent preparing a recruit for data collection), where EMG data were also collected. The left leg was selected based on the quality of kinematic marker tracking during pilot work. The positioning of the Coda units within the data collection site for the study in Chapter 7 likely influenced this quality. Light reflection on panels along one side wall may explain why the quality of data was better on one side than the other. 200 Hz was the maximum frequency available with the marker setup used. Marker locations were determined by palpation and secured using Micropore™ tape (3M, USA) in the positions outlined in Figure 3.3. For Chapters 4 and 6, pressure and kinematic data collection were synchronised using the RSscan system, which provided a digital signal into the Coda acquisition software. The signal changed (low to high) upon recruit contact with the pressure plate (vertical force > 10 N), allowing identification of stance frames.

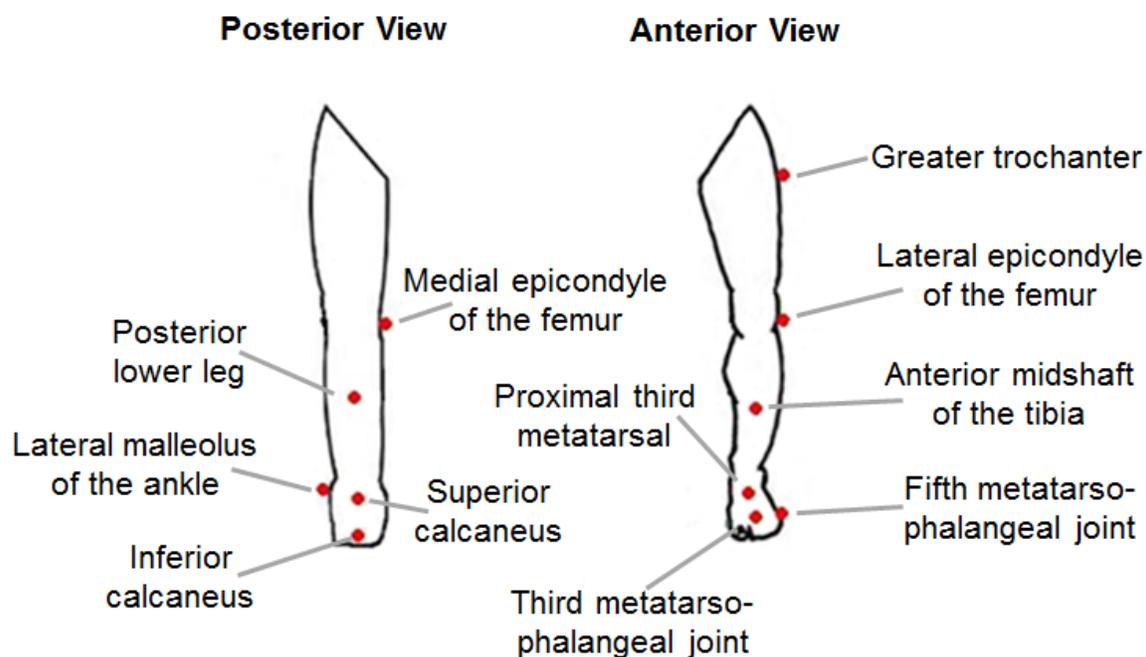


Figure 3.3: Coda Marker positions displayed on the left leg (Figure adapted from Nunns (2014), with permission)

3D joint angles were calculated using a Cartesian joint coordinate system (Grood & Suntay, 1983). The lower limb was considered as three segments (foot, shank and thigh), and three axes about which rotations occur were assigned to each segment. Two of the axes on each segment were fixed to the segment body, and therefore these axes moved with the body. The third axis was perpendicular to the two fixed axes, and was therefore obtained by taking the cross product of the two fixed axes, using the right-hand rule. For the foot, the z-axis was created using markers on the superior and inferior calcaneus. The y-axis was created using markers on the proximal third metatarsal and the superior calcaneus. The markers that created the y-axis were aligned by observation to try to ensure the axis created by these markers was perpendicular to the axis created using the superior and inferior calcaneus markers, which were positioned prior to the positioning of the marker on the third metatarsal. The x-axis was the cross product of the z- and y-axes (Figure 3.4).



Figure 3.4: Axes of the foot segment

A virtual mid-knee marker was created, which was equidistant in all three axes from the medial and lateral epicondyles of the femur. This allowed creation of a virtual mid-ankle marker which had the z-coordinate of the lateral ankle malleolus marker and the x- and y- coordinates of the mid-knee corrected for the difference in x- and y- coordinates between the lateral knee and the lateral malleolus of the

ankle in the global reference frame. The z-axis of the shank for the barefoot running protocol was created using markers on the lateral epicondyle of the femur and the lateral ankle malleolus, and the x-axis was created using the virtual mid-ankle marker and the lateral malleolus marker. The y-axis was the cross product of the x- and z-axes (Figure 3.5).



Figure 3.5: Axes of the shank segment (running protocol)

The shank segment was defined differently for the walking protocol in Chapter 7. A z-axis was defined in the same way as the barefoot protocol (lateral femur epicondyle and lateral ankle malleolus markers) and a y-axis was created using markers on the anterior midshaft of the tibia and posterior lower leg (Figure 3.6). The x-axis was the cross product of the z- and y-axes. The axes used during barefoot running to define the shank were not used during shod walking as the lateral ankle malleolus was more difficult to accurately locate through the military boot.



Figure 3.6: Axes of the shank segment (walking protocol)

The z-axis of the thigh was created using markers on the greater trochanter and the lateral epicondyle of the femur, and the x-axis was created using markers on the medial and lateral epicondyles of the femur (Figure 3.7). The y-axis was the cross product of the x- and z-axes.



Figure 3.7: Axes of the thigh segment

These axes allowed the calculation of angles in three planes at both the knee and the ankle/subtalar joint. To calculate joint angles between segments, a floating axis was created by taking the cross product of an axis from each of the segments of interest (Grood & Suntay, 1983). For motion of the foot relative to the shank, a floating axis was created using the cross product of the y-axis of the foot and the x-axis of the shank. Motion of the foot relative to the shank included ankle dorsiflexion, subtalar eversion and foot abduction. Ankle dorsiflexion angle was defined as the angle between the floating axis and the y-axis of the shank. Subtalar joint eversion angle was defined as the angle between the floating axis and the x-axis of the foot. Foot abduction was defined as the angle between the y-axis of the foot, and the x-axis of the shank. For motion of the shank relative to the thigh, a floating axis was created using the cross product of the z-axis of the shank, and the x-axis of the thigh. Knee flexion angle was defined as the angle between this floating axis and the z-axis of the shank. For these kinematic variables, angle at touchdown, peak angle, time of peak, range of motion (Figure 3.8) and rate of angular change could be obtained. Positive values were considered to represent ankle dorsiflexion, subtalar joint eversion, foot adduction and knee flexion. Large variability was observed in eversion touchdown angle and therefore peak angle. Consequently only time of peak, range of motion and rate of change were considered.

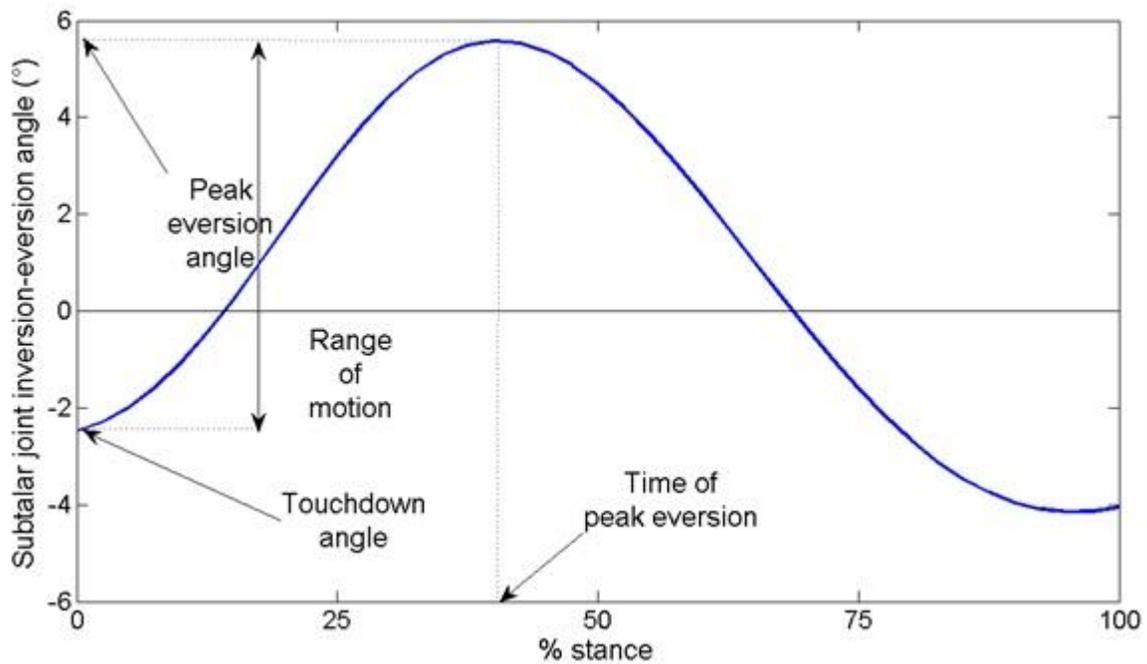


Figure 3.8: Sample subalar inversion-eversion time history during barefoot running (positive = eversion)

Range of motion in most cases was the difference between touchdown and peak angle and the rate of this change was calculated. During both walking and running, plantar flexion occurred prior to ankle dorsiflexion, resulting in two peak values (Figure 3.9). The range of motion and rate of change between touchdown and the first peak, and between the first and second peaks were obtained.

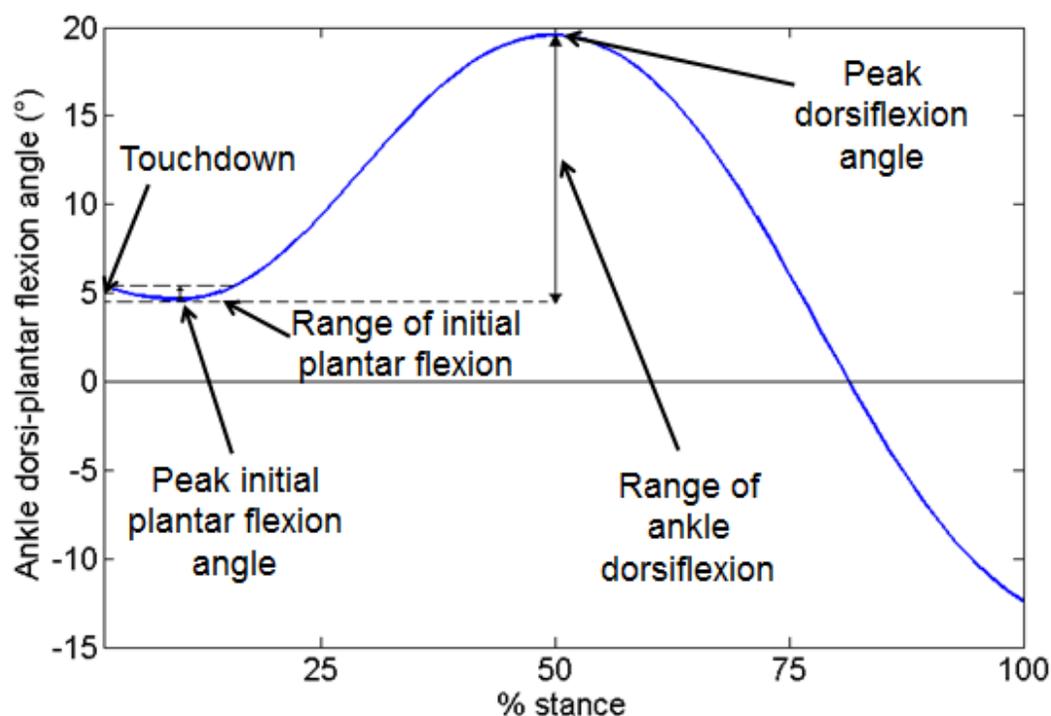


Figure 3.9: Sample ankle plantar-dorsiflexion time history during barefoot running (positive = dorsiflexion)

A standing trial was collected for each recruit, in each data collection session (both pre- and post-activity in Chapters 6 and 7). Recruits stood in a relaxed position, with feet shoulder-width apart. The values obtained allowed adjustment of dynamic joint angles to remove offsets, thus providing anatomically meaningful values. Kinematic data were filtered with a cutoff frequency of 12 Hz, consistent with that used during similar data collection methods (Hardin et al., 2004). All kinematic data were analysed using customised MATLAB scripts (R2012a, The MathWorks Inc. Natick, MA, USA), which were adapted for each study. Kinematics had a relative variability that was similar to other dynamic variables (Appendix D). The temporal variables had lower relative variability than other kinematic variables.

3.4.7 Force data

Force data were collected at 200 Hz using an AMTI (OR6-7-2000, Waterway, MA, USA) force plate, and recorded through the Coda software. The frequency of force data collection was necessarily the same as the frequency of kinematic data collection and therefore was determined by the number of kinematic markers used. Force data were filtered at the same frequency as kinematic data based on existing

recommendations (Bisseling & Hof, 2006). Stance was determined from force data (vertical force > 10 N).

3.4.8 Kinetic data

The relative mass, moments of inertia and location of the centre of mass of each segment were approximated using recruit anthropometric characteristics and regression equations (Shan & Bohn, 2003). 3D joint moments were calculated using an inverse dynamics approach (Zatsiorsky, 2002). All moments discussed throughout this thesis refer to internal, rather than external moments. The joint moment calculation considered the moments of the reaction forces, the segment weights, the acceleration of the segments, and the rate of change of angular momentum. Joint moments were expressed in the local reference frame of the distal segment. Moments could be calculated in three planes about the ankle/subtalar joint and the knee joint. Kinetic data were analysed using customised MATLAB scripts. Peak values were obtained for ankle plantar flexor and knee extensor moments. In the case of the ankle plantar flexor moment, there was an initial dorsiflexor moment prior to a considerably greater plantar flexor moment and the value of both the dorsiflexor and plantar flexor peaks could be obtained. There were two peak knee extensor moments observed during walking and these were independently obtained. All joint moments were normalised to recruit body mass. Relative variability of kinematic variables was similar to those for other dynamic variables (Appendix D).

3.4.9 Data collection setup

The equipment was set up for data collection for the studies in Chapter 4 and 6 as outlined in Figure 3.10. The setup was similar for the study in Chapter 7. In Chapter 7, a force plate (46 cm) replaced the pressure plate, and a longer runway (approximately 15 m) was used, without an EVA surface, as this study involved walking in military boots. The Coda mpx30 units were positioned 2 m from the force plate, and were positioned at an angle of approximately 45° from the line of the direction of walking.

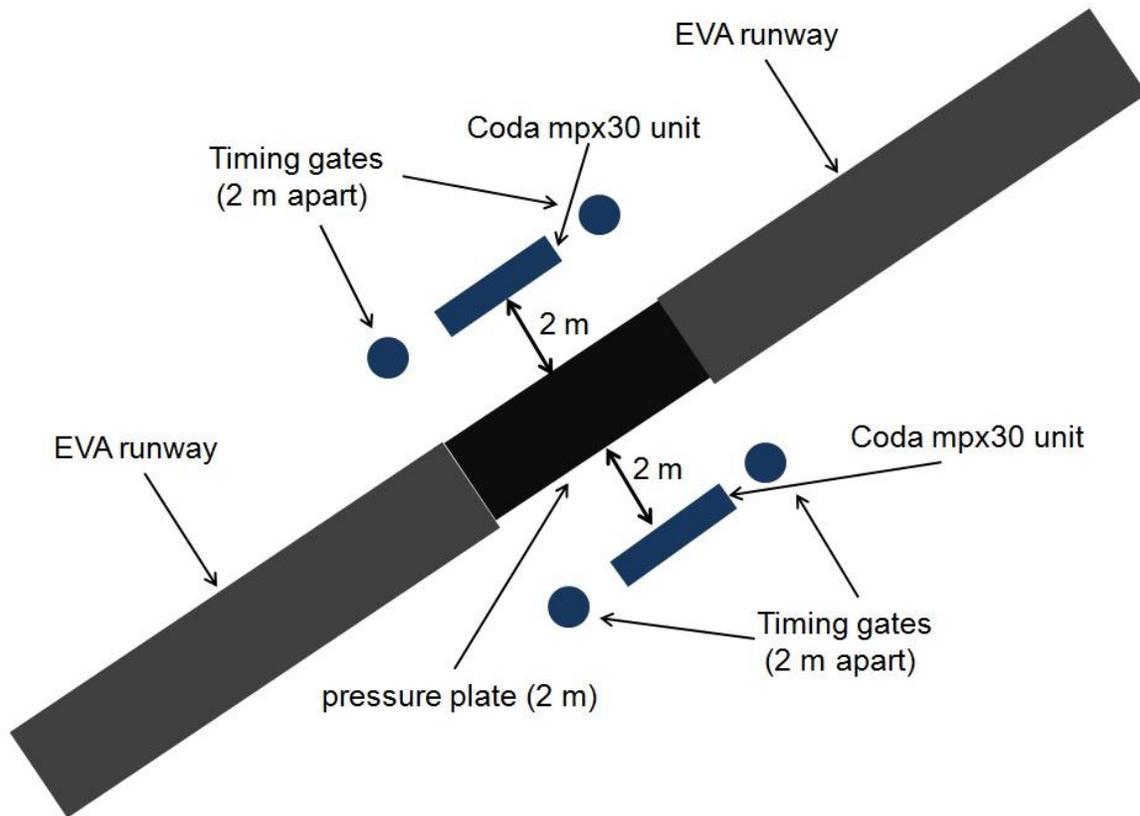


Figure 3.10: Equipment setup for the studies in Chapters 4 and 6

3.4.10 Reliability of 3D kinematics and kinetics

The use of different systems to capture 3D kinematics has been assessed, indicating suitable reliability for assessment of gait for the rotations included in this thesis (McGinley et al., 2009). Kinetic variables were found to be more reliable than kinematic variables when using the coda system (Maynard et al., 2003; Monaghan et al., 2007). Fair to good reliability was found for kinematics during midstance, which was more reliable than at touchdown (Maynard, et al., 2003). This was also the case with kinetic variables, where excellent reliability was reported for knee moments (Maynard, et al., 2003). Reliability was improved with increasing number of repeated trials up to ten (Monaghan, Delahunt, & Caulfield, 2007). Visual comparisons were made between moment time histories obtained within Chapter 7 and those reported in existing literature (Hunt et al., 2001; Umberger & Martin, 2007; Wit & Czaplicki, 2008) where joint moments were collected using differing motion analysis systems and force plates. Similar time histories were observed,

particularly for the ankle plantar flexor moments and this provided confidence in the validity of kinetic data collected for this thesis. The knee extensor moments in Chapter 7 had a second peak of greater magnitude than the first. This has previously been observed (Wit & Czaplicki, 2008), although the difference between peaks was more pronounced in Chapter 7. The difference between studies may be influenced by the mode of walking, the military boots or by differences between biomechanical models.

Within-recruit reliability of kinematic and kinetic data collected using the Coda system and the AMTI force plate for repeat trials, was assessed using data from 17 recruits who had each completed walking trials at $1.4 \text{ m}\cdot\text{s}^{-1}$ (Appendix G). There was excellent ($\text{ICC} \geq 0.92$) reliability for kinetic variables and sagittal plane kinematic variables, and good reliability ($\text{ICC} \geq 0.70$) for frontal plane kinematic variables.

3.4.11 EMG data

EMG data were collected at 4000 Hz during walking trials, using a wireless system (Trigno Wireless System, Delsys, Boston, MA, USA) and five sensors. EMG data collection was synchronised with the collection of kinematic and force data. An analogue signal was sent from the Coda system to the Delsys system so that the recording of five seconds of kinematic, force and EMG data all commenced simultaneously.

The five EMG sensors were positioned on the following left leg muscles, following SENIAM guidelines (Hermens et al., 1999): vastus lateralis (VL), biceps femoris (BF), gastrocnemius lateralis (GL), tibialis anterior (TA), and peroneus longus (PL). These muscles were considered the most important due to their role in walking (VL, GL, PL (Kepple, Siegel, & Stanhope, 1997)), or because they are antagonistic to those muscles which are important in walking (BF, TA). The BF, GL, TA and PL muscles are biarticular, which meant that the correct positioning of a sensor on these muscles could be confirmed using two different actions per muscle (Appendix H). This was not the case with the VL muscle but this muscle is visible

due to its superficial location, particularly in active male populations, and this increased the likelihood of correct sensor positioning.

Each muscle site was prepared prior to adhesion of the sensor following SENIAM guidelines. Prior to cleaning the site with alcohol, abrasive gel was also used, to maximise the cleanliness of the site. The signal quality from each muscle was tested using EMGworks® Acquisition Software (Delsys, Boston, MA, USA). Recruits were asked to complete specific muscle actions while the investigator held the sensor firmly in place (Appendix H). Sensors were secured using purpose-made adhesive interfaces (Biosense Medical Ltd, Essex, UK) and Micropore™ tape (Figure 3.11) and their positions were marked with permanent pen. Signal quality was reassessed following this process.



Figure 3.11: Positioning of EMG sensors on the left leg

EMG data were filtered with a fifth-order Butterworth band-pass filter between 5 and 500 Hz (Rose, 2011) and full-wave rectified, then low-pass filtered at 10 Hz (Konrad, 2006). A sample of a raw signal from the TA muscle during walking prior to a military activity, without carrying load is presented in Figure 3.12. This walking condition is considered to represent the control condition of this study, which also

included trials post-activity and during load carriage. After filtering and full-wave rectification the data were analysed to obtain the required values. EMG variables included maximum amplitude (Figure 3.13), mean and median frequencies and integrated EMG (iEMG) during ground contact. EMG amplitude was included to provide an indication of muscle activity (Konrad, 2006) and/or muscular fatigue (Kallenberg et al., 2007; Merletti et al., 1990). Mean and median frequencies are considered gold standard indicators of fatigue (Phinyomark et al., 2012). Muscular fatigue results in a shift in the frequency spectrum of the signal towards lower frequencies (De Luca, 1984). This shift in the power spectrum is indicative of muscular fatigue (Kallenberg, et al., 2007; Kumar et al., 2002; Merletti, Knaflitz, & De Luca, 1990; Merletti et al., 1991; Naeije & Zorn, 1982; Winter, 2009). This is reportedly associated with decreased intramuscular conduction velocity of the action potentials along the muscle fibres (Merletti et al., 1984) . A greater mean frequency is also indicative of greater force during a muscular contraction (Moritani & Muro, 1987). iEMG was the area under the curve of the filtered, full-wave rectified data, and was calculated using cumulative trapezoidal numerical integration (Smoliga et al., 2010). This variable is measured in $\mu\text{V}\cdot\text{sec}^{-1}$ and provides an indication of muscular activity. Maximum amplitude was normalised to an ensemble averaged mean amplitude value taken from each 5% of stance, during walking trials under the control condition. iEMG values were normalised to the maximum iEMG value of control condition trials. EMG data were analysed using customised MATLAB scripts.

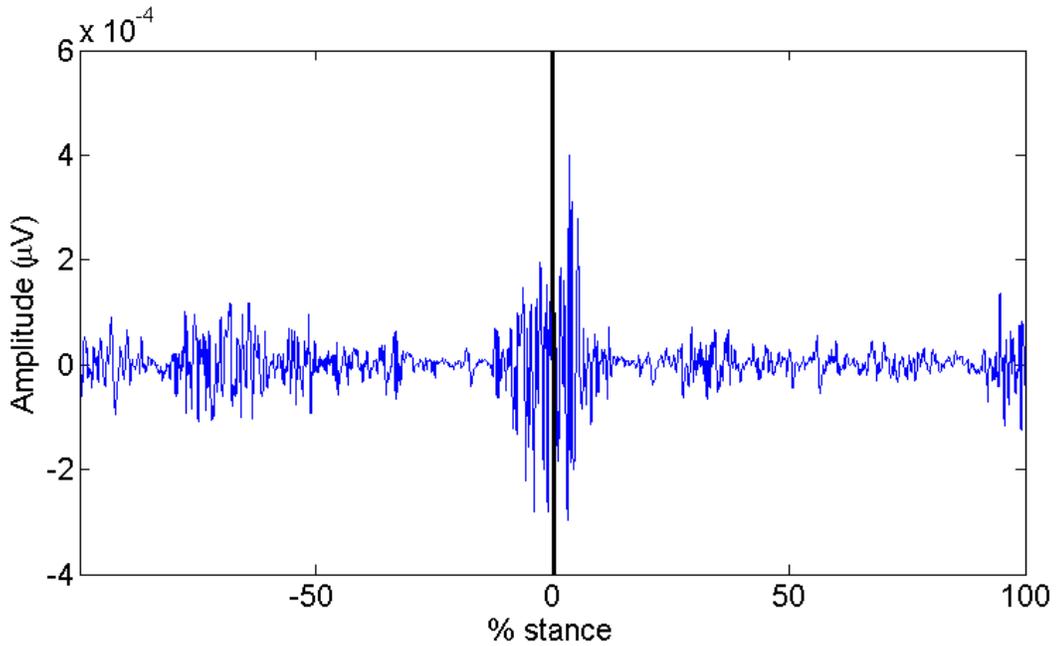


Figure 3.12: Sample raw TA data during walking
 Note: The solid vertical line at 0% stance indicates touchdown

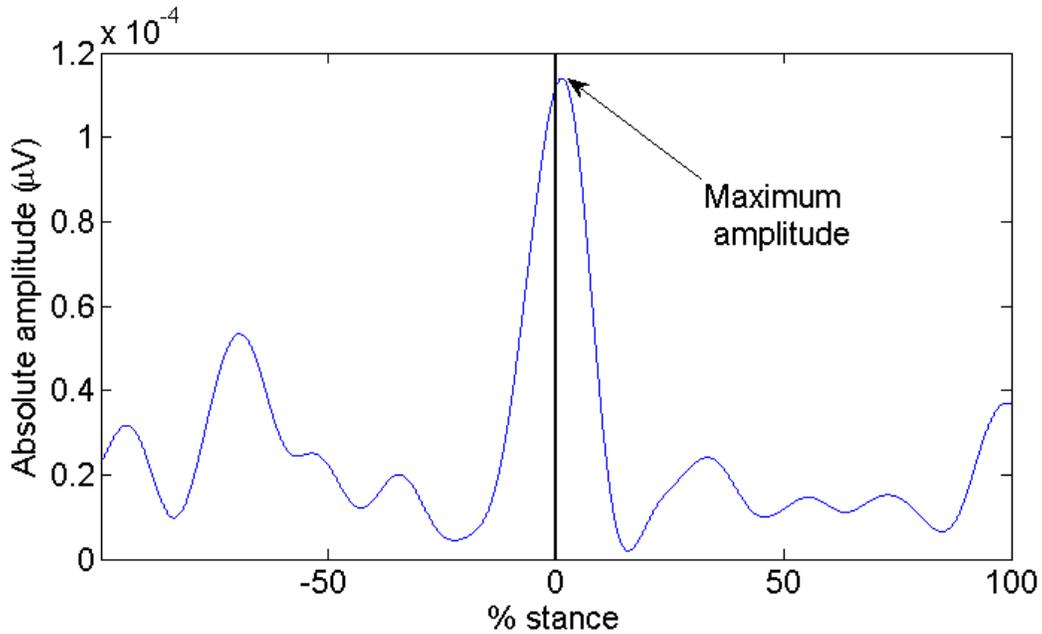


Figure 3.13: Sample filtered and full-wave rectified TA data obtained during walking
 Note: The solid vertical line at 0% stance indicates touchdown

The quality of EMG data collection is heavily influenced by the preparation (Konrad, 2006). Although preparation guidelines were followed (Hermens, et al.,

1999), perspiration could not be prevented and this may have impaired the quality of data collected. Relative variability of EMG data obtained during the control condition was similar to those for other dynamic measures used in this thesis (Appendix D). EMG data were considered to be valid based on comparisons of time histories with existing literature. A sample is presented in Figure 3.14, which displays bursts in muscle activity relative to stance time, similar to those previously reported (Murray et al., 1984).

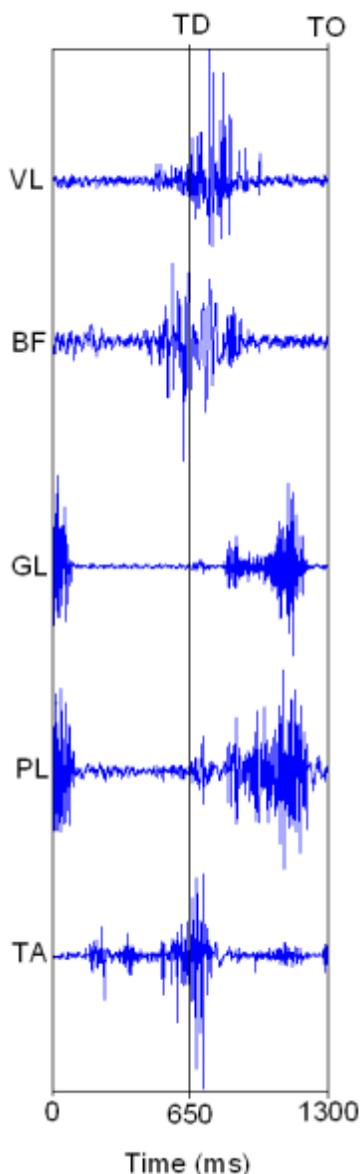


Figure 3.14: Sample raw EMG signal for five lower limb muscles during walking
Note: TD = touchdown, TO = take off, VL = vastus lateralis, BF = biceps femoris,
GL = gastrocnemius lateralis, PL = peroneus longus, TA = tibialis anterior

3.4.12 Reliability of EMG data

Within-participant reliability (Appendix J) was assessed from eight active males. Reliability was assessed within-day (five walking trials) and between days (mean of five trials across two consecutive days). Within-day reliability was good (ICC > 0.7) for all muscles and variables, with the exception of maximum PL amplitude which demonstrated poor reliability. Between-day reliability was poor in the BF and GL muscles. VL amplitude variables demonstrated good between-day reliability (ICC > 0.75) whereas frequency variables demonstrated poor reliability. TA between-day reliability was good (ICC > 0.69) for all variables and PL between-day reliability was good (ICC > 0.7) for all variables except for median frequency which demonstrated fair reliability.

CHAPTER 4: Prospectively identified anthropometric and gait characteristics associated with tibial stress fracture, metatarsal stress fracture, and ankle inversion injury occurrence in Royal Marine recruits

Findings from the study in this chapter have been published in *Gait & Posture* and *Footwear Science* and distributed as an Institute of Naval Medicine Report (see p.14). Further findings have been submitted for publication in an international journal.

4.1 Introduction

The high injury occurrence reported during the Royal Marines recruit training programme reinforces the necessity of research in this area. In particular, the mechanisms by which tibial stress fractures, metatarsal stress fractures and ankle inversion injuries occur during recruit training warrant investigation. Risk factors for these injuries are largely unknown and are likely to be site-specific, but site-specific research is lacking. However, existing research which has considered variables associated with overall injury occurrence or with lower limb stress fracture occurrence provides a basis for further investigation and is worth considering.

Lower BMI has been associated with overall injury risk in military populations (Blacker, et al., 2008; Davey, et al., 2011; Jones, et al., 1993a), including Royal Marine recruits (Davey, et al., 2011). A low body mass per se was associated with lower limb stress fracture occurrence in Royal Marine recruits (Davey, 2013) and United States Marine Corps (Beck, et al., 1996)). A smaller body size is likely to be associated with injury in military populations due to the requirement to carry absolute loads throughout training.

Research which has considered characteristics associated with tibial stress fracture, metatarsal stress fracture, and ankle inversion injury independently by site is essential in improving understanding of the mechanisms by which these injuries occur. A smaller medio-lateral tibial width has been associated with tibial stress fracture occurrence in a military population (Giladi, et al., 1987). Lower loading

under the fifth metatarsal, and greater rotation of the tibia relative to the foot have been associated with increased risk of overuse shin injury in prospective studies involving active populations (Willems, et al., 2006; Willems, et al., 2007). A later peak eversion and lower impulse under the lateral heel were also associated with this injury (Willems, et al., 2007) as were a greater peak eversion, eversion range of motion, and eversion velocity (Willems, et al., 2006). These findings have not been supported with further research, and mechanisms to explain why they may be associated with injury occurrence remain undetermined.

A low arch has been associated with metatarsal stress fractures in military recruits (Simkin, et al., 1989). No other anthropometric characteristics are known to have been associated specifically with metatarsal stress fractures, thus further investigation is required. Previous work involving Royal Marine recruits found that an earlier peak eversion was associated with third metatarsal stress fracture in a retrospective study design (Dixon, Creaby, & Allsopp, 2006). Plantar pressure variables have not been assessed in direct association with metatarsal stress fracture occurrence, but an increased risk of stress fracture would be expected in a metatarsal which is subjected to greater absolute loading (Beck, 2000). Characteristics associated specifically with stress fracture of the third metatarsal were considered in the present study, as it is the most commonly fractured metatarsal amongst Royal Marine recruits (Dixon, Creaby, & Allsopp, 2006).

A prospective study of military recruits reported that both a larger calf girth and a greater body mass were associated with ankle inversion injury (Milgrom, et al., 1991). It was not clear from this study whether a large calf girth was an indicator of a larger muscle mass or bone size. This study also found that a greater foot width was associated with increased risk of ankle inversion injury (Milgrom, et al., 1991). This could be due to a greater moment arm at the subtalar joint, and therefore greater inversion moments than would be observed in a narrower foot (Beynon, Murphy, & Alosa, 2002). Prospective study has found that a longer ground contact time, greater loading under the first metatarsal, and lower loading under the fifth metatarsal are associated with ankle inversion injury occurrence (Willems, et al.,

2005). Again, these findings require supporting evidence and further exploration of why these characteristics may predispose to injury.

Chapter 4 was conducted in collaboration with existing work for a doctoral thesis (Nunns, 2014). Data collection for this prospective study had started prior to the commencement of work for this thesis, and involved the author of this thesis. This study was designed to identify risk factors that predispose recruits to tibial and third metatarsal stress fractures, and did not consider ankle inversion injuries. Due to the large number of participants required for this study, and the time required from all involved, it was deemed ethical to maximise the use of the collected data. Therefore characteristics of recruits who sustained ankle inversion injuries were identified in addition to the characteristics of recruits who sustained tibial and metatarsal stress fractures. Ankle inversion injuries are prevalent throughout recruit training (Munnoch, 2008), and it was believed that identification of characteristics of those who sustain this injury may help to understand mechanisms which explain its occurrence.

Ankle inversion injuries are often considered to be acute (Knobloch et al., 2008; Nielsen & Yde, 1989), unlike stress fractures which develop through overuse (Rauh et al., 2006). Mechanisms for overuse injuries, which arise from repetitive loading, are likely to be more identifiable than those for acute injuries, which are less predictable. Anecdotally it is reported that ankle inversion injuries occur throughout Royal Marine training as a result of excessive inversion during a weight-bearing activity, such as stepping on uneven terrain. This is arguably different from a traumatic event, such as falling from a rope, which can also result in ankle inversion injury. Traumatic events were defined as those that a recruit could reasonably expect to avoid throughout the entirety of the training programme, and these were not considered in this thesis. Recruits are engaged in relatively high volumes of prolonged weight-bearing activity, on uneven terrain, throughout their military training. Therefore forced inversion is likely to occur regularly throughout the programme. It is unclear why certain recruits sustain an ankle inversion injury as a result of forced inversion, whereas others do not. There

may be characteristics of recruits who sustain this injury which differ from those who remain injury-free.

The raw data used in this study are the same as those used for analysis in Nunns' thesis (Nunns, 2014, pp.177-233). Data were analysed independently, prior to publication of any results, and using the methods deemed most appropriate for the present thesis. Variables considered most important to understanding mechanisms for injury development, based on existing literature, were evaluated.

The aim of this prospective study was to compare baseline anthropometric and dynamic biomechanical characteristics of Royal Marine recruits who went on to sustain a tibial stress fracture, a third metatarsal stress fracture, or an ankle inversion injury, with the characteristics of recruits who completed training injury-free. The following hypotheses were formed:

Compared with recruits who completed the training programme injury-free, those who sustained a tibial stress fracture would have:

- a smaller body mass
- a lower BMI
- a smaller calf girth
- less fifth metatarsal loading during barefoot running
- a later peak eversion angle during barefoot running
- greater tibial internal rotation range of motion during barefoot running

Compared with recruits who completed the training programme injury-free, those who sustained a third metatarsal stress fracture would have:

- a smaller body mass
- a lower BMI
- a smaller calf girth
- greater loading under the third metatarsal
- a greater midfoot contact area (indicating a lower dynamic arch)
- an earlier peak eversion angle during barefoot running

Compared with recruits who completed the training programme injury-free, those who sustained an ankle inversion injury would have:

- a greater body mass
- a greater calf girth
- greater first metatarsal loading during barefoot running
- less fifth metatarsal loading during barefoot running
- longer ground contact time during barefoot running

4.2 Methods

4.2.1 Participants

1065 injury-free male Royal Marine recruits who commenced the 32-week training programme between September 2010 and June 2012 volunteered to participate in this study. All measurements were recorded during week-2 of training at the Commando Training Centre Royal Marines, Lympstone, United Kingdom. The study was approved by the Ministry of Defence Research Ethics Committee (MODREC) and all recruits gave informed consent. Recruits were followed-up throughout the 32-week programme until either their training was interrupted for any reason, or until they completed training at the first attempt. Injuries sustained during training that resulted in removal from the training programme were initially reported to the Medical Centre, and then recorded by the Physiotherapy Department at the Commando Training Centre. The Physiotherapy Department provided investigators with anonymised, detailed injury information. The sample size was decided based on an estimated requirement of ten stress fractures per site for analysis. This number was determined based on retrospective study that successfully identified kinematic differences between Royal Marine recruits with and without a history of third metatarsal stress fracture, with ten recruits in each group (Dixon, Creaby, & Allsopp, 2006). It has been reported that 1.3% of recruits sustained a tibial stress fracture and a further 1.1% sustained a metatarsal stress fracture during the Royal Marine recruit training programme (Ross & Allsopp,

2002). Therefore data from over 1000 recruits were required to ensure that at least ten tibial and ten metatarsal stress fractures were likely to occur.

An injury-free group was created from those recruits who completed training at the first attempt without reporting an injury. Of the 1065 recruits included in this study, 419 (39.3%) completed training at the first attempt injury-free, 10 (0.9%) sustained a tibial stress fracture, 14 (1.3%) sustained a third metatarsal stress fracture, and 27 (2.5%) sustained an ankle inversion injury. Data from 120 of the 419 who remained injury-free were randomly selected to create an injury-free group. 120 was deemed an appropriate number based on estimates using cumulative means analysis (Bates et al., 1983) (Appendix K). The 171 recruits included in the final analysis (i.e. 120 injury-free recruits and 51 injured recruits) had mean (SD) age: 21.1 (3.0) years; height: 177.5 (5.5) cm; body mass: 75.5 (7.0) kg; and body mass index (BMI); 23.9 (1.9) kg.m⁻².

4.2.2 Protocol

Recruit height, body mass, calf girth, calf skinfold (to allow calculation of corrected calf girth) and bimalleolar breadth were recorded by a trained investigator following procedures outlined by the International Society for the Advancement of Kinanthropometry (Olds, et al., 2006). Bimalleolar breadth and calf skinfold measurements were included to help distinguish between bone and muscle mass in the calf. Bilateral, synchronised kinematic and plantar pressure measurements were recorded during barefoot running at 3.6 m.s⁻¹ ($\pm 5\%$), the speed which best represents recruits' training speed (Creaby & Dixon, 2008). Kinematic data were collected at 200 Hz (CodaMotion, Charnwood Dynamics, UK) using two Coda Mpx30 units and 11 active markers per leg, positioned as displayed in Figure 3.3 (p.40). Markers were fixed in position using MicroporeTM tape (3M, USA). Plantar pressure was simultaneously recorded at 200 Hz using a pressure plate (RSscan International, Belgium, 4 x 0.5 m x 0.4 m, 4096 sensors) positioned in the middle of a 10 m EVA runway. The setup is displayed in Figure 3.10 (p.48)

Recruits were asked to run with a relaxed style, ensuring two consecutive steps contacted the plate. Foot strike modality and order of foot placement on the plate were self-selected. Recruits completed familiarisation trials until successful trials were repeated. Successful trials were those in which stride was not adjusted for plate contact, the run appeared relaxed to the investigator, and the required speed was achieved. Five successful running trials were recorded per recruit, followed by a standing trial with recruits in a relaxed position with legs shoulder-width apart.

4.2.3 Data analysis

Pressure trials were exported from the Footscan software (RSscan International, Version 7) after manual adjustment of automatically identified zones. Zones were manually adjusted to represent the five metatarsals, the midfoot and the medial and lateral heel (Figure 4.1). Inter- and intra-observer reliability for this adjustment, assessed by three repeats of fifty pressure trials (peak pressure and impulses), were high (ICC>0.99, Appendix E). Bivariate correlation analyses were conducted between peak pressure and impulse for each zone, and body weight to determine whether each pressure variable should be normalised to body weight (as discussed in the General Methods (Section 3.4.4)). All pressure variables demonstrated a weak ($r < 0.3$, (Dancey & Reidy, 2007)) correlation with body weight (peak pressure variables: $r < 0.18$; impulse variables: $r < 0.27$), thus absolute rather than normalised pressure variables were considered. Pressure variables included peak pressure, impulse, and time of peak for each zone as well as ground contact time and midfoot contact area as a percentage of total foot contact area. Heel-off, the time the heel first loses contact with the ground, was also determined. Midfoot contact area was included as an indicator of foot type (pes cavus or pes planus), as arch height per se was not assessed. This variable was considered in association with metatarsal stress fracture. This method of using the ratio of midfoot contact area to total foot contact area has previously been used to identify foot structure characteristics associated with stress fracture in military recruits (Kaufman, et al., 1999). A greater midfoot contact area has been reported in low-arched feet (Morag & Cavanagh, 1999), suggesting midfoot contact can be used as an indicator of arch height.

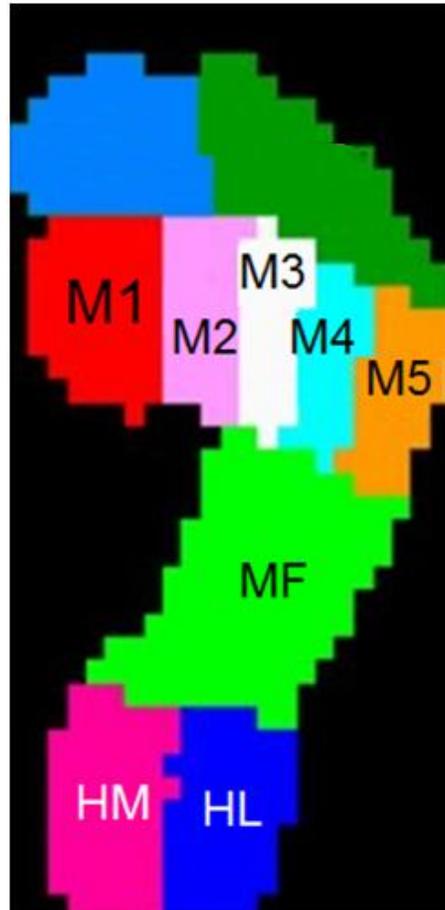


Figure 4.1: Automatically identified zones in RSscan software
M1-M5: metatarsals 1-5, MF: midfoot, HM: medial heel, HL: lateral heel

Ankle dorsiflexion, subtalar eversion, knee flexion and tibial internal rotation (shank rotation relative to the foot) variables were obtained using a 3D model (Soutas-Little et al., 1987). Range of motion, time of peak angle (as a percentage of stance) and rate of angular change were considered for each of these. Dorsiflexion range of motion was the difference between peak initial plantar flexion and peak dorsiflexion angle (Figure 3.9, p.46) and the rate of this change was recorded. Data analyses were performed using customised MATLAB scripts (R2012a, The MathWorks Inc. Natick, MA, USA).

4.2.4 Statistical analysis

All statistical analyses were undertaken using SPSS for Windows (Version 16.0, SPSS Inc., Chicago, IL, USA) with a statistical significance of $P < 0.05$. Normality

(skewness and kurtosis $|z|$ values < 1.96) of each variable was assessed. Means were compared using independent t-tests (normally distributed variables) and Mann Whitney U tests (non-normally distributed variables). 2-tailed significance values were reported despite directional hypotheses due to a lack of consistent existing evidence. Effect sizes (d (Cohen, 1988a)) were calculated for variables where $P < 0.1$. It is important to highlight that only a value of $P < 0.05$ was considered to show significance. Effect sizes were reported for variables where $P < 0.1$, in case variables that had previously been associated with injury occurrence had a value $0.05 < P < 0.1$, as well as a large effect size. In this case, further investigation of that variable may be warranted in the future.

4.3 Results

All anthropometric results are reported for each of the three injuries (Tables 4.1, 4.3 and 4.5 for tibial stress fractures, metatarsal stress fractures and ankle inversion injuries respectively). Biomechanical variables which were hypothesised to be different between groups are presented, along with any variable where $P < 0.05$ (Tables 4.2, 4.4 and 4.6). Ground contact time is additionally presented for reference.

4.3.1 Tibial stress fracture (TSF)

Anthropometric characteristics are reported in Table 4.1. Recruits who sustained a tibial stress fracture had a lower BMI, smaller calf girth and smaller bimalleolar breadth than those who remained injury free.

Table 4.1: Anthropometric variables (injury-free compared with tibial stress fracture group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	TSF (n = 10)		
Age (years)	21.3 (3.0)	20.3 (2.0)	0.301	-
Height (cm)	177.6 (5.3)	179.3 (7.0)	0.360	-
Mass (kg)	76.6 (6.6)	72.8 (7.3)	0.083	0.57
BMI (kg.m⁻²)	24.3 (1.8)	22.62 (1.7)	0.007*	0.88
Calf girth (cm)	37.6 (1.9)	36.09 (1.7)	0.017*	0.78
Corrected calf girth (mm)	367.8 (18.9)	352.8 (15.3)	0.016*	0.77
Bimalleolar breadth (cm)	7.2 (0.5)	6.8 (0.4)	0.008*	0.79

* Significant (P < 0.05) difference between groups

Plantar pressure and kinematic characteristics are reported in Table 4.2. Recruits who sustained a tibial stress fracture displayed a greater peak pressure under the lateral heel than those who remained injury-free. These recruits also had a later peak eversion angle (Figure 4.2) and less tibial rotation (Figure 4.3) than those who remained injury-free.

Table 4.2: Biomechanical variables (injury-free compared with tibial stress fracture group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	TSF (n = 10)		
Ground contact time (ms)	250.97 (24.37)	241.45 (23.18)	0.236	-
M5 peak pressure (N.cm ⁻²)	11.26 (5.38)	13.37 (6.21)	0.240	-
M5 impulse (N.s)	16.72 (9.43)	17.66 (8.40)	0.762	-
HL peak pressure (N.cm⁻²)	17.82 (5.54)	22.15 (10.56)	0.031*	0.40
Time of peak eversion (%)	40.58 (7.54)	45.99 (8.87)	0.042*	0.70
Tibial internal rotation range of motion (°)	9.72 (5.06)	6.41 (4.30)	0.029*	0.70

* Significant (P < 0.05) difference between groups
M5: fifth metatarsal; HL: lateral heel

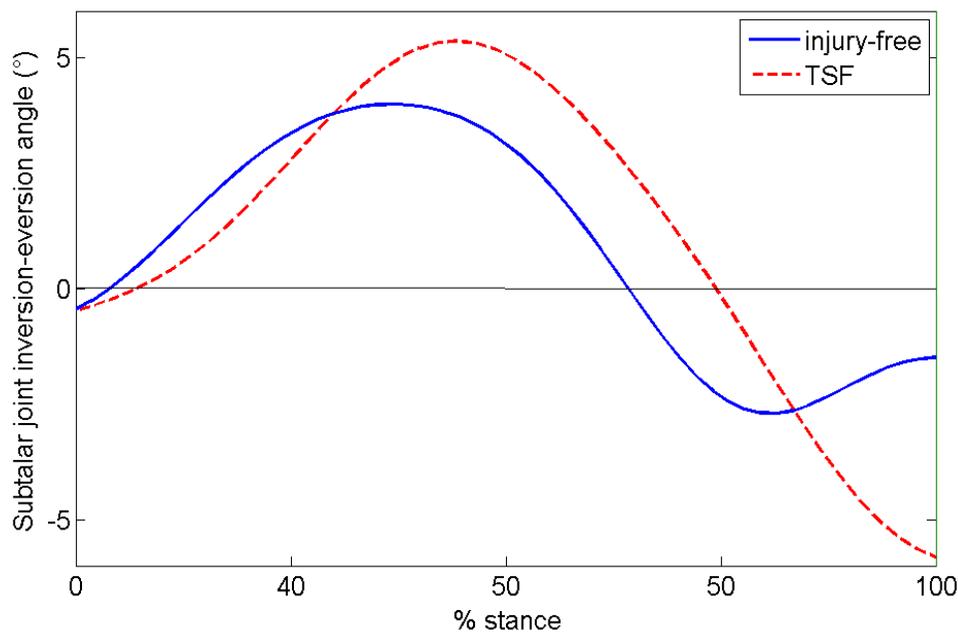


Figure 4.2: Sample time history demonstrating subtalar joint eversion during stance in an injury-free recruit and a recruit who sustained a tibial stress fracture

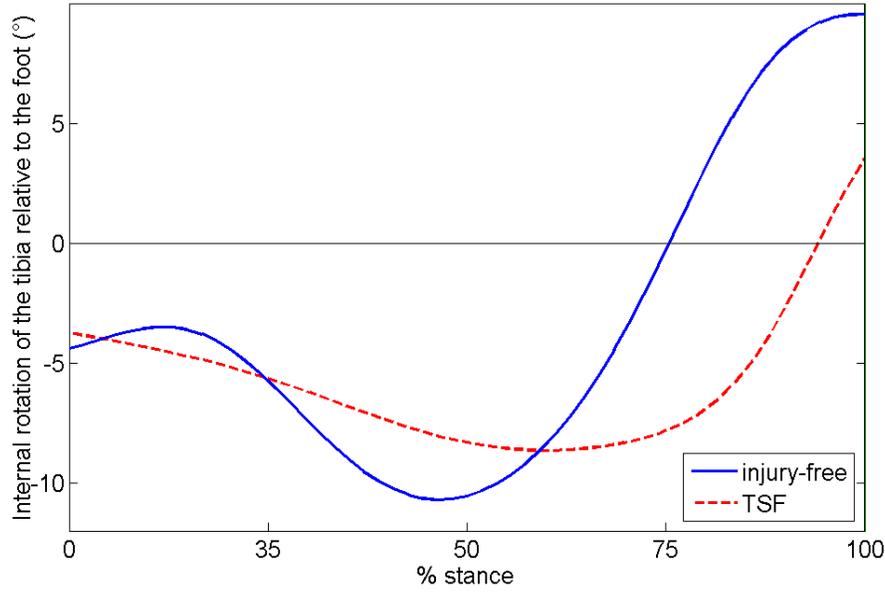


Figure 4.3: Sample time history demonstrating tibial internal rotation during stance in an injury-free recruit and a recruit who sustained a tibial stress fracture

4.3.2 Third metatarsal stress fracture (MSF)

Anthropometric characteristics are reported in Table 4.3. There were no differences between recruits who sustained a third metatarsal stress fracture and those who remained injury-free.

Table 4.3: Anthropometric variables (injury-free compared with metatarsal stress fracture group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	MSF (n = 14)		
Age (years)	21.3 (3.0)	19.9 (2.6)	0.087	-
Height (cm)	177.6 (5.3)	177.9 (5.1)	0.838	-
Mass (kg)	76.6 (6.6)	74.2 (6.9)	0.206	-
BMI (kg.m ⁻²)	24.3 (1.8)	23.4 (1.5)	0.090	0.48
Calf girth (cm)	37.6 (1.9)	37.3 (2.4)	0.608	-
Corrected calf girth (mm)	367.8 (18.9)	365.8 (22.4)	0.711	-
Bimalleolar breadth (cm)	7.2 (0.5)	7.0 (0.6)	0.103	-

* Significant (P < 0.05) difference between groups

Plantar pressure and kinematic characteristics are reported in Table 4.4. There was a greater peak pressure under the fourth metatarsal, a later peak pressure under the first, second and third metatarsals, and a later heel-off in recruits who sustained a third metatarsal stress fracture compared with those who remained injury-free.

Table 4.4: Plantar pressure variables (injury-free compared with metatarsal stress fracture group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	MSF (n = 14)		
Ground contact time (ms)	250.97 (24.37)	253.91 (24.59)	0.669	-
M3 peak pressure (N.cm ⁻²)	21.06 (6.12)	24.39 (8.13)	0.065	0.52
M3 impulse (N.s)	34.54 (10.27)	36.19 (14.56)	0.589	-
M4 peak pressure (N.cm⁻²)	18.57 (5.92)	22.39 (7.26)	0.027*	0.55
Time M1 peak pressure (%)	53.90 (5.94)	58.37 (8.44)	0.037*	0.61
Time M2 peak pressure (%)	56.65 (4.79)	60.40 (5.75)	0.004*	0.71
Time M3 peak pressure (%)	54.70 (5.01)	57.75 (3.88)	0.015*	0.68
Time of heel-off (%)	49.45 (5.52)	53.63 (7.67)	0.034*	0.63
Midfoot contact (%)	21.97 (4.63)	21.84 (3.40)	0.917	-
Time of peak eversion (%)	40.58 (7.54)	38.56 (14.95)	0.478	-

* Significant (P < 0.05) difference between groups
M1-M4: first to fourth metatarsals

4.3.3 Ankle inversion injury

Anthropometric characteristics are reported in Table 4.5. Those who sustained an ankle inversion injury had a significantly lower body mass and BMI, as well as a smaller calf girth and bimalleolar breadth than recruits who remained injury-free.

Table 4.5: Anthropometric variables (injury-free compared with ankle inversion injury group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	Ankle injury (n = 27)		
Age (years)	21.3 (3.0)	21.3 (3.3)	0.928	-
Height (cm)	177.6 (5.3)	176.3 (6.1)	0.249	-
Mass (kg)	76.6 (6.6)	72.4 (7.7)	0.004*	0.60
BMI (kg.m⁻²)	24.3 (1.8)	23.3 (1.8)	0.009*	0.55
Calf girth (cm)	37.6 (1.9)	36.4 (2.0)	0.005*	0.60
Corrected calf girth (mm)	367.8 (18.9)	357.0 (19.4)	0.008*	0.56
Bimalleolar breadth (cm)	7.2 (0.5)	6.8 (0.6)	< 0.001*	0.74

* Significant (P < 0.05) difference between groups

Plantar pressure and kinematic characteristics are reported in Table 4.6. Peak pressure under the fifth metatarsal occurred earlier in recruits who sustained an ankle inversion injury compared with those who remained injury-free. There were no differences in kinematic variables between groups.

Table 4.6: Plantar pressure variables (injury-free compared with ankle inversion injury group)

Variable	Mean (SD)		P	d
	Injury-free (n = 120)	Ankle (n = 27)		
Ground contact time (ms)	250.97 (24.37)	244.00 (22.28)	0.175	-
M1 peak pressure (N.cm ⁻²)	12.16 (4.41)	13.32 (4.00)	0.247	-
M1 impulse (N.s)	23.72 (10.35)	25.04 (9.51)	0.597	-
M5 peak pressure (N.cm ⁻²)	11.26 (5.38)	11.67 (4.59)	0.734	-
M5 impulse (N.s)	16.72 (9.43)	17.58 (9.51)	0.891	-
Time M5 peak pressure (%)	46.49 (6.35)	42.75 (7.93)	0.020*	0.57

* Significant (P < 0.05) difference between groups
M1: first metatarsal; M5: fifth metatarsal

4.4 Discussion

This large, prospective study identified anthropometric variables and biomechanical gait characteristics associated with tibial stress fractures, metatarsal stress fractures and ankle inversion injuries. This study involved reanalysis of data collected as a study for another thesis (Nunns, 2014), which was the first prospective study to assess gait variables associated with injury occurrence within a homogenous military population, who trained in a highly controlled environment. The present study additionally included ankle inversion injuries in the analyses. The rates of tibial (0.9%) and third metatarsal stress fracture (1.3%) were similar to those previously reported where 1.1% - 1.7% of recruits sustained a tibial stress fracture (Munnoch, 2008; Ross & Allsopp, 2002), and a further 1.1% (Ross & Allsopp, 2002) sustained a third metatarsal stress fracture during the same programme. The ankle inversion injury rate was 2.5%, which was also similar to the recently reported 1.5% during the same programme (Munnoch, 2008) .

The 1065 recruits involved in the present study did not include all recruits who commenced training during the testing period, as participation was voluntary. Data collection took place during the second week of training, during which time recruits were under regular assessment of their organisational skills, alongside other tasks. There were known stress fracture cases amongst recruits who commenced training during the data collection period, but were not involved in the study. The actual rate of injury occurrence obtained in this study may therefore not accurately present the rate of injury occurrence throughout recruit training. The same is true of the rates reported by Munnoch (2008). Furthermore, this suggests there may have been an element of selection bias. Only ankle injuries that resulted in removal from mainstream training were included in the analysis, and it is likely that there were a number of minor cases where recruits were not referred to the Physiotherapy Department which would therefore not have been included in this study. Unfortunately, the number of these cases and the number of stress fractures that occurred in recruits not involved in data collection could not be accurately determined.

4.4.1 Anthropometrics

A smaller overall body size was reported in recruits who sustained tibial stress fractures compared with those who remained injury-free, which supported the hypotheses and is consistent with previous findings (Beck, et al., 1996; Davey, 2013; Giladi, et al., 1987). However a smaller body size was also reported in recruits who sustained ankle inversion injuries compared with those who remained injury-free, and this was not consistent with the hypotheses, or with existing findings where a greater calf girth and body mass were associated with ankle injury in a military population (Milgrom, et al., 1991). However, this previous study reported a considerably higher incidence of lateral ankle injuries (18%) than reported in the present study, thus comparisons may not be justified. BMI was lower in recruits who sustained a tibial stress fracture or an ankle injury than those who remained injury-free. BMI in this population is likely to be an indicator of muscle mass, as all recruits are highly trained. Recruits of smaller stature likely have a smaller muscle mass and may find load carriage tasks more physically demanding than those with a larger stature, as the load carried throughout training is absolute and based on military operational equipment requirements rather than being relative to body mass. This increased physical demand may increase injury risk. This argument is supported by the higher prevalence of stress fractures in females compared with males in military populations (Wentz et al., 2011). Regular load carriage activities are an important feature of Royal Marine training, and such activities have previously been associated with lower limb injury occurrence in military populations (Birrell, Hooper, & Haslam, 2007; Knapik, et al., 1992; Orr, et al., 2014). Contrary to the hypotheses, there were no differences in anthropometric variables between recruits who sustained a third metatarsal stress fracture and those who remained injury-free. As discussed, existing literature has only considered these anthropometric variables in association with overall injury or overall lower limb stress fracture occurrence, rather than considering the metatarsals independently. Mechanisms by which metatarsal stress fractures develop may therefore be more greatly influenced by gait characteristics than anthropometrics.

A lower body mass was reported only in recruits who sustained ankle inversion injuries compared with those who remained injury-free. Body mass may be a confounding factor in these analyses. To assess this, body mass-stratified analyses were conducted, as used in existing epidemiological studies (Melton et al., 1989). This analysis excluded one-third of the recruits from each of the initial groups, who were removed because their body mass values were furthest from the injury-free group mean value. Reanalysis of anthropometric characteristics using these stratified groups revealed no differences between groups for body mass (as intended), BMI, calf girth or corrected calf girth, but there remained a significant difference between groups for bimalleolar breadth. This suggests that a small bimalleolar breadth is associated with ankle inversion injury independent of body mass. A smaller breadth is indicative of a smaller support base, thus reducing single-leg stability and increasing risk of excessive inversion. A smaller breadth may also be evidence of a smaller moment arm for the evertor muscles, reducing the ability to counter inversion.

The smaller calf girth in recruits who sustained tibial stress fractures compared with those who remained injury-free may be evidence of a smaller muscle mass (Rolland et al., 2003). Muscular contractions are reportedly protective against bending in the bone, due to their ability to convert tensile and sheer stresses to compressive stresses, under which bone is stronger (Beck, et al., 2000). A smaller muscle mass may diminish the ability to convert these stresses, resulting in increased risk of stress fracture. A smaller muscle mass may also be indicative of reduced calf muscle strength. Furthermore, as hypertrophy is known to be concurrent with increased muscular endurance (Bird et al., 2005), a smaller muscle size may be indicative of a muscle which is more susceptible to fatigue. Muscular fatigue has previously been shown to increase bone strain (Milgrom, et al., 2007; Yoshikawa et al., 1994), and increased bone strain has been associated with increased risk of stress fracture (Arndt, et al., 2002).

4.4.2 Dynamic variables associated with tibial stress fracture

Greater loading under the lateral heel in those who sustained tibial stress fractures compared with those who remained injury-free suggests higher vertical forces are

acting close to the tibia, and this may increase tibial loading, resulting in a faster rate of microdamage accumulation, and consequently increased stress fracture susceptibility (Beck, 2000). Lower fifth metatarsal loading was hypothesised in recruits who sustained tibial stress fractures compared with those who remained injury-free, but the results did not support this. This was previously observed in a non-military population (Willems, et al., 2006; Willems, et al., 2007) suggesting this mechanism may be population-specific. The lower internal rotation of the tibia in those who sustained tibial stress fractures was contrary to the hypothesis which was based on existing findings of a greater rotation in those who sustain overuse shin injuries compared with injury-free participants (Willems, et al., 2006; Willems, et al., 2007). Similar values were reported in the injury-free group of each study during barefoot running at similar running speeds (present study: 9.72 (5.06) °; Willems et al., (2006): 11.43 (4.02) °) so it is unclear why these differences arose. This may be a result of differences between overuse shin injuries and tibial stress fractures, and highlights the importance of a clear injury diagnosis. Internal rotation of the tibia relative to the foot during stance occurs partly about the subtalar joint. Tibial torsion results when one end of the tibia rotates relative to the other, which may occur if one end is fixed. Less rotation about the subtalar joint, as observed in recruits who sustained a tibial stress fracture compared with injury-free recruits, may be the result of a more fixed distal tibia. This may increase tibial torsion, if the distal tibia is fixed and the proximal tibia rotates, resulting in an increased risk of stress fracture, with bone known to be weaker when loaded in torsion than compression (Taylor, et al., 2003). The rotation of the tibia relative to the knee was not considered in the present study, and should be included in future to further assess this suggestion.

Like tibial rotation, eversion also occurs about the subtalar joint, thus reduced tibial rotation is likely to influence the time of peak eversion. This occurred later in recruits who sustained a tibial stress fracture compared with recruits who remained injury-free, as previously reported in those who sustain overuse shin injuries (Willems, et al., 2007). This was consistent with the hypothesis. The tibia internally rotates relative to the foot in initial stance, and this is concurrent with subtalar joint eversion (Dierks & Davis, 2007). Later eversion may therefore be influenced by a

more fixed tibia as the reduced motion of the tibia relative to the foot may limit the ability of the subtalar joint to evert. This may further contribute to the distal tibia being more fixed, resulting in increased tibial torsion. It has previously been suggested that military recruits with bone geometries which would be expected to result in greater torsional stresses may be at increased risk of stress fracture (Beck, et al., 2000). In summary, existing findings in combination with those from the present study, suggest that a more fixed tibia, manifested as less internal rotation of the tibia relative to the foot and a later peak eversion angle, may increase risk of tibial stress fracture. Increased tibial torsion is a potential mechanism for this.

4.4.3 Dynamic variables associated with third metatarsal stress fracture

The greater fourth metatarsal loading observed in recruits who sustained metatarsal stress fractures compared with injury-free recruits suggests greater loading towards the middle (in the medial-lateral direction) of the forefoot in these recruits. The positioning of zones within the RSscan software represents an approximation of each foot zone, which may not accurately represent the position of the metatarsals. Peak pressures were found to be less reliable under the metatarsals than under larger zones of the foot (Appendix F). Therefore these higher vertical forces acting under the fourth metatarsal may also be applied to the third metatarsal, which is less resistant to bending than the fourth (Gross & Bunch, 1989). The inaccuracies of the system may have influenced this finding. Stress fractures are known to result from excessive, repetitive bone stress (Arendt, 2000), thus greater vertical loading of the areas close to the third metatarsal may increase risk of stress fracture.

Later peak metatarsal pressures and heel-off may arise from a reduced contribution to forward propulsion from the foot plantar flexor muscles. Peak plantar flexor muscle activity has been shown to occur shortly after 50% of stance during running (Mann et al., 1986). In the present study, recruits who remained injury-free demonstrated a peak pressure under the metatarsals shortly after 50% of stance, which likely coincided with peak plantar flexor muscle activity. The later peak metatarsal pressure observed in those who sustained third metatarsal stress

fracture suggests a greater reliance on forward inertia to induce heel off, and relatively less reliance on an active contribution from the plantar flexor muscles. Reduced plantar flexor muscle activity is known to increase metatarsal strain and bending (Sharkey, et al., 1995), which increases risk of metatarsal stress fracture (Arndt, et al., 2002). However, plantar flexor muscle activity was not measured in the present study, thus this suggestion is speculative. No differences in kinematic knee flexion variables were reported between injury-free recruits and those who sustained a stress fracture.

Contrary to the hypothesis, there was no difference in time of peak eversion between recruits who sustained a third metatarsal stress fracture, and those who remained injury-free. It was previously suggested that this earlier peak eversion resulted in a greater time in the propulsive phase of stance, but this could not be confirmed in the present study. The observed similar values in midfoot contact area between recruits who sustained a third metatarsal stress fracture and those who remained injury-free suggest that this variable was not associated with metatarsal stress fracture. This was in contrast to the hypothesis. However, this should be further investigated in future work, as existing research is confounded by a number of factors. No known existing literature has considered this variable in terms of individual metatarsals, and the only known study to have considered metatarsal stress fractures independent of lower limb injuries measured arch characteristics using the ratio of navicular height to foot length (Simkin, et al., 1989), which is considerably different to the indicator of arch characteristics used in the present study. Cavanagh et al. (1997) found that radiographic indicators of foot structure explained only 35% of the variance of dynamic plantar pressure variables. A more controlled enquiry into the associations between static and dynamic arch characteristics, and site-specific metatarsal injuries is required.

4.4.4 Dynamic variables associated with ankle inversion injury

The earlier peak fifth metatarsal pressure was the only biomechanical difference reported between recruits who sustained an ankle inversion injury and injury-free recruits, and this was not hypothesised. The hypotheses of greater first metatarsal loading, lower fifth metatarsal loading and a longer ground contact time were not

supported. This again may be influenced by the population, as these variables had not been previously assessed in military recruits. The observed earlier peak fifth metatarsal pressure may be the result of a more inverted subtalar joint position at touchdown, but this could not be investigated due to the large variability in eversion touchdown angle. In both groups, peak pressure under the fifth metatarsal occurred prior to peak pressure under all other metatarsals, which peaked approximately in order from most lateral to most medial. Thus time of peak fifth metatarsal pressure can be assumed to indicate the start of forefoot eversion. Peak eversion occurred at 41.88 (8.03)% of stance in recruits who remained injury-free, and at 42.89 (11.69)% in those who sustained an ankle inversion injury. In those who remained injury-free, peak fifth metatarsal pressure (46.49 (6.35)%) occurred after peak eversion suggesting that subtalar eversion and forefoot eversion (not measured) occurred consecutively. Peak fifth metatarsal pressure (42.75 (7.93)%) in those who sustained an ankle inversion injury occurred closer to the time of peak eversion. This may be evidence of an earlier forefoot eversion, as a mechanism to avoid excessive inversion. This suggested mechanism is an alternative to the previously suggested mechanism of a more inverted touchdown position. The latter suggestion may be a mechanism adopted by recruits who have sustained previous ankle inversion injuries, which is a major risk factor for re-injury (Surve, et al., 1994). Injury history was self-reported, but it is likely that recruits under-reported these injuries, and no association with previous injury could be made. These suggestions are speculative as forefoot eversion was not measured. Future research in this area should therefore consider forefoot eversion.

The fact that few biomechanical differences were observed between recruits who sustained an ankle inversion injury and injury-free recruits may relate to the acute nature of this injury. Stress fractures are an overuse injury, thus mechanical factors are likely to be more influential in their progressive development than ankle inversion injuries, which may occur following an acute event. Therefore characteristics associated with ankle inversion injury may be more difficult to identify than those associated with stress fractures. As discussed, it is likely that recruits regularly sustain a forced or unexpected inversion of the subtalar joint during training that does not result in ankle injury. The results of this study suggest

that anthropometric characteristics, rather than biomechanical variables predispose certain recruits to ankle inversion injuries.

4.5 Limitations and implications for future study

A large sample was required to ensure that sufficient injuries occurred for analyses and this increased the time pressure of data collection during each session. Data quality could therefore not be assessed during data collection, and a number of trials had to be excluded retrospectively, most often due to poor tracking of kinematic markers. However, the size of the study and the controlled nature of data collection within a military training environment, provide confidence in the validity of the characteristic differences that were identified. This is the largest known prospective study to identify baseline anthropometric and biomechanical characteristics in a military population.

The majority of variables that would ideally be examined if designing this study with the intention of identifying characteristics associated with ankle inversion injury were included in the initial study design. Foot width was not included, but as a greater foot width has previously been associated with increased risk of ankle inversion injury (Beynnon, Murphy, & Alosa, 2002), this would have been worthwhile investigating, particularly as a conflicting finding of a smaller bimalleolar breadth was observed in recruits who sustained ankle inversion injuries, compared with those who remained injury-free. A measure of forefoot eversion as well as subtalar eversion would have helped to further interpret findings, although this is notoriously difficult to measure using non-invasive techniques (Lundgren et al., 2008).

Although a large initial sample was included, the study would have been strengthened by a greater number of cases for each injury, particularly for tibial and metatarsal stress fractures. Despite the fact that the recruits were from a population that can be considered to be highly homogenous in comparison to many athletic populations, there are likely to be confounding variables which were not considered in the present study. Every two weeks there was a new intake of recruits. Recruits from the majority of the troops that commenced training during

the 17 month data collection period, were included in the study. Although the same training programme was followed by each recruit, there may have been variation in the execution of this programme. Variables such as training intensity, nutritional intake, quality of recovery time as well as many sociological and psychological variables were likely to have differed between troops. All of these variables may have had an influence on injury risk, but were not considered. Furthermore, reporting of injuries may have varied between troops, for sociological reasons.

The anthropometric variables associated with injury may be used in future to identify recruits at increased risk of injury, either to exclude them or to introduce interventions for these recruits. Anthropometric variables were considered for this process due not only to their association with injuries, but also their relative ease of measurement, and cost-effectiveness. In order to provide an indication of the potential success of this approach, values to indicate the number of recruits from each group who would have been identified were calculated.

Body mass, BMI, corrected calf girth and bimalleolar breadth were associated with occurrence of at least one of the three injuries considered in this study. 95% confidence intervals were obtained from the univariate analyses for mass, BMI, corrected calf girth and bimalleolar breadth. These values were obtained for the injury-free group, and for each of the injury groups independently, (tibial stress fracture, metatarsal stress fracture and ankle inversion injury), and are presented in Table 4.7.

Table 4.7: Mean (SD) and 95% confidence intervals (CI) for selected anthropometric variables for each of the four groups

Variable	Injury-free (n=120)		TSF (n=10)		MSF (n=14)		Ankle injury (n=27)	
	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI
Mass (kg)	76.6 (6.6)	75.4, 77.8	72.8 (7.3)	67.5, 78.0	74.2 (6.9)	70.2, 78.2	72.4* (7.7)	69.3, 75.4
BMI (kg.m ⁻²)	24.3 (1.8)	23.9, 24.6	22.6* (1.7)	21.4, 23.8	23.4 (1.5)	22.6, 24.3	23.3* (1.8)	22.6, 23.9
Corrected calf girth (mm)	367.8 (18.9)	364.4, 371.3	352.8* (15.3)	341.8, 363.8	365.8 (22.4)	352.8, 378.7	357.0* (19.4)	349.3, 364.7
Bimalleolar breadth (cm)	7.2 (0.5)	7.1, 7.3	6.8* (0.4)	6.6, 7.1	7.0 (0.6)	6.7, 7.3	6.8* (0.6)	6.6, 7.1

*Significantly different (P < 0.05) from injury-free group mean

From these values, hypothetical cutoff values could be determined. These were obtained from confidence intervals. A lower BMI was observed in recruits who sustained tibial stress fractures and ankle inversion injuries than those who remained injury-free. Thus a cutoff value, from the lower confidence interval for each of these groups was assessed. A smaller body mass was associated with ankle inversion injuries. A cutoff value obtained from the lower confidence was used, in addition to the lower confidence interval from those who sustained tibial stress fractures, as this was the lowest value from all three injury groups. A small corrected calf girth was associated with both tibial stress fractures and ankle inversion injuries, thus the lower confidence interval from each of these groups was considered. For bimalleolar breadth, where a smaller value was associated with tibial stress fracture and ankle inversion injury, the lower confidence interval was also considered. As this value was the same for the two groups, the lower confidence interval for those who sustained metatarsal stress fractures was also considered. The combined influence of a small corrected calf girth and small bimalleolar breadth was additionally considered.

The number of recruits who would have been removed or identified as being at 'high risk' for an injury, based solely on these cutoff values was assessed. All 51 injury cases were considered, in addition to 149 recruits who completed training injury-free at the first attempt. This number is greater than the number of injury-free

recruits used throughout this study, as the anthropometric values were readily available for 149 recruits, thus it was logical to maximise the data used in this process.

The results of this process are presented in Table 4.8. This table reports the number and percentage of recruits who would have been identified as being at high risk, using the different cutoff values. The ratio presented is the percentage of injured recruits (all cases) who would have been identified, divided by the percentage of injury-free recruits who would have been identified. The purpose of this is to provide an indication of the number of injuries that could potentially have been screened out, relative to the number of injury-free recruits who would have been excluded, had recruits been excluded at the start of training based on these variables.

Table 4.8: Recruits who would have been identified as suitable for exclusion or intervention from each group, based on anthropometric variables

	Injury-free (n=149)	TSF (n=10)	MSF (n=14)	Ankle inversion injury (n=27)	All injury cases (n=51)	Ratio
BMI \leq 22.6 kg.m ⁻²	25 (16%)	4 (40%)	4 (28%)	10 (37%)	18 (35%)	2.2
BMI \leq 21.4 kg.m ⁻²	5 (3%)	3 (30%)	1 (7%)	2 (7%)	6 (12%)	4.0
Mass \leq 69.3 kg	21 (14%)	3 (30%)	3 (21%)	10 (37%)	16 (31%)	2.2
Mass \leq 67.5 kg	12 (8%)	3 (30%)	3 (21%)	7 (26%)	13 (25%)	3.1
Corrected calf girth \leq 349.3 mm	18 (12%)	4 (40%)	3 (21%)	12 (44%)	19 (37%)	3.1
Corrected calf girth \leq 341.8 mm	8 (5%)	2 (20%)	2 (14%)	9 (33%)	13 (25%)	1.0
Bimalleolar breadth \leq 6.7 cm	9 (6%)	5 (50%)	5 (36%)	9 (33%)	19 (37%)	6.2
Bimalleolar breadth \leq 6.6 cm	4 (3%)	5 (50%)	5 (36%)	8 (30%)	18 (35%)	11.7
Corrected calf girth \leq 349.3 mm & bimalleolar breadth \leq 6.7 cm	4 (3%)	3 (30%)	1 (7%)	7 (26%)	11 (22%)	7.3
Corrected calf girth \leq 341.8 mm & bimalleolar breadth \leq 6.6 cm	1 (1%)	2 (20%)	1 (7%)	4 (15%)	7 (14%)	14.0

As an example to facilitate interpretation of the table, if a cutoff value of BMI \leq 22.6 kg.m⁻² had been set prior to entry of these recruits into the training programme, and these recruits excluded, 25 (16%) of those who remained injury-free would have been excluded, whilst 18 (35%) injury cases would have been excluded. The ratio is improved, although fewer injury cases excluded, by using a more

conservative BMI value of $\text{BMI} \leq 21.4 \text{ kg.m}^{-2}$. In this case only 5 (3%) of those who remained injury-free would have been excluded, and 6 (12%) injury cases would have been excluded. It must be noted that a higher ratio may not necessarily be more favourable than a lower absolute number of injury-free recruits excluded, as the value of a recruit who completes training at the first attempt may outweigh the cost of a recruit sustaining an injury. These differing interpretations highlight the need for findings to be presented to those who can better judge the value of a trained recruit, compared to the cost of injury.

The combination that had both the highest ratio and the fewest control recruits excluded, was to identify those recruits with a corrected calf girth value ≤ 341.8 mm, as well as a bimalleolar breadth value ≤ 6.6 cm at the start of training. This would have excluded 1 (1%) recruit who remained injury-free and 7 (14%) injury cases. The method that would have potentially excluded the greatest number of injury cases was to exclude recruits with a bimalleolar breadth ≤ 6.7 mm. This would have resulted in 37% of injury cases being excluded. However, 6% of those who passed out at the first attempt would have been excluded. Assessments were made to combine corrected calf girth and bimalleolar breadth values with BMI, but the number of injury-free recruits excluded was the same as with previous restrictions, and these further restrictions by definition would not have identified further injury cases. Further analysis of this type could also consider the duration of rehabilitation required for recruits who sustain an injury. This information was not available for the work in this thesis.

4.6 Conclusions

This prospective study of 1065 Royal Marine recruits identified baseline anthropometric and biomechanical gait characteristics in recruits who sustained a tibial stress fracture, a third metatarsal stress fracture or an ankle inversion injury during training compared with recruits who completed training injury-free. This provides some indication of the mechanisms by which these injuries may develop. These measurements were obtained in relatively rested recruits at the start of training. Gait changes may occur as a result of physically demanding training activities, influencing the characteristics identified in the present study, and thereby

influencing injury risk. Identification of such changes may improve understanding of mechanisms for injury occurrence, as well as helping to explain why the characteristics identified in the present study may predispose some recruits, and not others, to suffer the relevant injury.

4.7 Progression from Chapter 4 to Chapter 5

Chapter 4 identified anthropometric and biomechanical gait characteristics of recruits who sustained tibial stress fractures, metatarsal stress fractures, and ankle inversion injuries. It has been suggested that the arduous nature of Royal Marine recruit training may be associated with the relatively high injury occurrence reported in this population, but specific training variables have not been examined in association with injury occurrence. Previous data collection from the same population has found a trend for increasing stress fracture rates with increasing training weeks, as the training becomes more demanding, suggesting a direct relationship between training load and stress fracture occurrence (Ross & Allsopp, 2002). However, this requires further investigation as numerous other extrinsic factors may influence this relationship. Identification of training variables associated with injury incidence in the Royal Marine recruit training programme is required to improve the understanding of mechanisms for injury development within this population.

CHAPTER 5: A review of the 32-week Royal Marines recruit training programme and the association with injury occurrence

A version of this chapter has been distributed as an Institute of Naval Medicine report.

5.1 Introduction

The Royal Marine recruit training programme is a physically and mentally challenging, 32-week progressive course, which is divided into two phases: Phase-1 (weeks 1-15) focuses on individual fitness and military-specific fitness; and Phase-2 (weeks 16-32) involves activities that are representative of occupational Royal Marine tasks, including regular load-carriage activities. This arduous training programme is associated with a relatively high occurrence of lower limb, musculoskeletal injury (Evans, 1982). 16% of recruits reportedly sustain such an injury during training, (Munnoch & Bridger, 2007) with a median recovery time of 14.3 weeks (Munnoch, 2008). This results in a loss of training time for injured recruits, and associated fiscal cost for the training establishment (Evans, 1982; Ross & Allsopp, 2002).

Stress fractures have frequently been reported as one of the most common injuries within military populations worldwide (Beck, 1998; Beck, et al., 2000; Knapik, Reynolds, & Harman, 2004; Milgrom et al., 1985; Orr, et al., 2014). Stress fractures result from excessive, repetitive bone stress (Arendt, 2000), which may explain their prevalence in this population, where load carriage weight-bearing activities are a common feature of the training programme. Load carriage is an important component of military training, as it is fundamental to deployed operational capability. Existing evidence has identified an association between prolonged, military load carriage activities and lower limb injury occurrence (Knapik, et al., 1992; Orr, et al., 2014), specifically tibial stress fracture and metatarsal stress fracture (Knapik, et al., 1992). Tibial and metatarsal stress fractures are the most prevalent stress fractures amongst Royal Marine recruits (Munnoch, 2008). As bone stress is considered to be a continuum culminating in stress fracture (Roub,

et al., 1979), such activities may also be associated with non-fracture tibial stress injuries that are difficult to distinguish from stress fractures (Jackson, 1978; Mubarak et al., 1982). These tibial stress injuries, which exclude stress fractures, can be termed exercise-related lower leg pain. Exercise-related lower leg pain has not been uniquely defined but usually involves presentation with shin pain (Reinking, 2007).

According to the overload principle, physical training must physiologically stress the body above normal levels to stimulate beneficial adaptations (Dick, 2007; Steinhaus, 1933), but this stress may increase injury risk. Overload is determined by the intensity, frequency, duration and type of training completed (Clark, 2009). Many of these variables (intensity, frequency and duration) are independently associated with injury risk (Jones, Cowan, & Knapik, 1994). High volumes of weight-bearing activity (Almeida, et al., 1999; Pope, 1999), insufficient recovery time (Kibler, Chandler, & Stracener, 1992) and sudden increases in training volume (Bullock, et al., 2010) have also been associated with increased injury risk. Preventing overtraining is recommended as the most important method of minimising injury risk in military training (Jones, Cowan, & Knapik, 1994). The influence of the footwear worn throughout recruit training (military boots, drill boots and sports trainers) on injury risk also warrants investigation (Kaufman et al., 2000) as it is presently unclear.

The aim of this review was to identify training variables within the 32-week Royal Marines recruit training programme, that are associated with injury incidence, and specifically with incidence of tibial stress fracture, metatarsal stress fracture and exercise-related lower leg pain. This cross-sectional, observational review was undertaken as a training management audit, where permission to access the anonymised data was provided by the Commando Training Centre Royal Marines (CTCRM) Headquarters.

5.2 Methods

This review was undertaken through analysis of the training serials for the 32-week Royal Marine recruit training programme, triangulated with data gathered during

interviews from CTCRM personnel involved in the programme implementation. Details from the training serials included training week, day, time and duration of all recruit activities throughout the programme. The duration of the activity, the footwear worn, and the mass of any additional load carried were recorded for all activities. Average speed and distance covered were recorded for all walking, running and marching activities. It was acknowledged that differences may have existed between troops due to external factors such as weather, and the approach of different training teams. All data were quantified systematically to provide an unbiased analysis.

Data from all injuries which required a recruit to be removed from training were recorded by the CTCRM Medical Centre and reported by week of training. These varied in severity and included both acute and chronic injuries. All injury data were anonymised to investigators prior to collation for this review, ensuring recruit confidentiality. Three data sets were examined: (1) all injuries (January-October 2010); (2) all injuries (January-October 2011); and, (3) tibial stress fracture, metatarsal stress fracture and exercise-related lower leg pain cases (January-December, 2011). Overall injury data were only available to investigators from January – October for 2010 and 2011 as these were periods of interest for previous work conducted within CTCRM. Injury cases were recorded from recruits who were undergoing rehabilitation within the data collection period, therefore the injury may have happened prior to the period of data collection. Information regarding the week of training during which ankle inversion injuries occur were not available to investigators, thus this injury was not considered in this review. Historically, the nature of physical military training has been associated with lower limb stress fracture occurrence (Beck, 1998; Beck, et al., 2000; Knapik, Reynolds, & Harman, 2004; Milgrom, et al., 1985; Orr, et al., 2014) rather than ankle inversion injuries.

The variables quantified for analysis in this review were training volume, distance covered, load carried, recovery time, criterion tests and footwear. Training volume was defined as the number of minutes assigned to each activity, per week of training. This was also determined independently for weight-bearing activities.

Activities which required distance to be covered on foot were divided into two categories: those in which a specified distance must be covered (e.g. 12-mile load carriage within 4 hours 40 minutes); and those with no specified distance (e.g. patrolling). Those with a specified distance were termed Distance Activities. Distance covered and load carried throughout training were quantified using only Distance Activities, as these values were detailed for each training serial in the programme. Accurate values for distance covered and load carried could not be determined for those activities with no specified distance, due to within- and between-troop variability. It was acknowledged that some variability would also exist for these variables during Distance Activities. Load was quantified as additional mass carried (kg) and was reported as an absolute value rather than relative to body mass. A variable was created by multiplying load carried by distance covered (LCxD). Although this variable was limited by an assumption that load carriage and distance covered are equally burdensome, it provides a useful indication of the combined effects of these two variables. For this variable, load was calculated as additional mass added to 77.3 kg, the mean body mass of this military training population (Davey, et al., 2011). This allowed inclusion of activities with no additional load carriage in the analysis. Cumulative values for each training week were reported. Recovery time was quantified as the number of complete leave days per week. The number of criterion tests per week was also reported. Footwear was quantified as the number of minutes per week spent in each footwear type during training activities. Correlations were assessed between each training variable and overall injury, tibial stress fracture, metatarsal stress fracture and exercise-related lower leg pain with a statistical significance of $P < 0.05$. A value of $|r| > 0.8$ was considered to represent a strong correlation (Peck et al., 2012).

5.3 Results

There were 737 injury cases across 20 months (Jan-Oct, 2010 and Jan-Oct, 2011). During these time periods, a total of 1458 recruits started training. These injuries may have occurred amongst recruits who had commenced training prior to this time. There are approximately 800 recruits in training at any given time, but this

number would also capture those who commenced training during this data collection period. It is therefore not possible to accurately report the proportion of recruits who sustained an injury from the available data. There were 25 tibial stress fractures, 42 metatarsal stress fractures and 36 exercise-related lower leg pain cases within a 12 month period (Jan-Dec 2011). This may have included cases which had occurred prior to January 2011, with the recruit still in rehabilitation at the time of data collection. This may partly explain the higher incidence reported in this review than in the 21-month period of data collection in Chapter 4. Furthermore, these values represent all cases within the data collection period, whereas Chapter 4 included only those which occurred in recruits who volunteered to participate in the study. The percentage of injuries which occurred in each phase of training are presented in Table 5.1. Overall injury occurrence (Figure 5.1) was highest in week-26 (16%), followed by weeks 31 (9%), 14 (7%) and 22 (7%). Metatarsal stress fracture occurrence was highest in week-26 of training (17%) followed by week-23 (14%). 88% of all metatarsal stress fractures occurred during Phase-2 of training, with 60% occurring between weeks 23 and 28 inclusive. Highest tibial stress fracture occurrence was in week-31 (24%) and was double the occurrence in weeks 14 (12%) and 17 (12%), which had the second highest values. The week of highest exercise-related lower leg pain occurrence was week-26 (19%), followed by week-9 (14%). In weeks 31 and 17, only 3% of exercise-related lower leg pain cases occurred, whilst 11% of cases occurred in week-14 (allowing comparison with tibial stress fracture occurrence).

Table 5.1: Percentage of injuries reported 01 Jan – 31 Oct 2010 and 2011 (n = 737) occurring in each phase of training

Injury	% Phase-1	% Phase-2
All	32	68
Tibial stress fracture	36	64
Metatarsal stress fracture	12	88
Exercise-related lower leg pain	53	47

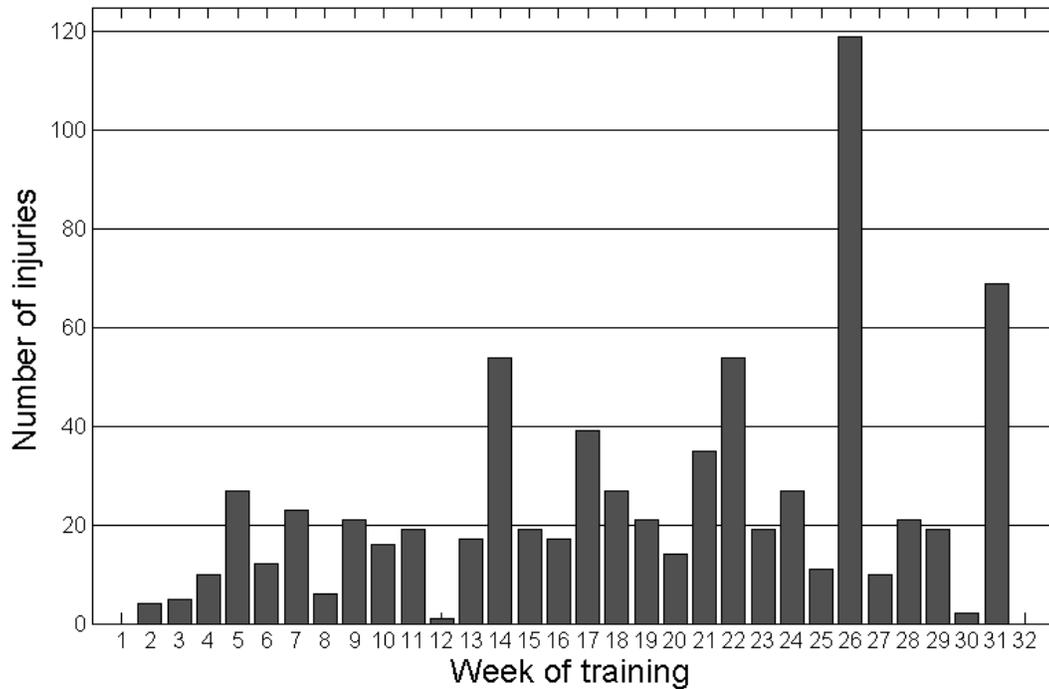


Figure 5.1: Injury cases per week of training (01 Jan to 31 Dec 2010 and 2011)

The greatest volume of training was in week-30 (2315 min), followed by weeks 29 (1725 min), 31 (1635 min) and 26 (1347 min). Values for volume of weight-bearing activity were very similar to the values for total training volume. There was no association between overall training volume or weight-bearing training volume and injury occurrence. Physical training took place on 4.7 (± 1.4) days per week. This was similar in Phase-1 (4.7 ± 1.2 days) and Phase-2 (4.7 ± 1.6 days). Peak total distance covered during Distance Activities occurred in week-31 (62.4 km), followed by week-26 (54.4 km) and week-22 (21.6 km). There was a strong positive relationship between distance covered and injury occurrence ($r = 0.88$, $P < 0.01$; Figure 5.2).

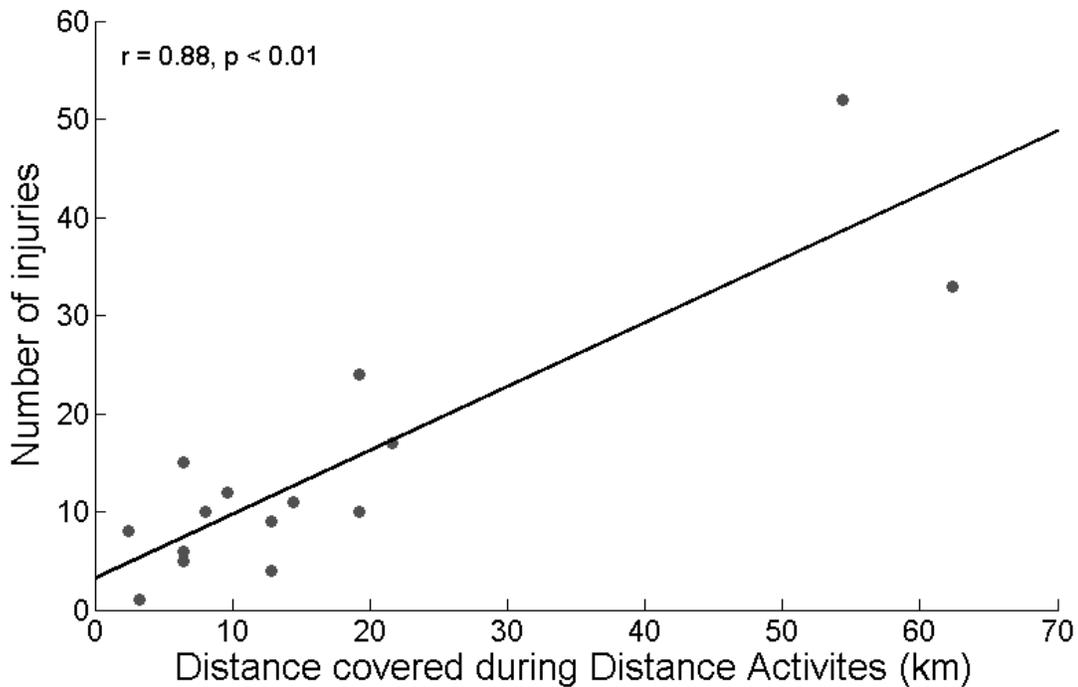


Figure 5.2: Relationship between distance covered during Distance Activities and injury occurrence

Note: each point represents a training week; weeks where the number of cases was zero have been excluded.

The greatest cumulative load carried during Distance Activities occurred in week-26 (119 kg) followed by week-22 (49 kg). There was a moderate relationship between load carriage and injury occurrence ($r = 0.78$, $P < 0.01$). The greatest frequency of load carriage activities occurred in week-26 (ten activities) followed by weeks 30 and 18 (eight activities). There was no association between frequency of load carriage events and injury occurrence. Peak values for load carriage multiplied by distance covered (LCxD) occurred in weeks 31 and 26, with high values in weeks 14, 22 and 24 (Figure 5.3). The four weeks of highest injury incidence in order were weeks 26, 31, 14 and 22 (Figure 5.1), which correspond with four of the weeks of highest values for LCxD. There was a strong association between LCxD and injury occurrence ($r = 0.81$, $P < 0.0$, Figure 5.4).

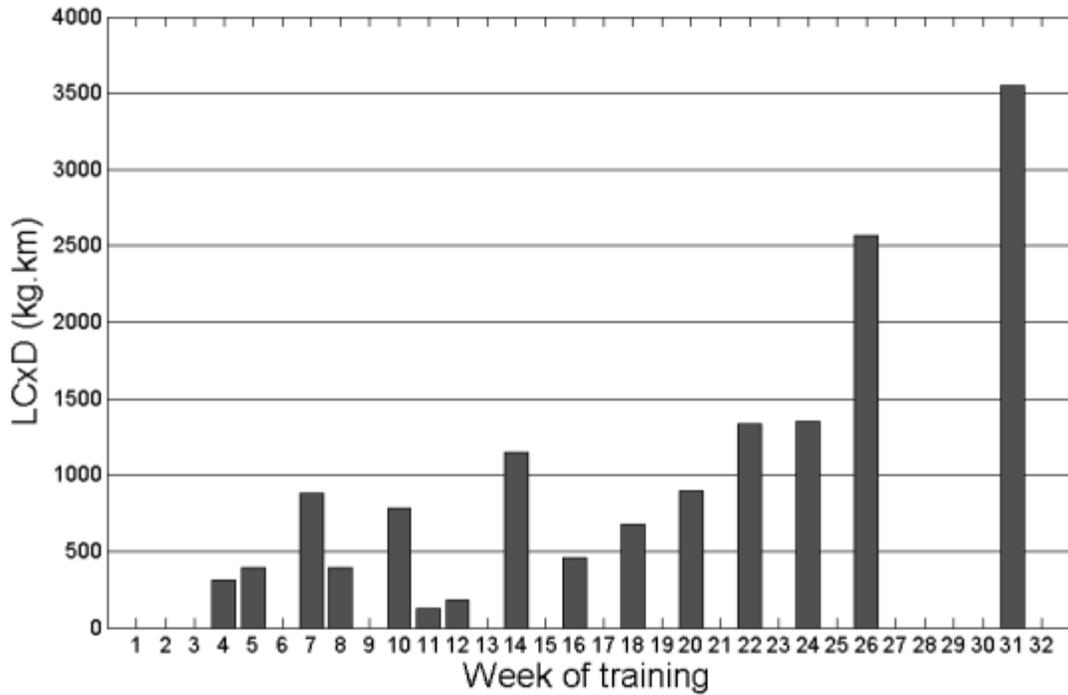


Figure 5.3: Weekly sum of load carriage multiplied by distance covered during Distance Activities

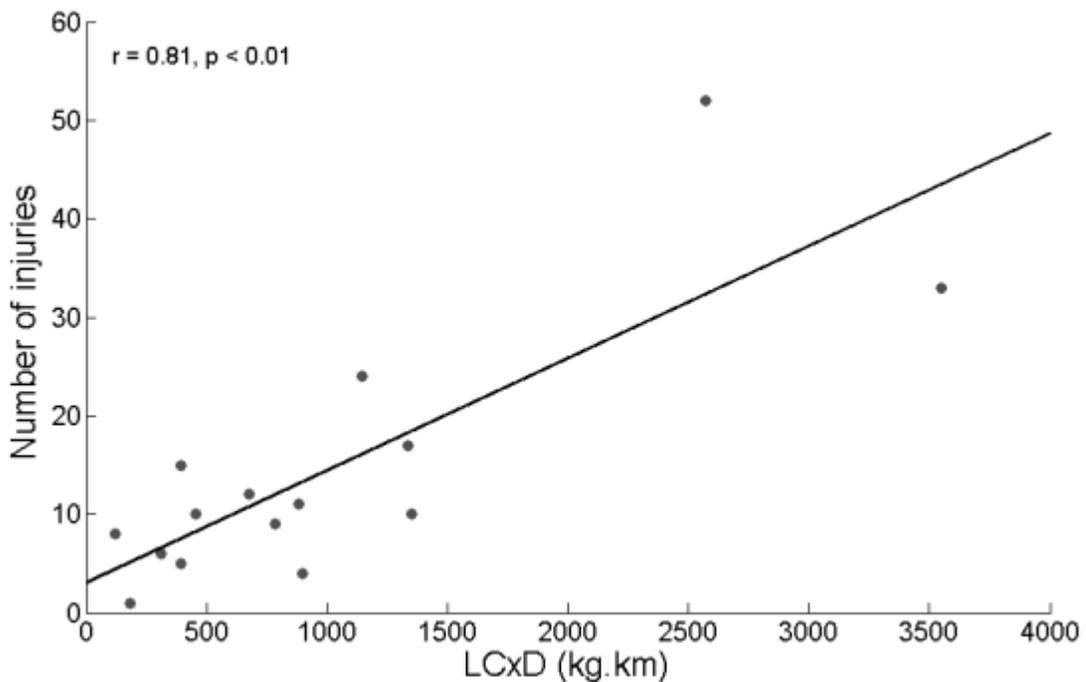


Figure 5.4: Relationship between LCxD and injury occurrence
 Note: Each point represents a training week; weeks where the number of cases was zero have been excluded.

There were eight weeks of training with no recovery time (full days of leave), including weeks 22, 26 and 31 (three of the four weeks of highest injury occurrence). However, there was no association between recovery time and injury occurrence. Criterion tests took place in weeks 7, 9, 14 (two tests), 24, 30 and 31 (three tests). There was a strong association between the number of criterion tests per week of training and tibial stress fracture occurrence ($r = 0.92$, $P < 0.05$). There was no association between type of footwear worn and injury occurrence.

5.4 Discussion

The purpose of this observational review was to quantify training variables associated with the Royal Marine recruit training programme by week of training, in order to identify relationships between training variables and injury incidence. The review was limited by its observational nature and the requirement to approximately quantify training variables in order to support the objective analysis. However, it provides a useful overview of the training programme and has successfully identified associations between training variables and injury incidence. The results can therefore direct future study in this area.

The injury incidence in week-26 is considerably higher than during all other weeks of training. Injuries are an inevitable part of an arduous physical training programme, but such a high relative value suggests an association with the training programme. The first four days of week-26 include six load carriage activities (each with 13.7 kg additional load). Day five includes two Distance Activities (19.2 km and 9.6 km with 35.5 kg additional load). Day six includes one load carriage activity (13.7 kg additional load) and day seven includes a 16 km Distance Activity (35.5 kg additional load). The combination of repeated load carriage activities and limited opportunities to recover during week-26 may contribute to the high injury incidence in this week.

Overall injury incidence and incidence of metatarsal stress fracture were considerably higher in Phase-2 of training than Phase-1. This is likely to be the result of a number of factors. The training becomes more demanding as it progresses, with recruits required to carry heavier loads and to cover longer

distances on foot. There are also more consecutive days of demanding physical activities, with no increase in recovery time. This may result in an accumulation of microdamage as the programme progresses, increasing the risk of stress fracture (Beck, 2000). Unaccustomed activity is also known to result in microdamage (Teague, 2009). However, the fact that the incidence of metatarsal stress fractures was higher in the latter phases of training suggests that the majority of recruits were sufficiently accustomed to the activities at the start of training. Therefore stress fractures likely developed as a result of excessive loading, insufficient recovery or a combination of the two, rather than as a result of unaccustomed activity. Royal Marine recruits are required to complete initial military fitness tests, and to attain a minimum standard of physical fitness, prior to commencing the training programme and thus recruits typically train for activities of this nature in preparation for these tests. This supports the suggestion that the majority of stress fractures in this population do not occur as a result of unaccustomed activity,

It is interesting that peak tibial stress fracture occurrence (week-31) coincides with low exercise-related lower leg pain occurrence and vice versa. Peak exercise-related lower leg pain (week-26) occurs earlier in the programme, which supports the notion that the two injuries are on a continuum, with tibial stress fractures being a development of exercise-related lower leg pain (Roub, et al., 1979). It may be that recruits who sustained tibial stress fractures in week-31 were experiencing symptoms of exercise-related lower leg pain in week-26, but did not report the injury such that this developed into a tibial stress fracture.

Existing evidence has demonstrated that high volumes of military training are associated with injury risk within military populations (Almeida, et al., 1999; Pope, 1999). Training volume was not associated with injury occurrence in this review, but the volume of training within a military population is likely to be high throughout the programme relative to the training volumes of civilian populations. The nature of military training may be more important than total time assigned to training, hence the strong association between distance covered and injury occurrence, as previously reported (Jones, Cowan, & Knapik, 1994). Alternatively, as increased distance covered is likely to be associated with increased training volume, it may

be that the method of quantifying training volume did not provide a valid representation of actual training volume. Distance covered was determined from Distance Activities which could be more accurately quantified. The high volumes of training in weeks 29 and 30 preceded week-31, which was the week of second highest injury occurrence. The cumulative effects of this training may have influenced injury risk, but this could not be assessed. Volume of weight-bearing activity was assessed by excluding swimming training (which comprised only a small proportion of all training), with the majority of swimming training occurring in the first nine weeks. Therefore there was little difference between volume of training with and without the inclusion of non-weight-bearing activity. There was insufficient evidence to understand the influence of footwear on injury incidence. The variable was very closely associated with the nature of the activity, for example drill boots were exclusively worn during drill activity. The influence of different activities and footwear on injury risk requires further, independent investigation.

Load carriage during Distance Activities was associated with increased injury occurrence, with a particularly high cumulative load carried during week-26. The addition of load has previously been associated with increased risk of metatarsal stress fracture (Arndt, et al., 2002), and this may explain the high incidence of metatarsal stress fractures in week-26. The load recruits are required to carry is determined relative to military occupational requirements, and is not proportional to body mass. Recruits with a lower body mass are therefore required to carry a greater relative mass, and may be at increased risk of injury (Davey, et al., 2011). The value calculated for cumulative load has no practical meaning and is influenced by frequency of load carriage activities. Thus, LCxD may provide a more useful indicator of the influence of Distance Activities on injury incidence, despite its limitations. The statistical analyses, which identified distance covered and LCxD as being strongly associated with injury occurrence, may have been influenced by two very high data points (Figures 5.2 and 5.4). These data points should not be ignored as they represent weeks 26 and 31, which were the two weeks of highest injury incidence (25.5% of total injury incidence when combined). The results of this review strongly suggest an association between load carriage Distance

Activities and injury incidence. This supports previous associations between load carriage activities and injury occurrence (Birrell, Hooper, & Haslam, 2007; Knapik, et al., 1992; Orr, et al., 2014), and particularly stress fracture occurrence (Knapik, Reynolds, & Harman, 2004; Orr, et al., 2014) in military populations.

The values for recovery time do not provide an indication of the time between the more demanding activities or the quality of recovery time. However, three of the weeks of highest injury incidence included no full days of recovery, which supports previous findings, that insufficient recovery and injury occurrence are associated (Kibler, Chandler, & Stracener, 1992). The risk of excessive microdamage accumulation is increased with insufficient recovery from loading (Brukner & Bennell, 2001). This mechanism may contribute to the high metatarsal stress fracture incidence in week-26 during which there were ten load carriage activities with no days of recovery. The high proportion of metatarsal stress fractures occurring in Phase-2 may be the result of excessive bone damage accumulation in the latter training phase.

The strong association between tibial stress fracture incidence and number of criterion tests should be interpreted with caution, as there were few data points for this variable. There was more than one test in two of the four weeks of highest injury incidence (weeks 14 and 31) and this may be important. Recruits are likely to exert maximal efforts during career-defining criterion tests, increasing the risk of injury as a result of increased training intensity (Jones, Cowan, & Knapik, 1994). The low incidence of exercise-related lower leg pain in week-31 (week of peak tibial stress fracture occurrence) suggests that the exertion of a maximal effort may have resulted in critical limits being exceeded, resulting in fracture. It is important to consider that reporting of injuries may be influenced by the timing of activities within the training programme. Recruits may delay the reporting of an injury until they have completed an exercise, particularly if this exercise takes place away from the Commando Training Centre. Furthermore, recruits may consider that failure of a criterion test as a result of injury is more honourable than failure as a result of not meeting standards.

Although training variables have been associated with injury incidence in this report, changing the training programme may not be a realistic solution. The challenge of completing physically demanding tasks with minimum recovery time is essential to the physical and psychological development of recruits during training. Furthermore, serving Royal Marine personnel have confidence that colleagues have achieved the required standard, and this is important for frontline operational decisions. However, these training variables should be further investigated to inform how recruits might be better prepared to minimise injury risk. In particular an understanding of the mechanistic changes to the lower limb during load carriage Distance Activities may help to understand stress fracture development, allowing interventions to be tested.

5.5 Conclusions

This review identified the weeks of training during the Royal Marine recruit training programme in which injury incidence was highest. Total distance covered, as well as the burden of prolonged load carriage activities, were associated with increased injury incidence. The timing of criterion tests, which require a maximal effort, was associated with tibial stress fracture incidence. Further investigation is required to understand the mechanisms by which these activities may increase risk of lower limb injury. Assessment of gait changes which result from completion of a load carriage Distance Activity may improve understanding of mechanisms for lower limb injury development.

5.6 Progression from Chapter 5 to Chapter 6

Chapter 4 identified characteristics associated with injury occurrence. An understanding of gait changes as a result of completing a physically demanding training activity may help to further understand mechanisms by which injuries develop. The aim of Chapter 6 was to identify these changes. It was decided that it would be most beneficial if the training activity selected for this study was one that has previously been associated with injury occurrence. The findings from Chapter 5 can be used to identify the most relevant military activity for this assessment. Using a real-life training activity which is part of the recruit training programme was considered important when assessing gait changes, as the injuries sustained during training are likely to be influenced by the specific nature of these training activities. A laboratory-based activity that is representative of a training activity would have allowed more control of many variables. However, the training programme is highly demanding, and it would have been unethical and practically very difficult to include an additional training activity within the programme for the benefit of research. Furthermore, external factors such as the recovery time prior to the activity used in the protocol, and the influence of completing the activity as part of a troop may be influential in the development of injury. Such ecologically specific factors could only be captured using a training activity that is already part of the recruit training programme.

The review of the training highlighted that overall injury occurrence was more than two times greater in the latter phase of training compared with the earlier phase, and metatarsal stress fracture incidence was over seven times greater in this latter phase. Therefore, the first criterion for selection of an activity for the assessment of gait changes was that the activity occurred in the latter phase of training. Prolonged load carriage activities and criterion tests were the activities most strongly associated with injury occurrence, and specifically stress fracture occurrence. Thus the second criterion was that the selected activity would be either a prolonged load carriage activity or a criterion test. There were several appropriate activities in terms of these criteria. The activity ultimately selected was influenced by logistics and practicalities in addition to the results of the review. A

number of the prolonged load carriage activities and criterion tests that occur throughout the programme transition immediately into another training activity, often skill-based. These skill-based activities are compulsory and are timed to be completed following a demanding training activity in order to assess the ability of recruits to complete tasks when mentally and physically fatigued, simulating the conditions a trained Royal Marine may face when deployed on operations. To assess gait characteristics after recruits had completed a physically demanding activity followed by a less physically demanding skill-based activity would give recruits an opportunity to recover, which may influence the findings. Therefore a third criterion was that recruits would be able to commence data collection immediately upon completion of the training activity.

A 12.8 km load carriage activity, with 35.5 kg of load was selected as the most suitable activity for the assessment of gait changes. This training activity is colloquially named the '8-miler' amongst personnel at the Commando Training Centre. The 8-miler occurs in week-21 of training and is a prolonged load carriage activity, thus meets the first two criteria. The third criterion is also met, as recruits were able to commence the data collection process immediately upon completion of the activity, which finished within approximately 300 metres of the data collection site. This activity is the longest recruit training activity that met all of the criteria detailed above. It has been anecdotally reported that altered gait can be observed in recruits following this activity. Furthermore, observation of a 19.3 km load carriage (35.5 kg) activity by investigators increased confidence in this anecdotal evidence, as investigators observed qualitative gait changes from as early as 6 km into the activity. This activity followed six days of training which were not designed to be physically demanding, focusing predominantly on skill-based tasks. It must be acknowledged that these tasks included a physical component, but they were deemed less physically demanding than the majority of physical training activities within the programme. Therefore any gait changes observed would be likely to be the result of the 8-miler, rather than the result of an accumulation of physically demanding activities. It must be noted that at the time this review was conducted, the 8-miler occurred in week-22, the week of fourth-highest injury occurrence. This makes this activity highly suitable for the assessment of gait changes. Prior to the

commencement of data collection for the following experimental studies, this activity was moved to week-21 of training. It would be interesting to monitor injury occurrence by week of training in future to see whether injury incidence in week-21 increases as a result of the inclusion of the 8-miler in this week.

CHAPTER 6: Influence of completing a prolonged load carriage activity on plantar pressure and lower limb kinematics

A version of this chapter has been distributed as an Institute of Naval Medicine Report (see p.14), and submitted for publication in an international journal.

6.1 Introduction

The high injury rate reported in the Royal Marine recruit population may reflect the attributes of the training programme, which includes frequent, prolonged load carriage activities. Such activities are known to be associated with lower limb injury occurrence in military recruits (Birrell, Hooper, & Haslam, 2007; Knapik, et al., 1992; Orr, et al., 2014), and specifically with the high stress fracture occurrence in the Royal Marine recruit population (Ross & Allsopp, 2002). This was supported by the results from the observational review of the recruit training programme (Chapter 5), which identified an association between prolonged load carriage activities and stress fracture occurrence.

Stress fractures are the result of excessive, repetitive stress on a bone (Arendt, 2000), which may explain their prevalence in populations who frequently participate in weight-bearing, endurance activities. The mechanisms by which prolonged load carriage activities may exacerbate stress fracture risk are presently unclear. Following walking and running activities, metatarsal loading and heel loading have been reported to increase (Escamilla, Weist, Rosenbaum, Willems), whereas loading under the lesser toes (Escamilla-Martínez, et al., 2013; Nagel, et al., 2008; Stolwijk, et al., 2010; Willems, De Ridder, & Roosen, 2012) and hallux (Bisiaux & Moretto, 2008; Nagel, et al., 2008; Stolwijk, et al., 2010) have been reported to reduce. Increased loading under the metatarsals may increase risk of metatarsal stress fracture. Following consecutive days of walking activity, reduced metatarsal loading was reported in addition to further increases in heel loading (Stolwijk, et al., 2010). This shift of loading to the rearfoot may be a mechanism to avoid pain, with 88% of the study population reporting foot pain, 22% of which occurred in the forefoot.

Low arch height has been proposed as a risk factor for metatarsal stress fracture due to its suggested greater susceptibility to fatigue (Bennell, et al., 1999). Indeed, fatigue of the plantar intrinsic foot muscles has been shown to increase navicular drop (Headlee et al., 2008). It is unknown whether changes to midfoot loading occur as a result of completing a prolonged weight-bearing activity, and measures of midfoot contact percentage could be used to give an indication of this. This variable was used in Chapter 4 to give an indication of dynamic foot characteristics.

Lower limb kinematic changes are likely to occur following a prolonged load carriage activity as a result of muscular fatigue, although there is currently a lack of understanding in this area. Dynamometer-induced knee extensor fatigue has been associated with increased knee flexion and a more plantar flexed ankle at touchdown during walking (Parijat & Lockhart, 2008). However, kinematic changes following prolonged weight-bearing activities may differ from these. Investigation of synchronised plantar pressure and kinematic changes following a military-specific load carriage activity is required. Gait changes as a result of such an activity may relate to the characteristics associated with Royal Marine training injuries in Chapter 4, particularly as activities of this type were associated with stress fracture occurrence in Chapter 5.

The aim of this study was to investigate changes to barefoot plantar loading and lower limb kinematics following a prolonged load carriage activity in Royal Marine recruits. It was hypothesised that there would be reduced loading under the toes and hallux, accompanied by increased metatarsal and rearfoot loading, as well as increased knee flexion and ankle plantar flexion at touchdown post- compared with pre-activity.

6.2 Methods

6.2.1 Participants

Thirty-two Royal Marine recruits volunteered to participate in the study, which was undertaken in week-21 of their 32-week training programme. The sample size was determined based on previous findings of altered plantar pressure variables

following running in studies of 30 participants (Weist, Eils, & Rosenbaum, 2004) and 11 participants (Bisiaux & Moretto, 2008). Effect sizes from this latter study were used to determine sample size. A mean difference of peak plantar pressure under the hallux of 15 kPa with a standard deviation of 14.5 kPa indicated that a sample of approximately 30 recruits would give an 80% chance of detecting changes to plantar loading at the 5% significance level (Altman, 1980). All volunteer recruits were injury-free and had completed the required training up to the point of data collection without being removed from mainstream training for any reason. Within these criteria, recruits were randomly selected from three different training troops who had followed the same training programme. All data were collected in an 8-week period between April and June 2013. Volunteer recruits had a mean (SD) age: 22.2 (3.8) years, body mass: 82.4 (8.4) kg, height: 178.4 (6.1) cm, and body mass index (BMI): 25.9 (2.0) kg.m⁻². The study was approved by the Ministry of Defence Research Ethics Committee (MODREC), and all recruits gave informed consent.

6.2.2 Protocol

As part of the Royal Marines recruit training programme, all recruits are required to complete a prolonged load carriage activity, covering 12.8 km on foot, whilst carrying an additional load of 35.5 kg, in week-21 of the training programme (the 8-miler). The mode of activity is described as 'yomping', and includes predominantly walking activity, with occasional short periods of running activity. This study collected barefoot running data pre- and immediately post- this load carriage activity. The training activity took place on uneven terrain at varying paces. The approximate duration of the activity was 150 minutes, thus the average speed was 5.12 km.h⁻¹ (1.4 m.s⁻¹). The training team determined the pace of the activity, and all recruits were required to complete the activity together. Recruits wore military issue clothing and boots throughout the activity. The activity paused approximately every hour for water breaks, and recruits were encouraged to eat regularly throughout the activity. The load consisted of a filled Bergen (large rucksack) and

webbing (worn like a belt to carry additional military equipment) with a combined mass of 31.3 kg (Figure 6.1), and a weapon (4.2 kg).



Figure 6.1: Bergen and webbing worn throughout the prolonged load carriage activity

6.2.3 Data collection

Bilateral, synchronised plantar pressure and lower limb kinematic measurements were recorded during barefoot running at $3.6 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$). This protocol was used in Chapter 4 to identify lower limb biomechanical gait characteristics associated with tibial stress fracture, metatarsal stress fracture and ankle inversion injury occurrence in the same population. Administering the same protocol allowed assessment of changes to the variables associated with injury occurrence, as a result of the prolonged load carriage activity. Furthermore, the decision to use a barefoot rather than shod running protocol was influenced by previous findings which suggest that gait characteristics are more pronounced when barefoot than shod (Willems, et al., 2007).

Kinematic data were collected with two Coda Mpx30 units at 200 Hz (CodaMotion, Charnwood Dynamics, UK) using eleven active markers per leg. The marker locations were displayed in Figure 3.3 (p.40). Marker positions were identified with pen to allow reliable replacement following the training activity, with the exception of the hip marker, which was relocated by palpation of the greater trochanter. Markers were held in position using Micropore™ tape (3M, USA). Plantar pressure was recorded using a 2 m pressure plate (RSscan International, Belgium, 4 x 0.5 m x 0.4 m, 4096 sensors, 125 Hz) positioned and marked in the middle of a 10 m EVA runway. The data collection setup is displayed in Figure 3.10 (p.48).

Recruits were asked to complete running trials with a relaxed running style, ensuring that two consecutive steps contacted the plate. Foot strike modality and order of foot placement were self-selected. Standard issue shorts and combat shirts were worn during data collection. Recruits completed familiarisation trials until successful trials were repeated. A successful trial was one in which the run appeared relaxed, the speed was within the required range, and there was no observed adjustment for plate contact. Five successful running trials were recorded per recruit, followed by a standing trial, in which recruits stood in a relaxed position with legs shoulder-width apart. Post-activity data collection commenced as soon as possible upon completion of the activity. Recruits finished the activity at the location of data collection and immediately removed their Bergen, webbing and weapon, and replaced their combat trousers with shorts. The time between recruits completing the activity and starting running trials was recorded (range: 10-84 min, mean (SD): 44 (21) min). Gait changes as a result of the prolonged load carriage activity are likely to reduce with increased recovery time. There is limited assessment of recovery of biomechanical variables following fatiguing activity, and these have involved fatigue induced using diverse protocols (Bisiaux & Moretto, 2008; Horita et al., 1999; Tsai et al., 2009). Consequently a range of recovery times of biomechanical variables have been reported (30 – 120 min). Recovery time is likely to be influenced by the levels of fatigue induced. A maximum recovery time of approximately 90 min was set, based on these existing findings as well as considerations about the practicalities of data collection from the required number of recruits, within a time-pressured environment. Energy and water intake were not

controlled upon completion of the activity, as these factors were not controlled during the training activity.

6.2.4 Data analysis

Pressure trials were exported from the Footscan software (RSscan International, Version 7). The software automatically divides the foot into zones (Figure 6.2) and these were manually adjusted (Appendix E). Peak pressure, time of peak pressure, and impulse under each zone were evaluated. The foot was also divided into rearfoot (medial and lateral heel zones), midfoot, and forefoot (hallux, lesser toe and metatarsal zones) regions. The relative impulse (%) under each of these regions, and their relative contribution to total ground contact area (contact %) were also examined.

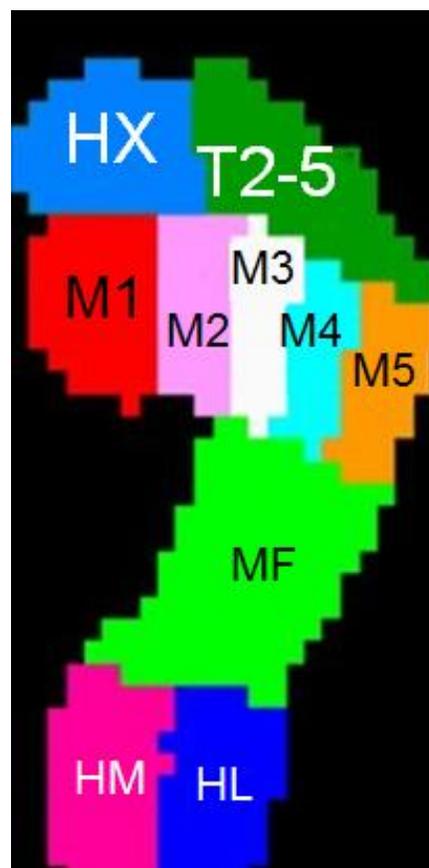


Figure 6.2 (Replica of Figure 3.2 for convenience): Plantar zone divisions within Footscan software

HX: Hallux; T2-5: lesser toes; M1-M5; first to fifth metatarsals; MF: midfoot; HM: medial heel; HL: lateral heel

Kinematic data were obtained using a 3D model, as described in section 3.4.6. Knee flexion and ankle dorsiflexion were characterised by calculation of touchdown angle, peak angle, range of motion from touchdown to peak, and relative occurrence of peak angle as a percentage of ground contact time, as well as rate of angular change from touchdown to peak angle. Touchdown angle of the foot relative to the ground (Figure 6.3) was obtained, as well as stride length, which was the distance between the y coordinate of the left and right inferior calcaneus markers, at the first frame of each respective touchdown. Ground contact time was determined from pressure data. Kinematic variables were analysed using customised MATLAB scripts (R2012a, The MathWorks Inc. Natick, MA, USA). Angle time histories were observed for all exported variables, and anomalous trials were excluded. Only trials in which the time history was a distinctly different shape compared with the other time histories for that recruit were removed, as the different shape was considered to indicate an error caused either by a marker moving from its original location, or errors in tracking of the marker. This process was completed by one investigator. If more than two of the five trials were excluded, the variables associated with that time history were excluded for that recruit. The majority of cases of exclusion were deemed to be the result of insufficient marker tracking quality. Time histories subjectively appeared highly consistent throughout.

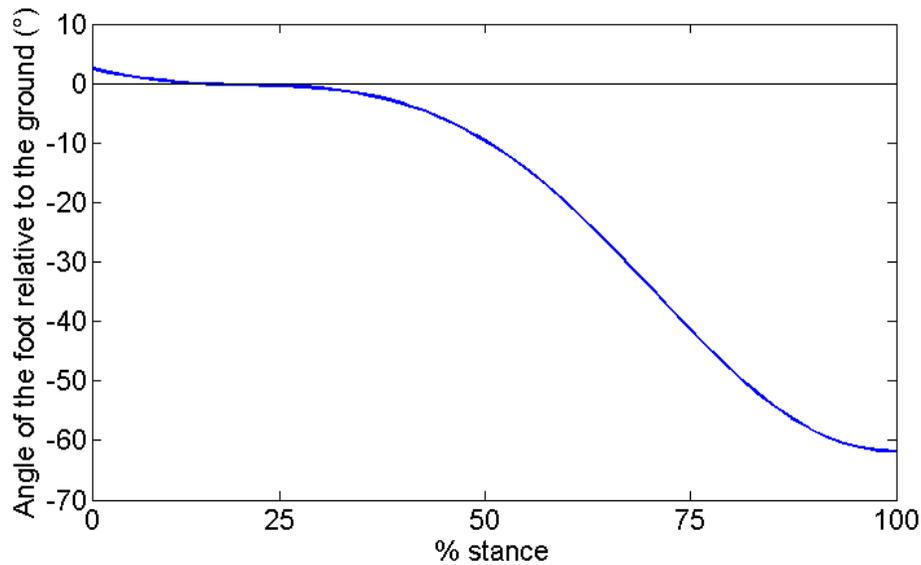


Figure 6.3: Representation of the angle between the foot and the ground during running stance (positive indicates the toes are raised relative to the heel)

6.2.5 Statistical analyses

All statistical analyses were undertaken using SPSS for Windows (Version 16.0, SPSS Inc., Chicago, IL, USA) with a statistical significance of $P < 0.05$. To determine whether pressure variables should be normalised to body weight, bivariate correlation analyses between these variables were conducted (as described in General Methods (Section 3.4.4)). Neither peak pressure ($r < 0.23$), nor impulse variables ($r < 0.32$) were associated with body weight pre- or post-activity, thus pressure variables were not normalised to body weight. Normality was determined for all variables by assessment of skewness and kurtosis values ($|z| < 1.96$ indicated normality). Data from one randomly selected leg was assessed for each recruit. Means were compared between pre- and post-activity conditions using paired t-tests (normally distributed variables) and Wilcoxon-signed rank tests (not normally distributed variables). Two-tailed values were considered for all variables, as hypotheses were based on literature that used a range of activity protocols which were different from that used in the present study. Effect sizes (d , (Cohen, 1988a)) were displayed for variables where means differed between conditions ($P < 0.05$).

6.3 Results

Following the training activity, there was a reduction in peak pressure and impulse under the hallux, toes, and first and second metatarsals (Table 6.1, Figures 6.4, 6.5, 6.6). Peak pressure occurred earlier under the hallux and lesser toes (Figure 6.5), and later under the second to fifth metatarsals (Figure 6.6), with no change in ground contact time (Table 6.2).

Table 6.1: Absolute pressure variables pre- and post-activity

Variable	N	Mean (SD)		P	d
		Pre-	Post-		
Peak HX (N.cm⁻²)	25	11.27 (5.45)	6.04 (3.86)	P < 0.001*	1.08
Peak T2-5 (N.cm⁻²)	21	2.93 (1.28)	1.59 (1.04)	P < 0.001*	1.14
Peak M1 (N.cm⁻²)	31	16.95 (6.17)	10.42 (5.22)	P < 0.001*	0.87
Peak M2 (N.cm⁻²)	29	21.98 (5.70)	17.75 (4.35)	0.002*	0.64
Peak M3 (N.cm ⁻²)	29	25.22 (8.82)	22.59 (8.49)	0.115	-
Peak M4 (N.cm ⁻²)	29	25.31 (12.23)	23.15 (9.58)	0.314	-
Peak M5 (N.cm ⁻²)	29	15.40 (7.80)	15.99 (6.88)	0.618	-
Peak HM (N.cm ⁻²)	28	15.48 (6.63)	15.98 (6.92)	0.728	-
Peak HL (N.cm ⁻²)	27	15.53 (8.15)	15.34 (9.37)	0.773	-
Impulse HX (N.s)	27	11.09 (8.04)	4.71 (3.84)	P < 0.001*	0.95
Impulse T2-5 (N.s)	27	2.61 (2.30)	1.27 (1.43)	P < 0.001*	0.88
Impulse M1 (N.s)	29	17.90 (6.29)	11.01 (6.79)	P < 0.001*	0.97
Impulse M2 (N.s)	29	23.81 (6.82)	19.19 (6.33)	0.003*	0.59
Impulse M3 (N.s)	29	24.04 (8.03)	21.76 (8.17)	0.197	-
Impulse M4 (N.s)	28	20.62 (8.95)	20.65 (9.14)	0.988	-
Impulse M5 (N.s)	28	12.60 (6.93)	13.00 (6.60)	0.649	-
Impulse HM (N.s)	29	10.01 (6.14)	11.54 (8.19)	0.300	-
Impulse HL (N.s)	29	6.74 (5.13)	7.43 (6.11)	0.533	-

* Significant (P < 0.05) difference between groups

Peak: peak pressure; HX: hallux; T2-5: lesser toes; M1- M5: first to fifth metatarsals; HM: medial heel; HL: lateral heel

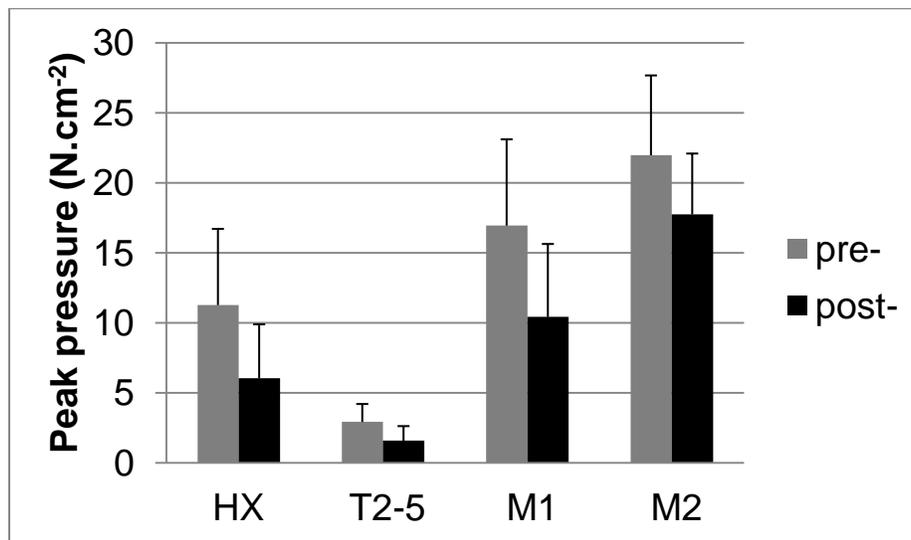


Figure 6.4: Mean (SD) peak pressures during running stance pre- and post-activity
 HX: hallux; T2-5: lesser toes; M1: first metatarsal; M2: second metatarsal

Table 6.2: Temporal pressure variables pre- and post-activity

Variable	N	Mean (SD)		P	d
		Pre-	Post-		
Ground contact time (ms)	28	209.11 (19.59)	213.40 (17.95)	0.202	-
Time Peak HX (%)	27	65.36 (6.86)	57.36 (17.38)	0.011*	0.52
Time Peak T2-5 (%)	26	59.60 (15.80)	42.53 (21.62)	P < 0.001*	0.94
Time Peak M1 (%)	29	51.97 (6.78)	51.28 (5.78)	0.575	-
Time Peak M2 (%)	29	54.90 (4.86)	59.18 (5.27)	P < 0.001*	0.86
Time Peak M3 (%)	29	53.56 (5.25)	56.32 (4.95)	0.018*	0.47
Time Peak M4 (%)	29	47.33 (6.41)	52.63 (5.90)	P < 0.001*	0.74
Time Peak M5 (%)	29	42.04 (10.30)	48.37 (9.24)	P < 0.001*	0.96
Time Peak HM (%)	30	10.38 (5.98)	12.96 (6.93)	0.065	-
Time Peak HL (%)	29	8.03 (3.30)	8.99 (4.77)	0.325	-

* Significant (P < 0.05) difference between groups

Time Peak: time of peak pressure; HX: hallux; T2-5: lesser toes; M1- M5: first to fifth metatarsals; HM: medial heel; HL: lateral heel

There was an increase in loading under the rearfoot and midfoot, and a corresponding decrease under the forefoot following the training activity (Table 6.3).

Table 6.3: Impulse and contact percentage under the rearfoot, midfoot and forefoot pre- and post-activity

Variable	N	Mean (SD)		P	d
		Pre-	Post-		
Rearfoot contact (%)	28	20.81 (2.60)	22.44 (2.42)	P < 0.001*	0.68
Midfoot contact (%)	29	21.19 (4.46)	23.31 (4.96)	0.06	-
Forefoot contact (%)	28	58.54 (5.52)	55.11 (5.22)	P < 0.001*	0.97
Rearfoot impulse (%)	30	10.56 (5.42)	12.69 (5.65)	0.028*	0.42
Midfoot impulse (%)	30	5.02 (1.51)	6.10 (2.24)	P < 0.001*	0.74
Forefoot impulse (%)	30	84.23 (5.53)	81.21 (6.44)	0.001*	0.50

* Significant (P < 0.05) difference between groups

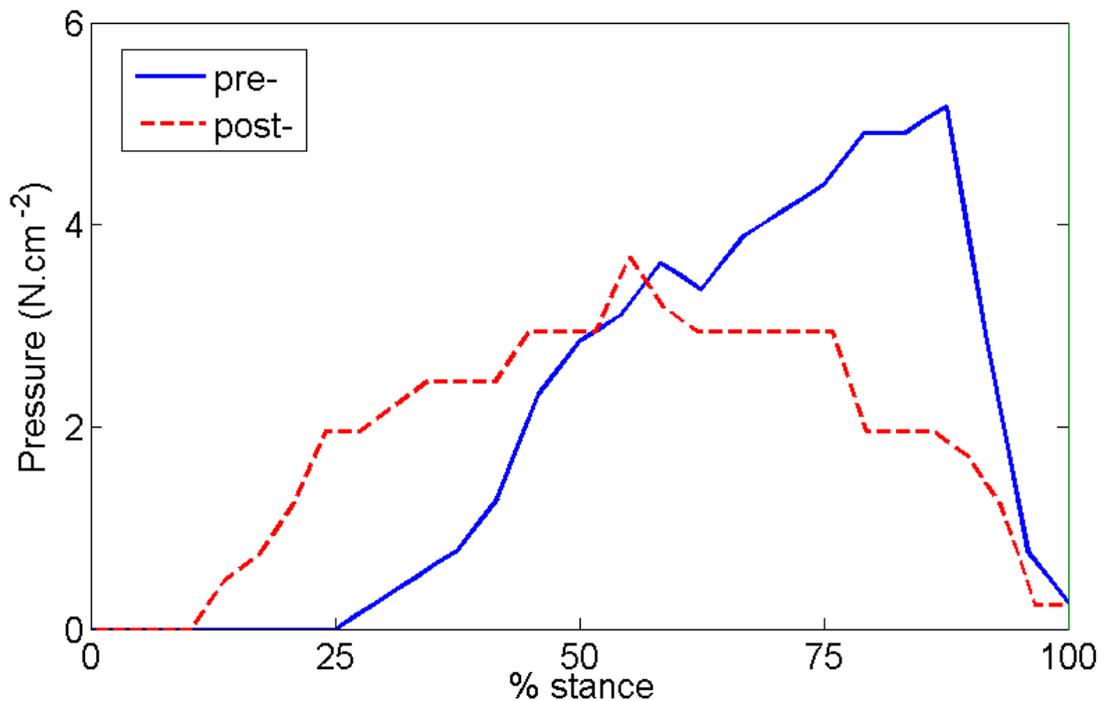


Figure 6.5: Sample time history demonstrating pressure under the lesser toes during running stance, pre- and post-activity

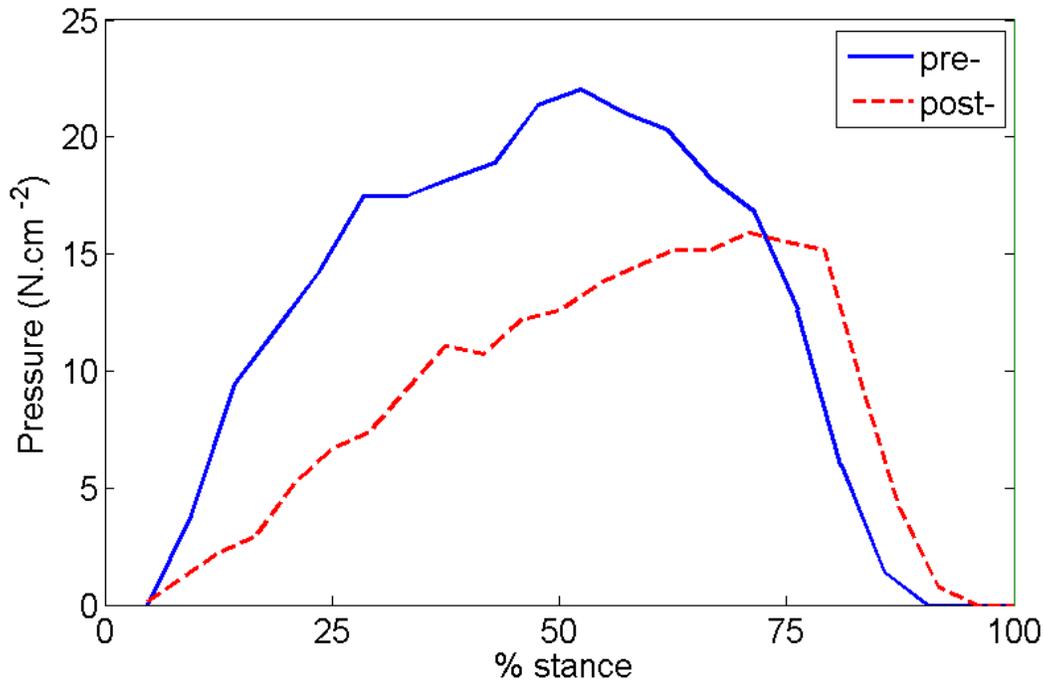


Figure 6.6: Sample time history demonstrating pressure under the second metatarsal during running stance, pre- and post-activity

Kinematic data are reported in Table 6.4. Following the activity, there was no change in stride length. There was no change in the angle between the foot and the ground, with the toes raised relative to the heel at touchdown in both conditions, typical of a heel strike running style. There was no difference in dorsiflexion touchdown angle or rate, but an increase in peak dorsiflexion angle and dorsiflexion range of motion post-activity (Figure 6.7). There were no changes to knee flexion variables as a result of the activity.

Table 6.4: Kinematic variables pre- and post- activity

Variable	N	Mean (SD)		P	d
		Pre-	Post-		
Stride length (%)	31	69.25 (5.98)	69.67 (6.38)	0.630	
Foot angle at touchdown (°)	22	2.67 (3.99)	2.40 (2.37)	0.961	
Dorsiflexion touchdown (°)	18	-2.49 (4.66)	-0.69 (6.14)	0.343	
Peak dorsiflexion (°)	18	10.48 (3.83)	15.34 (5.16)	0.001*	0.95
Time of peak dorsiflexion (%)	19	46.62 (5.91)	50.78 (8.07)	0.075	
Dorsiflexion ROM (°)	19	13.28 (3.12)	16.15 (4.81)	0.031*	0.54
Dorsiflexion rate (°.sec ⁻¹)	17	137.93 (24.06)	138.96 (28.61)	0.910	
Knee flexion touchdown (°)	23	21.72 (5.32)	20.69 (6.37)	0.398	
Peak knee flexion (°)	23	31.31 (4.26)	31.00 (6.87)	0.822	
Time of peak knee flexion (%)	27	32.59 (4.92)	34.14 (5.92)	0.810	
Knee flexion ROM (°)	28	8.76 (3.87)	10.30 (2.97)	0.058	
Knee flexion rate (°.sec ⁻¹)	27	129.72 (41.03)	141.33 (31.08)	0.128	

* Significant (P < 0.05) difference between groups

ROM: range of motion.

Note: Angles are reported relative to the standing 'neutral' position, such that zero degrees of dorsiflexion and knee flexion would be reported in the standing trial. A positive dorsiflexion angle indicates a dorsiflexed ankle relative to standing. A positive knee flexion angle indicates a flexed knee relative to standing. A positive foot angle at touchdown indicates that the toes are raised relative to the heel. The reduced N values are a result of values being required both pre- and post-activity to allow comparisons. If data were missing in either condition, that variable had to be excluded for that recruit.

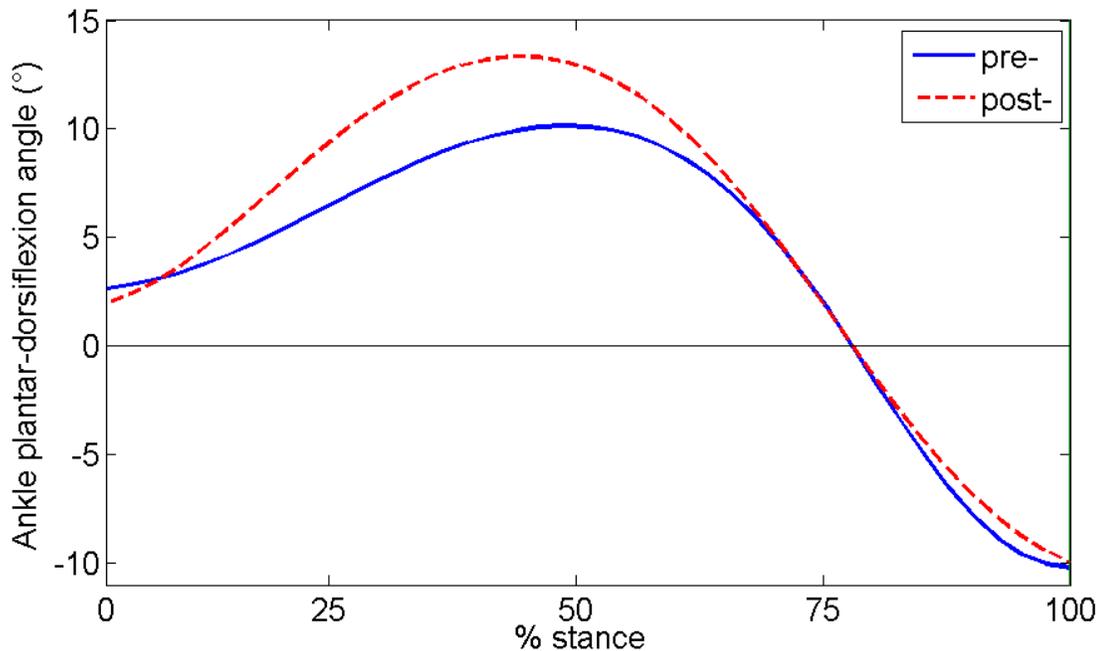


Figure 6.7: Sample time history demonstrating ankle plantar-dorsiflexion angle during running stance, pre- and post-activity

6.4 Discussion

As hypothesised, there was reduced loading under the lesser toes and hallux following the training activity, which was consistent with previous findings (Bisiaux & Moretto, 2008; Escamilla-Martínez, et al., 2013; Nagel, et al., 2008; Stolwijk, et al., 2010; Willems, De Ridder, & Roosen, 2012). The increased rearfoot loading was also consistent with previous findings after over 40 km of walking activity (Stolwijk, et al., 2010) and consistent with the hypothesis. These findings are likely associated with the observed increase in midfoot loading, and corresponding decrease in forefoot loading. The results are indicative of a reduced ability to transfer load from the rearfoot to the forefoot following the activity. Further evidence of this was provided by the changes in time of peak pressure occurrence.

Peak pressure under the lesser toes occurred at 60% of stance pre-activity, which coincides with usual time of forefoot push-off as determined by De Cock et al., (2005), during running trials at a similar speed ($3.3 \text{ m}\cdot\text{s}^{-1}$). This peak pressure occurred at 43% of stance post-activity, prior to this typical push-off phase. This

suggests that the toes have a reduced contribution to push-off following the activity. Reduced contribution of the toes during push-off has previously been reported following a marathon running race (Nagel, et al., 2008). This reduced contribution was suggested to result in increased dorsiflexion at the metatarsophalangeal joint, which reportedly results in increased second metatarsal bending load (Jacob, 2001), and may therefore explain the relatively high incidence of metatarsal stress fractures amongst long distance runners. Future research in this area would benefit from the measurement of metatarsophalangeal dorsiflexion. Overall, the results of the present study which are consistent with existing literature, suggest that a reduced toe contribution to push-off may be a mechanism for metatarsal stress fracture development following prolonged load carriage activity in Royal Marine recruits.

The reduced loading under the metatarsals was contrary to the hypothesis and to previous findings (Bisiaux & Moretto, 2008; Escamilla-Martínez, et al., 2013; Nagel, et al., 2008; Weist, Eils, & Rosenbaum, 2004; Willems, De Ridder, & Roosen, 2012), which have reported increased metatarsal loading following running activities. However, reduced metatarsal loading has previously been reported following consecutive days of walking activity (Stolwijk, et al., 2010), suggesting that this change may be influenced by the mode of activity. The existing results were suggested to be a mechanism of pain avoidance. This may be true of the reduced metatarsal loading observed in the present study, as Royal Marine recruits complete regular load carriage activities throughout the programme, and the additional demands of carrying load may advance the onset of pain. Pain was not reported by recruits during data collection in the present study, but recruits may have altered their gait as a mechanism to reduce metatarsal discomfort.

The increased midfoot loading may be evidence of plantar intrinsic foot muscle fatigue, where fatigue of these muscles has previously been shown to increase navicular drop (Headlee, et al., 2008). It has been suggested that these muscles are influential in the push-off phase of stance (Bennell, et al., 1999), which means they would be susceptible to muscular fatigue. The plantar intrinsic foot muscles play a role in countering metatarsal bending, and may be less able to do so

following the activity, thereby increasing risk of stress fracture (Sharkey, et al., 1995).

Peak metatarsal pressures occurred later post-activity than pre-activity. The later peak pressures occurred closer to the time of typical foot push-off (De Cock, et al., 2005). This suggests a reduced active contribution to push-off, instead relying on forward inertia to induce this action. This is further indication of a reduced ability to push-off which is likely influenced by muscular fatigue. Later peak metatarsal pressures were also found in recruits who sustained metatarsal stress fractures during training in the prospective study in this thesis (Chapter 4). Thus recruits who exhibit this characteristic at the start of training may have a reduced muscular contribution to the push-off phase of stance, resulting in increased metatarsal bending and therefore increased risk of stress fracture (Sharkey, et al., 1995).

The observed increases in peak dorsiflexion angle post-activity were in contrast to the hypothesis. Increased dorsiflexion may be a mechanism to lower the centre of mass in order to maintain postural stability. Existing findings have reported increased plantar flexion angle at touchdown following dynamometer-induced knee extensor muscle fatigue (Parijat & Lockhart, 2008). The specific activity may influence the mechanistic changes, and this highlights the importance of assessing activity-specific gait changes. Furthermore, there is no evidence from the present study to suggest there was knee extensor muscle fatigue which may explain the difference in findings between the studies. This may also explain why no differences in knee flexion angle were observed, contrary to the hypothesis. Increased dorsiflexion may increase sagittal plane bending of the tibia by increasing the bending moment arm length. During running, the proximal tibia bends to the posterior in the sagittal plane (Yang et al., 2014) (Figure 6.8). Increased sagittal plane bending has been suggested to result in increased tibial bending moments, which may increase risk of stress fracture (Haris Phuah et al., 2010). The observed increase in peak dorsiflexion angle following the activity may also indicate reduced function of the ankle plantar flexor muscles, which provide eccentric dorsiflexion control during midstance. These muscles have been found to be susceptible to fatigue during walking due to their important contribution to push-

off (Meinders et al., 1998; Stefanyshyn & Nigg, 1997). Fatigue of these muscles has been associated with increased tensile strain in the tibia (Milgrom, et al., 2007), and this may increase the risk of stress fracture. This suggested mechanism for tibial stress fractures is consistent with that proposed previously (Chapter 4), where evidence linking a smaller calf girth to increased tibial stress fracture risk in Royal Marine recruits was reported. There are known associations between muscle size and fatigability as a result of resistance training (Bird, Tarpenning, & Marino, 2005), thus a smaller calf girth may be an indication of greater fatigue susceptibility in the calf plantar flexor muscles. Training in a fatigued state has been suggested as a major contributor to the relatively high stress fracture occurrence in military populations (Milgrom, et al., 2007). It should be acknowledged that calf girth in isolation does not provide an indication of muscle fibre type, and these suggestions are therefore speculative.

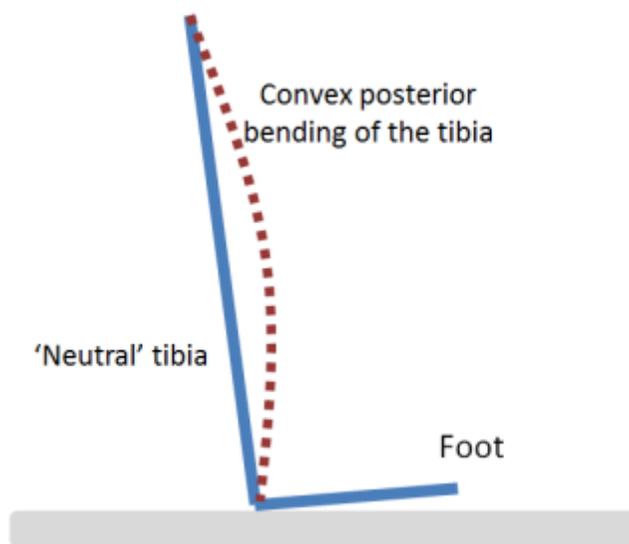


Figure 6.8: Representation of convex posterior bending of the tibia (dashed line)

As well as their role in minimising tensile strain in the tibia, activity of the plantar flexor muscles has been shown to reduce metatarsal bending moments (Sharkey, et al., 1995). Therefore reduced plantar flexor muscle activity, as indicated by the increased peak dorsiflexion angle and the reduced ability to transfer load from the

rearfoot to the forefoot, may cause increased metatarsal bending moments. Reduced plantar flexor muscle activity also reportedly results in increased metatarsal strain and therefore risk of stress fracture (Arndt, et al., 2002). Cadaver models have indicated that with reduced activity of the foot plantar flexor muscles (flexor hallucis longus and flexor digitorum longus) there is reduced pressure under the toes during push-off (Ferris et al., 1995). Therefore the decrease in loading under the toes and hallux post-activity in the present study provide further evidence of plantar flexor muscle fatigue. Data from the present study strongly suggest plantar flexor muscle fatigue post-activity, but it is acknowledged that muscular activity was not measured. Future studies in this area should consider the assessment of foot muscle strength and endurance post- compared with pre-activity.

The barefoot running protocol used in the present study was the same as that used in the prospective study in Chapter 4, in order to identify associations between altered gait as a result of prolonged load carriage activity, and gait characteristics that predispose to injury occurrence. In Chapter 4, greater heel loading was identified in recruits who sustained tibial stress fractures compared with injury-free recruits. The increased rearfoot loading reported post-activity in the present study may be associated with this finding. Recruits who sustained tibial stress fractures (Chapter 4) demonstrated higher vertical loading close to the tibia without having completed a prolonged load carriage activity. An increase in rearfoot loading following such an activity may further increase these vertical forces, and therefore risk of stress fracture development. Recruits who sustained metatarsal stress fractures in Chapter 4 demonstrated later peak metatarsal pressures during barefoot running than injury-free recruits. The later peak metatarsal pressures post-activity reported in the present study may be associated with this. Peak metatarsal pressures post-activity occurred at a similar time to those reported in recruits who sustained third metatarsal stress fractures (Table 6.5). This was suggested to be evidence of a reduced ability to push-off during stance following the activity. Recruits who sustained metatarsal stress fractures (Chapter 4) may have a reduced ability to push-off prior to undertaking such an activity. These characteristics may be more pronounced post-activity.

Table 6.5: Time of peak second and third metatarsal pressure during barefoot running ($3.6 \text{ m}\cdot\text{s}^{-1}$) from Chapters 4 and 6

	Time of peak pressure	Injury-free	Metatarsal stress fracture
Chapter 4	Second metatarsal	56.65 (4.79)%	60.40 (5.75)%
	Third metatarsal	54.70 (5.01)%	57.75 (3.88)%
	Time of peak pressure	Pre-activity	Post-activity
Chapter 6	Second metatarsal	54.90 (4.86)%	59.18 (5.27)%
	Third metatarsal	53.56 (5.25)%	56.32 (4.95)%

The present study assessed the influence of a real-life Royal Marines training activity on barefoot running gait. The results support existing findings and provide additional evidence to improve understanding of mechanistic changes as a result of a prolonged load carriage activity. Many of the findings were indicative of plantar flexor muscle fatigue, but this was not measured in the present study. To support these findings, measures of plantar flexor muscle fatigue following the same activity would be beneficial. Measurement of changes to lower limb joint moments, which are influenced by muscular activity (Robertson, et al., 2013), would further improve understanding. In summary, the evidence presented in this study suggests that a prolonged load carriage activity results in a reduced ability to transfer load from the rearfoot to the forefoot, thereby increasing rearfoot loading. There is also an avoidance of metatarsal loading, possibly due to increased forefoot discomfort post-activity. This study has provided further understanding of potential mechanisms by which tibial and metatarsal stress fractures occur in this military population.

6.5 Limitations

Although the use of a barefoot running protocol has been justified, the absence of shod gait data is a limitation, as gait during barefoot running may differ from shod running, and therefore may differ from gait during the prolonged activity. It must also be acknowledged that the division of the foot into zones is a limitation of the assessment of plantar pressure changes using pressure plates. The zones

determined using Footscan software provide an estimate of the location of each anatomical area, but the validity of this is unclear. A further limitation of the study was the unavoidable recovery time which was a result of the time taken for data collection for each recruit. However, it is likely that if recruits had recovered, changes would not have been observed. The magnitude of change reported may therefore be less than would have been reported if there had been less recovery time. The data are indicative of a reduced ability to push off, with a shift of loading from the forefoot to the rearfoot. Assessment of the centre of pressure trace in addition to the variables assessed in this study may help to support this suggestion and therefore should be included in future research.

6.6 Conclusions

Completion of a prolonged load carriage activity resulted in a shift of loading from the forefoot to the rearfoot and midfoot, and an increase in peak dorsiflexion angle. This is indicative of reduced plantar flexor muscle activity, which is known to increase risk of both tibial and metatarsal stress fracture. This shift of loading may therefore be a key mechanism contributing to the high incidence of stress fractures in this population.

6.7 Progression from Chapter 6 to Chapter 7

The second experimental study (Chapter 6) assessed the influence of the 8-miler on gait changes observed during barefoot running. The findings provided insight into mechanisms by which stress fractures may develop. The suggested mechanisms were consistent with the characteristics identified in Chapter 4 as being associated with stress fracture. Gait changes were assessed during barefoot running, as this protocol was used for gait analysis in Chapter 4. The 8-miler involves both walking and running and recruits are required to wear military boots during the activity. Thus assessment of changes to walking gait whilst wearing boots may be important. Furthermore, Chapter 6 assessed plantar pressure and kinematics, but assessment of joint moments and muscular activity were not included. The findings suggested plantar flexor muscle fatigue following the activity, but this could not be confirmed. Joint moments indicate the level of muscular control required, and EMG data indicate muscular activity. Therefore these measures were included in the next study to build upon the findings presented in Chapter 6.

The 8-miler was selected as the prolonged load carriage activity in the protocol for Chapter 6 based on the findings from the training review (Chapter 5). The same protocol was also selected for Chapter 7 to build upon the findings of Chapter 6 by assessing the influence of the activity on walking in boots, with the inclusion of measures of joint moments and muscular activity. The training review (Chapter 5) also indicated that the combined effect of covering distance whilst carrying load was a more important factor in injury development than the independent influence of carrying load. However, this was determined using a variable that assumed that load carriage and distance covered are equally burdensome. The independent influence of carrying load required further investigation. The next experimental chapter assessed the influence of carrying additional load as well as completing the prolonged load carriage activity, to provide further insight into this.

CHAPTER 7: Influence of carrying load and of completing a prolonged load carriage activity on lower limb gait mechanics and muscle activity

A version of this chapter has been distributed as an Institute of Naval Medicine Report (see p.14), and submitted for publication in an international journal.

7.1 Introduction

During walking, sagittal plane movement is produced predominantly by the ankle plantar flexor and knee extensor muscles (Kepple, Siegel, & Stanhope, 1997). When a load is carried, there is an increase in ankle dorsiflexion and knee flexion angles (Harman, 2000; Kinoshita, 1985; Wang, et al., 2013), which is suggested to be a mechanism to lower the centre of mass in order to maintain postural stability (Harman, 2000). To achieve this, greater ankle plantar flexor (Harman, 2000; Quesada, et al., 2000) and knee extensor moments (Harman, 2000; Quesada, et al., 2000; Wang, et al., 2013) are required due to an increase in moment arm length induced by greater flexion. The lower limb gait changes that occur as a result of load carriage are reported to occur predominantly in the sagittal plane (Harman, 2000; Kinoshita, 1985; Quesada, et al., 2000; Wang, et al., 2013). Sagittal plane bending moments are believed to be important in the development of tibial stress fractures (Haris Phuah, et al., 2010), thus the altered sagittal plane mechanics during load carriage may be associated with stress fracture development.

As muscles contribute the primary forces to joint motion (Robertson, et al., 2013), the greater plantar flexor and knee extensor moments reported during load carriage likely coincide with greater plantar flexor and knee extensor muscle activity. Indeed, greater EMG amplitudes, which are indicative of greater muscle activity (Konrad, 2006) and/or muscular fatigue (Kallenberg, et al., 2007; Merletti, Knaflitz, & De Luca, 1990), have previously been observed in the plantar flexor muscles and knee extensor muscles during load carriage activities (Harman, 2000). Load carriage activities may therefore increase muscular fatigue. Plantar flexor muscle fatigue has been associated with both tibial (Milgrom, et al., 2007)

and metatarsal (Arndt, et al., 2002; Sharkey, et al., 1995) stress fractures, due to increased bone strain.

The influence of load carriage on gait has been investigated, and the previous chapter examined the influence of the fatiguing effects of completing a prolonged load carriage training activity on kinematic and plantar pressure variables. However, the influence of such an activity on kinetic and EMG variables remains unclear. A reduction in knee extensor moments has been reported following 40 minutes of treadmill marching whilst carrying load (Quesada, et al., 2000). A reduction in median frequency of the plantar flexor muscles (gastrocnemius lateralis and peroneus longus) has been reported following 2 km of treadmill marching (Gefen, 2002). This shift in the EMG power spectrum to the lower frequencies (both mean and median frequencies) is considered to be representative of muscular fatigue (Kallenberg, et al., 2007; Kumar, et al., 2002; Merletti, Knafitz, & De Luca, 1990; Merletti, Lo Conte, & Orizio, 1991; Naeije & Zorn, 1982; Winter, 2009). Therefore Gefen's (2002) results suggest plantar flexor muscle fatigue following just 2 km of treadmill walking. As discussed, plantar flexor muscle fatigue may be associated with increased risk of lower leg stress fracture. Furthermore the peroneus longus muscle is both a plantar flexor and subtalar joint evtor, thus it plays a role in preventing ankle inversion injuries (Gefen, 2002), which are prevalent amongst military recruits (Milgrom, et al., 1991). Fatigue of this muscle may increase risk of ankle inversion injury. Chapter 4 found that recruits with a smaller calf girth were predisposed to risk of ankle inversion injury. There are known associations between muscle size and muscular endurance as a result of resistance training (Bird, Tarpinning, & Marino, 2005), thus a smaller calf girth may be observed in those who are less resistant to muscular fatigue. Calf muscle fatigue may play an important role in the development of tibial and metatarsal stress fractures as well as the occurrence of ankle inversion injuries.

The aim of this study was to assess the influence of load carriage, and of completing a prolonged load carriage training activity, on lower limb kinematics, kinetics and EMG activity. It was hypothesised that the addition of load would result

in increased ankle dorsiflexion and knee flexion, greater plantar flexor and knee extensor moments, and greater plantar flexor and knee extensor muscle activity. It was hypothesised that following a military load carriage training activity, recruits would display reduced knee extensor moments and evidence of fatigued plantar flexor muscles, as indicated by reduced mean and/or median frequency of these muscles.

7.2 Methods

7.2.1 Participants

Thirty-two Royal Marines recruits volunteered to participate in the study which took place in week-21 of their 32-week recruit training programme. The sample size for this study was determined by the successful identification of gait changes following the same activity in the previous study, as well as differences reported in kinematic, kinetic and EMG variables during a military load carriage activity with 16 participants (Harman, 2000). All volunteer recruits were injury-free and had not been removed from training for any reason at the time of data collection. Within these criteria, recruits were randomly selected from four troops (eight per troop) and data were collected during an 11-week period between September and December 2013. Recruits had a mean (SD) age: 23.8 (3.5) years, body mass: 79.2 (6.5) kg, height: 175.4 (5.5) cm and body mass index: 25.8 (1.9) kg.m⁻². The study was approved by the Ministry of Defence Ethics Committee (MODREC), and all recruits gave informed consent.

7.2.2 Protocol

The prolonged load carriage activity which recruits were asked to complete for the protocol of this study was the same as that used in Chapter 6 (the 8-miler). The activity was a 12.8 km military load carriage training activity that was part of the recruit training programme, taking place in week-21. Throughout the activity, recruits carried a Bergen, webbing and a weapon as in Chapter 6, providing a total additional load of 35.5 kg. Recruits completed this activity with their troop, at a pre-determined pace, at an average speed of 1.4 m.s⁻¹ (5.12 km.h⁻¹). The training

activity paused approximately every hour during which time recruits were encouraged to intake energy and water.

7.2.3 Data collection

Synchronised force, kinematic and EMG data were collected from the left leg of recruits during walking in military boots, both pre- and post- the load carriage activity. Recruits completed walking trials at $1.4 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$), the average speed of the training activity. Five walking trials included 35.5 kg of additional load and a further five were unloaded. Order of loading condition was counterbalanced. Recruits completed familiarisation trials until successful trials were repeated. A successful trial was within the correct speed range, with the left foot fully contacting the force plate without adjusting stride length. Data collection post-activity commenced immediately upon completion of the activity, and time between completion and data collection was recorded for each recruit (range 6 – 98 min, mean (SD): 49 (26) min). Based on existing literature (Bisiaux & Moretto, 2008; Horita, et al., 1999; Tsai, et al., 2009) and the successful identification of gait changes following the same training activity in Chapter 6, 90 minutes was considered an appropriate maximum time between completion and data collection. This was achieved with 31 of 32 recruits. Energy and water intake were not controlled post-activity, as they were not controlled during it.

Kinematic and force data were collected at 200 Hz with two Coda Mpx30 units (CodaMotion, Charnwood Dynamics, UK) and an AMTI (OR6-7-2000, Waterway, MA, USA) force plate. Eleven active markers were positioned as shown in Figure 3.3 (p.40). Markers were positioned using MicroporeTM tape (3M, USA). Positions were identified with pen to allow reliable replacement post-activity, with the exception of the greater trochanter marker, which was repositioned by palpation. A standing trial was recorded both pre- and post- activity in the unloaded condition, allowing adjustment of joint angles during both loaded and unloaded walking, relative to a 'neutral' standing position.

EMG data (Trigno Wireless System, Delsys, Boston, MA, UK) were collected at 4000 Hz from the vastus lateralis (VL), biceps femoris (BF), gastrocnemius lateralis

(GL), tibialis anterior (TA), and peroneus longus (PL) muscles following SENIAM guidelines (Hermens, et al., 1999). Wireless EMG sensors were secured using purpose-made adhesive interfaces (Biosense Medical Ltd, Essex, UK) and Micropore™ (3M, USA) tape. The position of each sensor was marked with permanent pen to allow reliable replacement post-activity. Within-day and between-day reliability of EMG data was assessed in a separate study using active male adult participants (Appendix J), where reliability values were classified as fair ($0.4 < ICC \leq 0.6$), good ($0.6 < ICC \leq 0.8$) or excellent ($0.8 < ICC \leq 1$) (Landis & Koch, 1977). Within-day reliability was good or excellent for all muscles and variables, with the exception of maximum PL amplitude which demonstrated poor reliability. Between-day reliability was lower than within-day reliability overall, as expected. Between-day BF and GL variables were not included in this thesis due to poor reliability. VL amplitude variables demonstrated good or excellent between-day reliability whereas frequency variables demonstrated poor between-day reliability. TA between-day reliability was good or excellent for all variables and PL between-day reliability was good or excellent for all variables except for median frequency which demonstrated fair reliability.

7.2.4 Data analysis

Data were analysed using customised MATLAB scripts (R2012a, The MathWorks Inc. Natick, MA, USA). Kinematic data were filtered with a cutoff frequency of 12 Hz. Force data were filtered at the same frequency as kinematic data based on recommendations (Bisseling & Hof, 2006). EMG data were filtered with a fifth-order Butterworth band-pass filter between 5 and 500 Hz (Rose, 2011) and full-wave rectified, then low-pass filtered at 10 Hz (Konrad, 2006). Ground contact time was determined from force data (vertical force > 10 N indicating stance). Ankle kinematic variables were: touchdown and peak dorsiflexion angle, initial peak plantar flexion angle (prior to onset of dorsiflexion), range of motion (from initial peak plantar flexion to peak dorsiflexion) and rate of dorsiflexion. Subtalar eversion kinematic variables were: touchdown and peak eversion angle, range of motion from touchdown to peak, and rate of eversion. Knee kinematic variables were: knee flexion touchdown angle, peak flexion angle (in the first two-thirds of stance,

in order to ensure that flexion angle at push-off was not included), range of motion, and rate of flexion. Kinetic variables were: peak ankle plantar flexor moments and peak knee extensor moments. Two peaks in knee extensor moments were displayed during stance (Figure 7.1), with an initial peak of smaller magnitude than the later peak. Both were quantified independently and termed 'initial' and 'peak' knee extensor moments respectively. Joint moments were normalised to body mass.

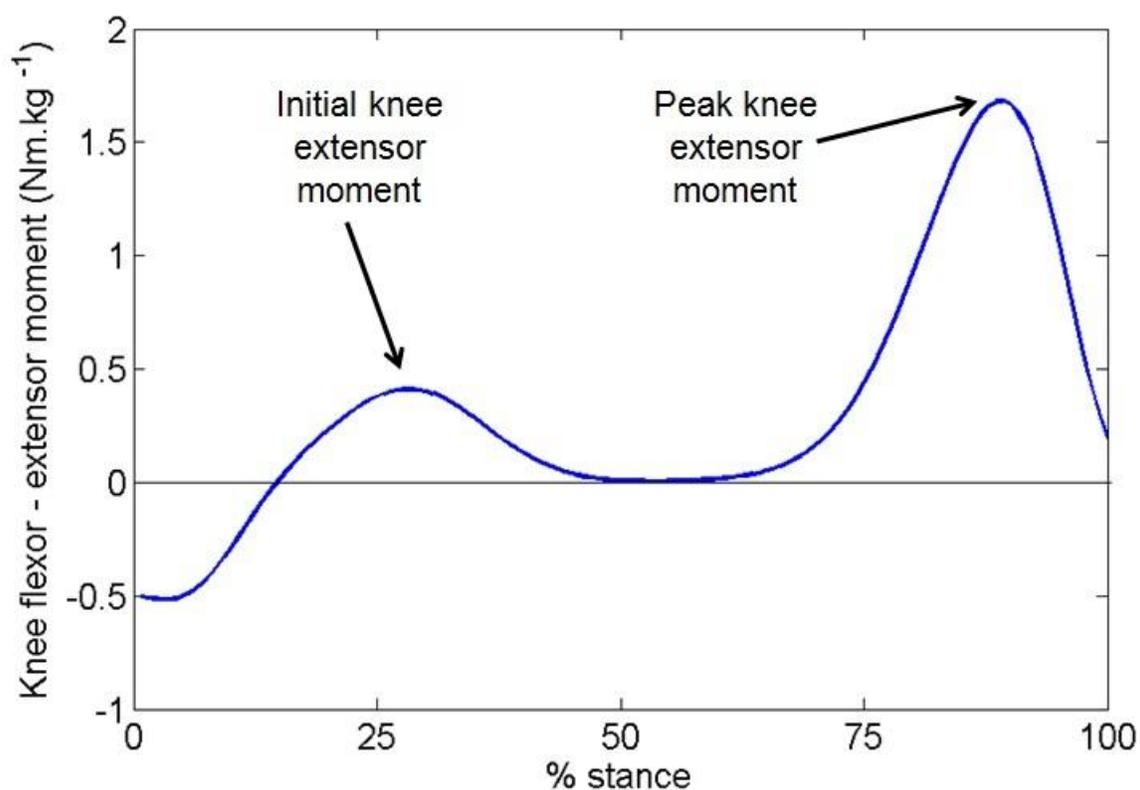


Figure 7.1: Sample knee flexor-extensor moment during walking (positive = knee extensor moment)

EMG variables included maximum amplitude, integrated EMG (iEMG) and mean and median frequencies. Maximum amplitude was normalised to an ensemble averaged mean value taken from each 5% of stance, during unloaded pre-activity walking trials. iEMG values were normalised to the maximum iEMG value from each recruit, obtained during five unloaded pre-activity walking trials. Maximum amplitude and iEMG were provided to give an indication of muscular activity, and mean and median frequencies were used as gold standard indicators of muscular

fatigue (Phinyomark, et al., 2012). Increased mean frequency is also an indicator of increased force during a muscular contraction (Moritani & Muro, 1987).

7.2.5 Statistical analysis

Statistical analyses were conducted with a statistical significance of $P < 0.05$, using SPSS software (Version 16.0, SPSS Inc., Chicago, IL, USA). Two-way repeated measures ANOVAs were conducted to determine the effect of load carriage (loaded and unloaded) and time (pre- and post-activity). Order of loading was the between-subjects variable. Where there was no significant effect of order of loading, this variable was removed before repeating the ANOVA. Effect size was calculated ($0.01 \leq \text{small} < 0.3$, $0.3 \leq \text{medium} < 0.5$, $0.5 \leq \text{large}$ (Cohen, 1988b)) using the equation below, where $F(1, dfR)$ is the F-ratio for the effect and dfR is the degrees of freedom for the error term on which the F-ratio is based (Field, 2005).

$$r = \frac{F(1, dfR)}{F(1, dfR) + dfR}$$

7.3 Results

There was no effect of the order of trials on any variables. Mean (SD) values are reported for variables where there was a main or interactive effect for kinematics, kinetics and EMG in Tables 7.1, 7.2 and 7.3 respectively. Main effects for load are reported in Table 7.4. When loaded compared with unloaded, there was a longer ground contact time (Figure 7.2), greater dorsiflexion range of motion (Figure 7.3), and greater knee flexion (Figure 7.4). There were also greater plantar flexor (Figure 7.5) and knee extensor moments (Figure 7.6). Mean frequency of the BF muscle was lower when loaded compared with unloaded, whereas mean frequency of the GL and PL muscles was greater, indicating greater muscular force in the GL and PL muscles when carrying load. iEMG of the GL and TA muscles was greater when loaded, as was the maximum VL amplitude, indicating greater activity of these muscles.

Table 7.1: Kinematics mean (SD) values and effects

Variable	Pre- Unloaded	Pre- Loaded	Post- Unloaded	Post- Loaded	Effects
Ground contact time (ms)	655.03 (29.80)	674.00 (31.05)	642.45 (26.72)	673.03 (27.19)	Load
Dorsiflexion range of motion (°)	18.66 (5.76)	20.22 (5.92)	16.79 (3.36)	18.12 (3.63)	Load
Eversion rate (°.sec ⁻¹)	19.83 (11.76)	21.50 (10.82)	37.20 (19.43)	28.95 (23.65)	Time
Peak knee flexion (°)	17.64 (4.65)	19.06 (5.91)	18.65 (4.62)	21.12 (4.92)	Load
Knee flexion touchdown (°)	-1.80 (4.22)	0.63 (4.95)	-0.21 (3.33)	2.31 (4.28)	Load

Note: A greater knee flexion angle indicates a more flexed knee

Table 7.2: Kinetics mean (SD) values and effects

Variable	Pre- Unloaded	Pre- Loaded	Post- Unloaded	Post- Loaded	Effects
Peak plantar flexor moment (Nm.kg ⁻¹)	1.73 (0.60)	2.46 (0.72)	1.77 (0.20)	2.46 (0.36)	Load
Initial knee extensor moment (Nm.kg ⁻¹)	0.69 (0.29)	1.29 (0.69)	0.74 (0.27)	1.29 (0.48)	Load
Peak knee extensor moment (Nm.kg ⁻¹)	1.59 (0.39)	2.17 (0.50)	1.37 (0.34)	1.89 (0.39)	Load Time

Table 7.3: EMG mean (SD) values and effects

Variable	Pre- Unloaded	Pre- Loaded	Post- Unloaded	Post- Loaded	Effects
VL max (multiples of mean)	3.99 (1.12)	6.00 (1.30)	4.52 (2.96)	6.79 (2.18)	Load
BF mean frequency (Hz)	83.76 (13.38)	78.72 (14.09)	74.54 (26.36)	65.96 (22.67)	Load
GL mean frequency (Hz)	105.19 (32.41)	109.42 (32.20)	95.58 (39.16)	99.13 (40.15)	Load
GL iEMG (multiples of max)	0.86 (0.08)	1.39 (0.35)	2.12 (5.78)	2.79 (6.71)	Load
TA iEMG (multiples of max)	0.86 (0.08)	1.10 (0.32)	1.00 (0.37)	1.39 (0.94)	Load
PL median frequency (Hz)	112.83 (24.68)	115.45 (29.59)	61.92 (43.40)	65.34 (45.89)	Time
PL mean frequency (Hz)	126.00 (21.59)	136.95 (22.10)	87.20 (51.04)	89.75 (53.71)	Load Time

VL: vastus lateralis; BF: biceps femoris; GL gastrocnemius lateralis; TA: tibialis anterior; PL: peroneus longus

Table 7.4: Effect of load

Variable	Change with load	F value	p	r
Kinematics				
Ground contact time (ms)	Longer	F(1,30) = 97.332	< 0.001	0.874
Dorsiflexion range of motion (°)	Greater	F(1,14) = 31.474	0.039	0.832
Peak knee flexion (°)	More flexed	F(1,14) = 13.078	0.003	0.695
Knee flexion touchdown (°)	More flexed	F(1,13) = 15.883	0.002	0.742
Kinetics				
Peak plantar flexor moment (Nm.kg ⁻¹)	Greater	F(1,21) = 251.983	< 0.001	0.961
Initial knee extensor moment (Nm.kg ⁻¹)	Greater	F(1,19) = 44.830	< 0.001	0.838
Peak knee extensor moment (Nm.kg ⁻¹)	Greater	F(1,19) = 117.683	< 0.001	0.928
EMG				
VL max (multiples of mean)	Greater	F(1,9) = 14.831	0.004	0.662
BF mean frequency (Hz)	Lower	F(1,18) = 13.034	0.002	0.648
GL mean frequency (Hz)	Greater	F(1,20) = 8.635	0.008	0.549
PL mean frequency (Hz)	Greater	F(1,12) = 14.350	0.003	0.738
GL iEMG (multiples of max (μV.s))	Greater	F(1,24) = 23.669	< 0.001	0.704
TA iEMG (multiples of max (μV.s))	Greater	F(1,25) = 9.155	0.006	0.518

VL: vastus lateralis; BF: biceps femoris; GL gastrocnemius lateralis; TA: tibialis anterior; PL: peroneus longus

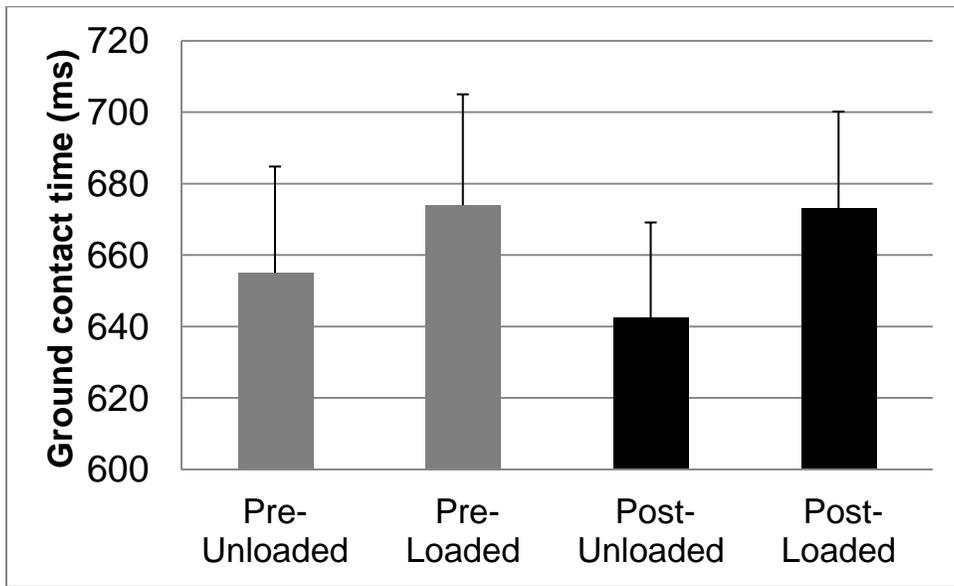


Figure 7.2: Mean (SD) ground contact time during walking pre- and post- activity, with and without load

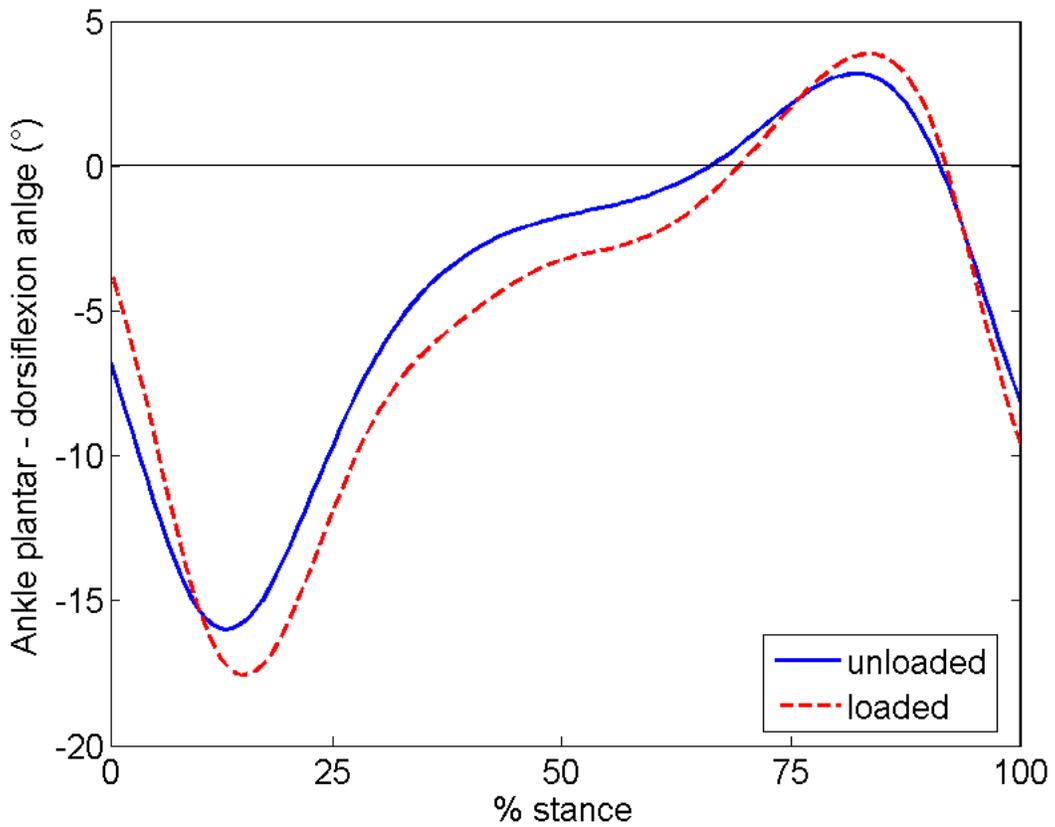


Figure 7.3: Sample ankle plantar-dorsiflexion angle during walking stance, with and without load (positive = dorsiflexion)

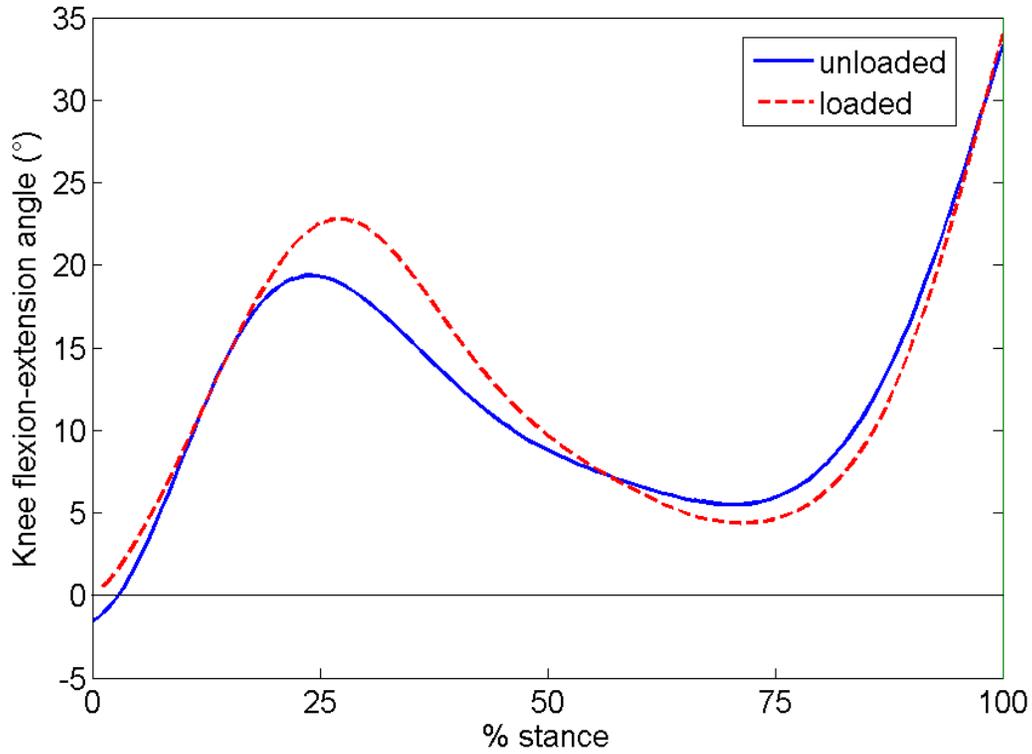


Figure 7.4: Sample knee flexion–extension angle during walking stance, with and without load (positive = knee flexion)

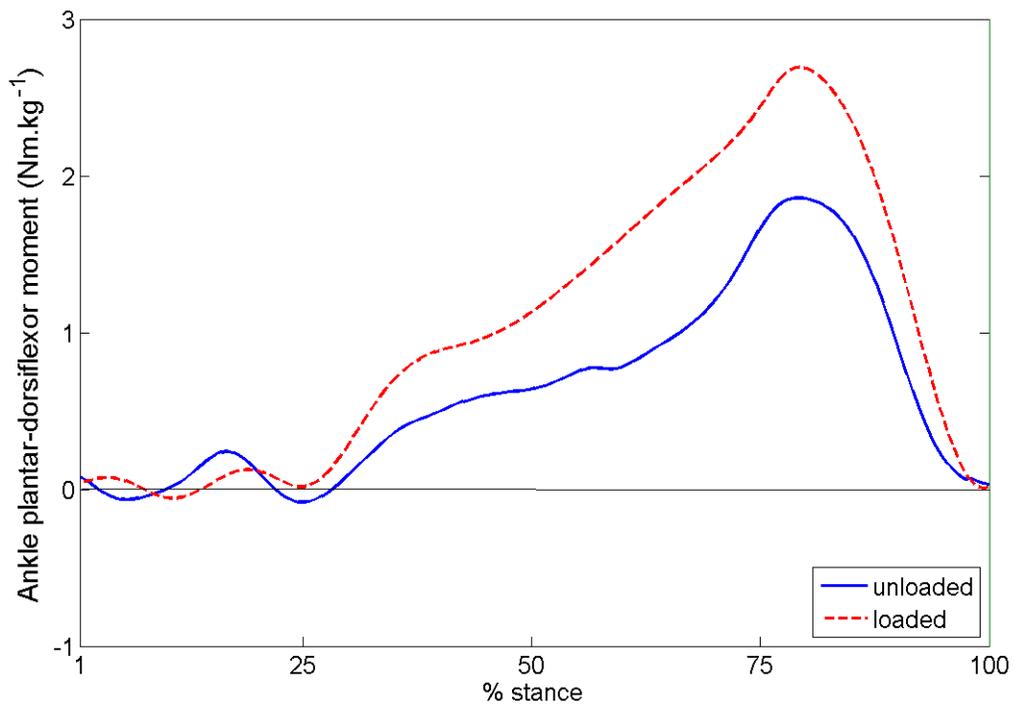


Figure 7.5: Sample ankle plantar-dorsiflexor moment during walking stance, with and without load (positive = plantar flexor moment)

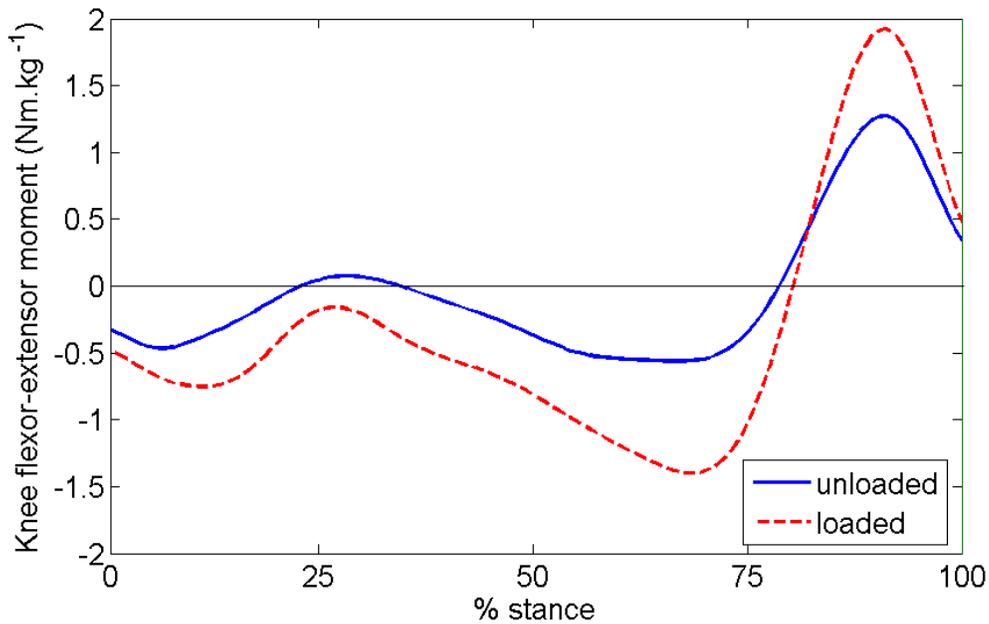


Figure 7.6: Sample knee flexor–extensor moment during walking stance, with and without load (positive = knee extensor moment)

Main effects for time are reported in Table 7.5. Post-activity there was an increased rate of subtalar eversion, reduced peak knee extensor moments (Figure 7.7), and reduced mean and median PL frequency (Figure 7.8), indicating PL muscle fatigue. All main effects were associated with large effect sizes.

Table 7.5: Effect of time

Variable	Change with time	F value	p	r
Kinematics				
Eversion rate (°.sec ⁻¹)	Faster post-	F(1,13) = 7.911	0.015	0.615
Kinetics				
Peak knee extensor moment (Nm.kg ⁻¹)	Reduced post-	F(1,19) = 8.540	0.008	0.557
EMG				
PL median frequency	Reduced post-	F(1,11) = 9.156	0.012	0.674
PL mean frequency	Reduced post-	F(1,12) = 5.989	0.031	0.577

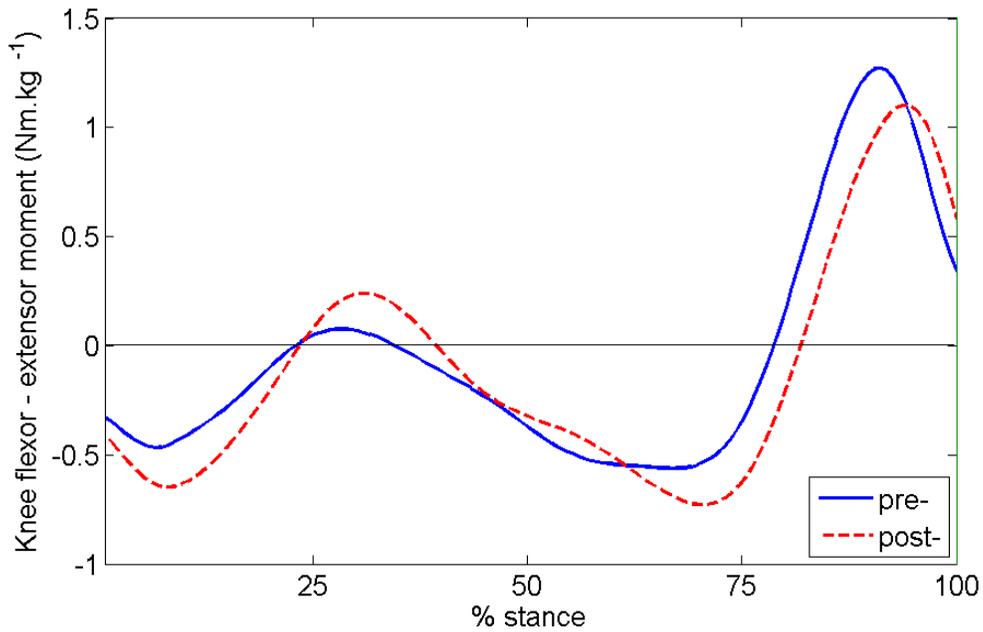


Figure 7.7: Sample knee flexor–extensor moment during walking stance, pre- and post-activity (positive = knee extensor moment)

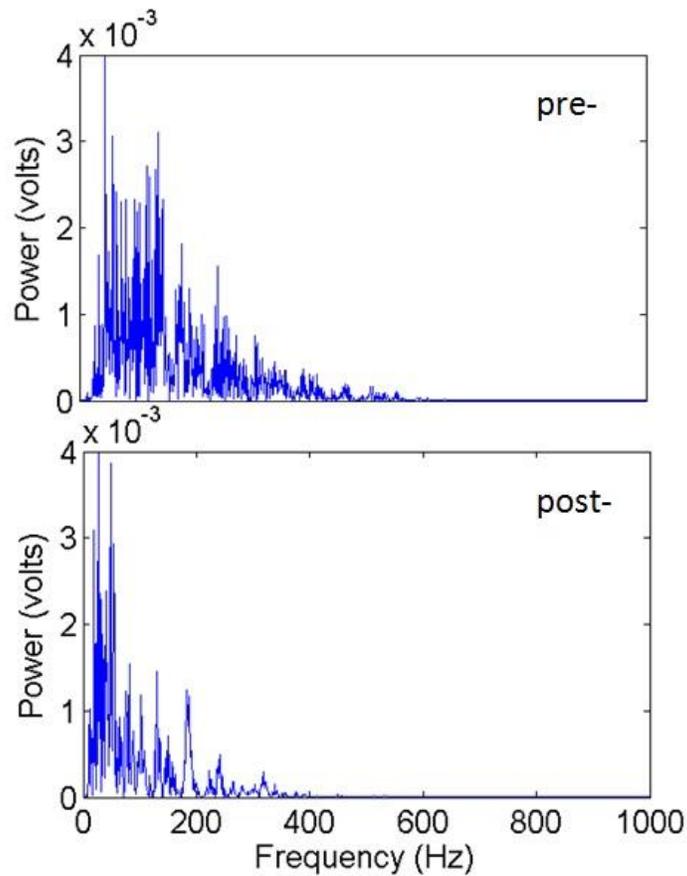


Figure 7.8: Sample peroneus longus muscle power spectrum pre- and post- activity demonstrating the shift to the lower frequencies

7.4 Discussion

This was the first known study to assess changes to lower limb kinematics, kinetics and muscle activity as a result of a real-life prolonged load carriage training activity. The study benefitted from the inclusion of recruits from a homogeneous population, all of whom had completed the same 20 weeks of training within a highly-controlled living and working environment, prior to data collection. The effects of carrying load and the effects of completing the military activity were both assessed. The assessment of synchronised kinematic, kinetic and EMG data to determine the influence of load carriage and the effects of completing a prolonged load carriage activity was novel. These findings build upon existing findings within this thesis, providing further understanding of mechanisms for injury occurrence.

7.4.1 Effect of load carriage

Ground contact time was longer when walking whilst carrying load compared with unloaded walking, and this change was not hypothesised. The change was approximately 25ms, and was associated with a large effect size. Carrying load is known to increase loading on the lower limb (Harman, 2000; Quesada, et al., 2000). Therefore a longer ground contact time may result in a longer period during which the lower limb is under this increased loading, which may increase injury risk. This risk may be particularly increased when this occurs repeatedly for prolonged periods such as during the training activity. Load carriage increases metatarsal compression (Arndt, et al., 2002) resulting in faster fatigue damage accumulation in the metatarsals (Carter, et al., 1981), which may increase risk of metatarsal stress fracture. With a longer ground contact time, the metatarsals would be expected to be under increased compression for longer, which could further increase the rate of fatigue damage accumulation. Alternatively, a longer ground contact time may be a mechanism to lower the loading rate on the internal structures in order to reduce the potential negative effects of increased load. It is therefore unclear whether a longer ground contact time is a mechanism to minimise the risk of injury, or if it is a cause of injury. Assessment of loading rates within the metatarsals would help to make this distinction.

The observed changes in sagittal plane lower limb mechanics when carrying load are consistent with previous findings (Harman, 2000; Kinoshita, 1985; Wang, et al., 2013) and with the hypotheses. Greater dorsiflexion and knee flexion are suggested to help to maintain postural stability by lowering the body centre of mass (Harman, 2000). Motion of the centre of mass can be used as an indicator of postural stability (Betker et al., 2009; González et al., 2013). Although the location of the centre of mass could not be obtained in the present study, the height of the greater trochanter marker was used as a crude indicator of centre of mass position. The peak vertical height of the greater trochanter marker and the amount of oscillation (difference between maximum and minimum height of the marker) during stance were investigated retrospectively. Paired t-test analyses revealed that the maximum height of the greater trochanter during stance pre-activity, was significantly reduced during loaded walking compared with unloaded walking (mean (SD) unloaded: 933.65 (41.48) mm, loaded: 929.87 (42.29) mm, $P = 0.039$). Although this statistically supports the suggestion that the body centre of mass is lowered during load carriage, a reduction of less than 4 mm may not be meaningful. Two-way repeated measures ANOVAs revealed no main effect for load carriage or time (pre- and post-activity) for oscillation of the greater trochanter during stance (mean (SD) pre-unloaded: 60.02 (10.64) mm; pre-loaded: 60.13 (10.57) mm; post-unloaded: 60.09 (10.32) mm; 60.24 (9.47) mm). This suggests an ability to maintain postural stability both during load carriage, and after completing a prolonged load carriage activity. As previously suggested, this stability may be maintained through lowering the body centre of mass by increasing ankle dorsiflexion and knee flexion.

The hypothesised increases in plantar flexor and knee extensor moments (40% and 72% respectively) observed when carrying load, were suggested to be mechanisms to control the greater flexion observed at the respective joints. Harman (2000) reported similar increases in plantar flexor and knee extensor moments during loaded compared with unloaded walking (38% and 98% respectively) with an additional load of 49% of body mass (compared with an additional load of approximately 44% of body mass in the present study). Harman's results, along with those from the present study suggest that the knee extensor

muscles assume a greater proportion of the burden of load carriage than the plantar flexor muscles. The temporal aspects of the kinematic and kinetic time histories were similar for ankle dorsiflexion angle and plantar flexor moments (Figure 7.9), and for knee flexion angle and knee extensor moments (Figure 7.10). The shape of the curves may be specific to the walking style, and the military boots worn. The time of peak dorsiflexion angle coincides approximately with the time of peak plantar flexor moment during stance, and similarly the two peaks in knee flexion angle coincide approximately with the two peaks in knee extensor moments observed during stance. This suggests that the observed angular changes and corresponding joint moment changes are related. This relationship is likely influenced by the increased moment arm length which results from increased flexion.

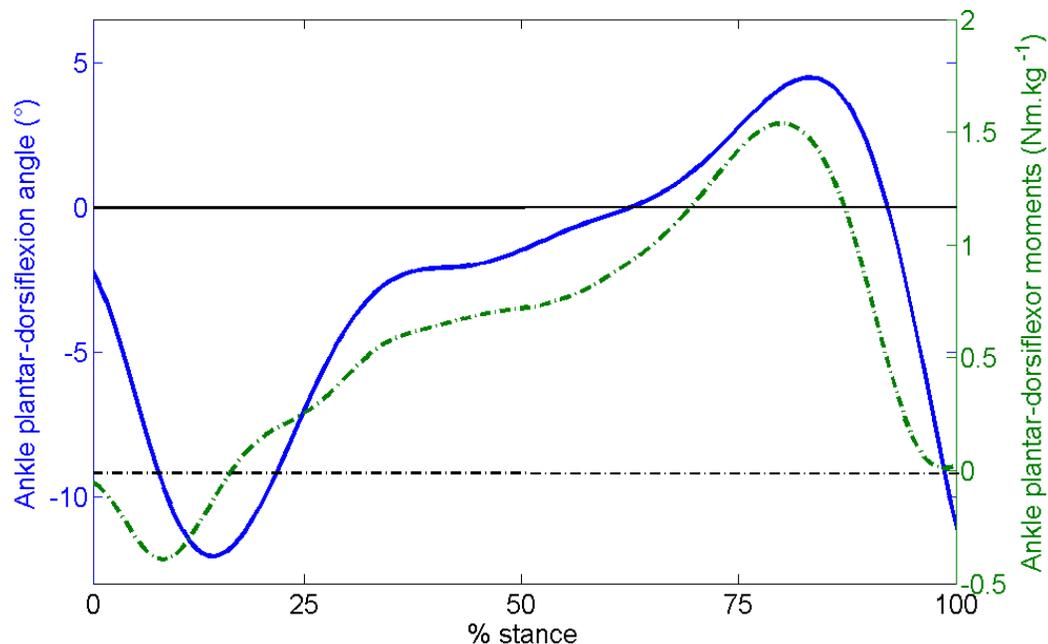


Figure 7.9: Sample kinematics (solid line) and kinetics (dashed line) time histories for sagittal plane ankle during walking stance.

Note: positive values indicate dorsiflexion angles and plantar flexor moments respectively.

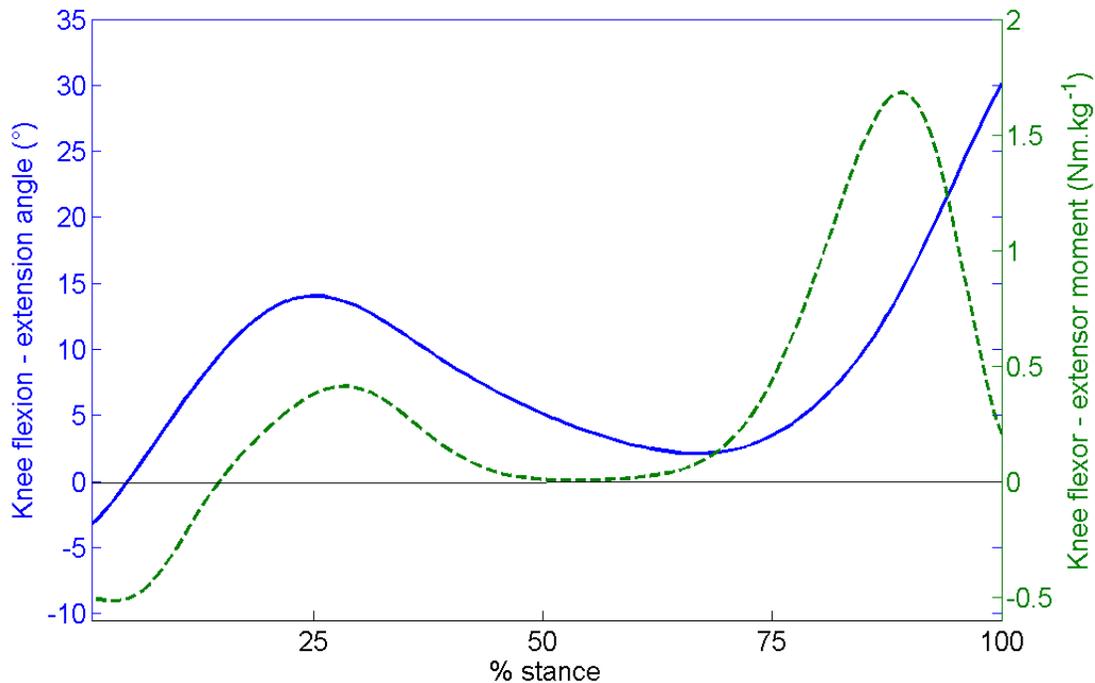


Figure 7.10: Sample kinematics (solid line) and kinetics (dashed line) time histories for sagittal plane knee during walking stance.

Note: positive values represent knee flexion angles and knee extensor moments respectively.

Both the plantar flexor and knee extensor muscles demonstrated increased activity whilst carrying load, in support of the hypotheses. The quadriceps muscles act eccentrically during walking to control knee flexion during early stance and midstance. It is suggested therefore that the greater VL muscle activity that was observed with additional load is associated with the greater knee extensor moments exhibited, which contribute to postural stability maintenance. The plantar flexors act concentrically towards the end of stance to contribute to the push-off phase, as demonstrated by the peak in ankle plantar flexor moment close to the end of stance (Figure 7.9). The greater GL muscle activity during load carriage suggests a greater concentric contraction is required to push-off when carrying load, compared with unloaded walking. Greater plantar flexor force production when carrying load was also indicated by the increased GL and PL mean frequencies observed. A greater force is likely to be required in order to push-off when overall mass is increased, and this may increase plantar flexor muscle fatigue. The greater plantar flexor and knee extensor muscle activity observed was

consistent with earlier findings (Harman, 2000), and demonstrated high within-day reliability (ICC > 0.93, Appendix J). The greater moments and muscle activity observed when carrying load, are likely to contribute to plantar flexor and knee extensor muscle fatigue.

The observed greater TA (a dorsiflexor and invertor) muscle activity when carrying load is an indication that this activity is demanding on the invertor muscles. These muscles eccentrically control eversion at the subtalar joint. The increased activity is likely to contribute to invertor muscle fatigue. Although the EMG variables did not suggest TA muscle fatigue post- compared with pre-activity, fatigue of this muscle is suggested by the faster eversion reported post- compared with pre-activity. The lower mean frequency of the BF muscles when loaded compared with unloaded was not expected but this variable demonstrated high within-day reliability. This shift in the power spectrum is indicative of fatigue (Gerdle et al., 2000; Hägg et al., 2000), but can be influenced by additional factors such as fibre size and composition (Bilodeau et al., 2003). The term 'fatigue' may be misleading in this context, where it is defined as a reduced ability to generate force or power output (Vøllestad, 1997). The addition of load is likely to result in a reduced ability to generate force, independent of the 'fatiguing' effects of completing a prolonged load carriage activity.

7.4.2 Effect of completing the load carriage activity

The results discussed so far present evidence that walking whilst carrying load is more physically demanding than unloaded walking, requiring greater plantar flexor and knee extensor moments, and consequently increased plantar flexor and knee extensor muscle activity. Although a weight-bearing activity of 12.8 km would be likely to result in fatigue without the addition of load, the increased demand of carrying the load is likely to result in earlier fatigue onset, and greater levels of fatigue upon completion of the activity than would be observed completing an activity of the same distance without load carriage.

The reduction in knee extensor moments post-activity was hypothesised. As plantar flexor and knee extensor moments are key contributors to walking, (Kepple,

Siegel, & Stanhope, 1997), the observed reduction in knee extensor moments post-activity, whilst plantar flexor moments were maintained, suggests an increased reliance on the plantar flexor moments to maintain postural stability. Reduced knee extensor moments may be the result of knee extensor muscle fatigue, although there was no evidence of this from the EMG data. The EMG frequency variables were shown to be unreliable in this muscle, making it unclear whether this change was the result of knee extensor muscle fatigue. Alternatively, an increased reliance on plantar flexor moments to maintain postural stability would likely result in plantar flexor muscle fatigue, of which there was evidence post- compared with pre-activity. Fatigue of the plantar flexor muscles has previously been associated with increased tension strain in the tibia, which may increase stress fracture risk (Milgrom, et al., 2007).

The reduced mean and median frequency of the PL muscle post-activity (a plantar flexor and subtalar evertor) is indicative of plantar flexor muscle fatigue (Kallenberg, et al., 2007; Kumar, et al., 2002; Merletti, Knafnitz, & De Luca, 1990; Merletti, Lo Conte, & Orizio, 1991; Naeije & Zorn, 1982; Winter, 2009) This change was hypothesised. A 44% reduction in PL median frequency was reported post-compared with pre-activity, exactly the same reduction as previously reported following 2 km of marching (Gefen, 2002). As discussed, plantar flexor muscle fatigue has been demonstrated to result in increased tensile strain in the tibia (Milgrom, et al., 2007) and therefore increased risk of tibial stress fracture. Similarly, the plantar flexor muscles in the foot are reportedly involved in reducing metatarsal strain (Arndt, et al., 2002; Sharkey, et al., 1995) and bending moments (Sharkey, et al., 1995), thus reduced plantar flexor muscle activity may also be associated with the development of metatarsal stress fractures. There was evidence of a reduced ability to push-off during barefoot running following the same prolonged load carriage activity (Chapter 6) which was indicative of plantar flexor muscle fatigue. Reduced ability to push-off has previously been associated with metatarsal stress fracture occurrence (Nagel, et al., 2008), and reduced ankle plantar flexor muscle endurance has been associated with overuse tibial pain in a cross-sectional study (Madeley et al., 2007).

The PL muscle is a plantar flexor and also plays an important role in subtalar joint control, as it is an evertor muscle (Hunt, Smith, & Torode, 2001), thus the observed fatigue of this muscle may be associated with an increased risk of ankle inversion injury (Gefen, 2002). Median frequency of the PL muscle displayed only fair between-day reliability. However, the fact that changes to this variable were observed with large effect sizes, and that the reductions compared well with existing findings (Gefen, 2002), suggests that the result is likely to be valid. It is further validated by the similar magnitude of reduction in PL mean frequency observed, which displayed good between-day reliability.

Plantar flexor muscle fatigue has been assumed based on evidence of a fatigued PL muscle. However, the poor between-day reliability of GL variables meant this could not be supported by evidence of fatigue in the GL muscle. There were indications of increased GL muscle activity and force production during load carriage, which would be likely to induce GL muscle fatigue. The extent of plantar flexor muscle fatigue cannot be accurately reported, but the greater plantar flexor moments and muscular activity during load carriage, and the evidence of PL muscle fatigue strongly suggest plantar flexor muscle fatigue occurred post-activity. Future research in this area should include a test of plantar flexor muscle strength or fatigability pre- and post-activity. This could be assessed through the use of a calf raise test to exhaustion (Lunsford & Perry, 1995), or a foot plantar flexor dynamometer (Spink et al., 2010). There was no evidence of knee extensor muscle fatigue post-activity. Fatigue of the knee extensors would be expected given their increased demand during load carriage and the reduced knee extensor moments reported post- compared with pre-activity. Between-day reliability for the VL muscle spectral variables was categorised only as fair. This muscle may have been fatigued following the activity without being captured by the data collection methods. Alternatively, this muscle group may be better able to withstand the demands of a prolonged load carriage activity than the plantar flexor muscles. This may explain the greater relative increases in knee extensor moments than plantar flexor moments observed during load carriage, and may also contribute to the prevalence of stress fractures below the knee in this population. Consideration of ankle and knee joint power (dot product of the joint moment and the angular

velocity) would provide further indication of the rate of work done at these joints, and this may help to improve understanding of the influence of the prolonged activity on gait characteristics.

7.5 Limitations

A greater dorsiflexion ROM was observed pre-activity compared with post-activity in the unloaded condition, whereas the opposite was observed when assessed during barefoot running following the same activity (Chapter 6). This may be the result of variability in the measurement, influenced by inaccuracies arising from marker placement. Differences may also occur as a result of the difference in marker placement on the boot (Chapter 7) compared with the barefoot (Chapter 6). The variable itself may also have been influenced by the difference in footwear condition and mode of activity between the two studies.

A number of EMG variables for all muscles had greater standard deviations post-compared with pre-activity. This may be a result of the conditions of data collection. Despite following skin preparation guidelines for EMG sensor application (SENIAM), perspiration could not be prevented and would have been increased post-activity. This may have impaired the quality of EMG data collection (Konrad, 2006).

The use of a real-life military training activity in the present study allowed identification of gait changes that are likely to occur in the wider Royal Marine recruit population, and may explain some of the mechanisms for the prevalent injuries within this population. In order to assess the real-life influences of the training activity, it was not modified in any way, such that all recruits within each troop completed the activity together. Therefore recovery time varied within the eight recruits from whom data were collected in each session. It is likely that if recovery time was excessive, these changes would not have been observed and as such, this factor does not reduce confidence in the reported changes. The study only included recruits who had not been injured during the first 20 weeks of recruit training, thus they were arguably more resistant to injury than many Royal Marine recruits. More pronounced or additional changes may have been observed

following this prolonged load carriage activity in recruits who were at higher risk of injury. Recruits at greater risk may already have sustained an injury prior to week-21, when the training activity for this study took place. However, as demonstrated in the review of the training programme (Chapter 5), many stress fractures occurred after this week of training.

7.6 Conclusions

Load carriage during a military training activity resulted in altered sagittal plane lower limb mechanics. The changes observed following the load carriage activity in the present study are likely to also be evident following similar load carriage activities taking place throughout the recruit training programme. Greater dorsiflexion range of motion and knee flexion angles, greater plantar flexor and knee extensor moments, and greater activity of the plantar flexor and knee extensor muscles were observed during walking with load compared with unloaded walking. Following the activity, there was a reduction in knee extensor moments, and evidence of plantar flexor muscle fatigue. Increased sagittal plane loading and plantar flexor muscle fatigue may increase tibial and metatarsal strain and bending, which could contribute to the high incidence of tibial and metatarsal stress fractures in the Royal Marine recruit population. Specifically, the mechanistic changes and potential explanations for injury development presented may be used to explain the high injury occurrence in training weeks in which the demanding effects of completing prolonged load carriage activities was greatest (Chapter 5).

CHAPTER 8: General Discussion

The Royal Marine recruit population has a high incidence of lower limb injury. Mechanisms by which these injuries develop were previously unclear, making evidence-based intervention difficult. The aim of this thesis was to improve understanding of the mechanisms by which prevalent lower limb injuries occur within the Royal Marine recruit population. The investigations conducted throughout this thesis were designed to improve existing knowledge and to overcome recurrent limitations in the assessment of injury mechanisms.

Prior to the prospective work conducted by Nunns (2014) and in Chapter 4 of this thesis, there was a lack of prospective evidence identifying biomechanical risk factors for lower limb injuries. Certain anthropometric characteristics had previously been identified in association with lower limb injuries, but there were some contradictory findings. Anthropometric variables are likely to be site-specific, with existing research often considering overall injury occurrence, rather than considering individual injuries independently. Existing dynamic biomechanical variables that have been associated with injury occurrence in prospective studies have only been reported in non-military populations (Willems, et al., 2005; Willems, et al., 2006; Willems, et al., 2007), where mechanisms for injury development may differ to those in the Royal Marine recruit population.

Numerous studies that have investigated variables associated with injury occurrence have done so using retrospective and cross-sectional study design, and therefore causality could not be determined. To build upon existing evidence, Chapter 4 was a prospective study that identified anthropometric and dynamic biomechanical gait characteristics of recruits who sustained a tibial stress fracture, metatarsal stress fracture, or ankle inversion injury during training which differed from the characteristics of those who remained injury-free throughout. The identification of these characteristics was intended to provide insight into why certain recruits sustain an injury during training, whilst others complete the training programme injury-free.

It has been widely reported that the nature of military training is associated with the high lower limb injury and stress fracture occurrence in military populations. It is suggested that the frequent load carriage activities undertaken throughout military training are implicated in this. However, injury occurrence by week of training, and its association with quantifiable training variables had not been previously investigated within the Royal Marine recruit training programme. The training review investigated these associations (Chapter 5). This review highlighted that the combination of load carriage and distance was important in terms of injury occurrence. A prolonged load carriage activity was therefore selected as the protocol to induce gait changes in the two experimental studies which followed.

Previous research has been successful in identifying mechanical lower limb changes that occur as a result of carrying load. Similarly, gait changes have been reported following prolonged weight-bearing activity, although this had only been investigated in non-military populations prior to the investigations for this thesis. The influence of completing a prolonged load carriage activity on gait mechanics had not been previously assessed. Chapters 6 and 7 assessed gait changes as a result of a prolonged load carriage activity (8-miler) which was part of the Royal Marine recruit training programme. These gait changes were believed to be instrumental in the development of lower limb injuries in this population.

Injuries are undoubtedly multifactorial. Studies assessing injury mechanisms often necessarily require participants to have sustained a specific injury, resulting in selection bias. Relative to existing scientific research involving humans, the studies in this thesis benefitted from large, highly homogenous recruit populations who undertook the same training programme, in the same living and working environment. Many extrinsic variables such as diet, training, footwear and recovery time could be controlled to an extent in these studies. This increased the likelihood of detecting valid intrinsic characteristics and mechanisms associated with injury development.

8.1 Summary of key findings

A schematic was presented in Chapter 2 (Figure 2.1, p.33), which outlined the intended aims of this thesis, and the research questions that were to be addressed. An updated version of this schematic (Figure 8.1) is presented which summarises how those aims were achieved.

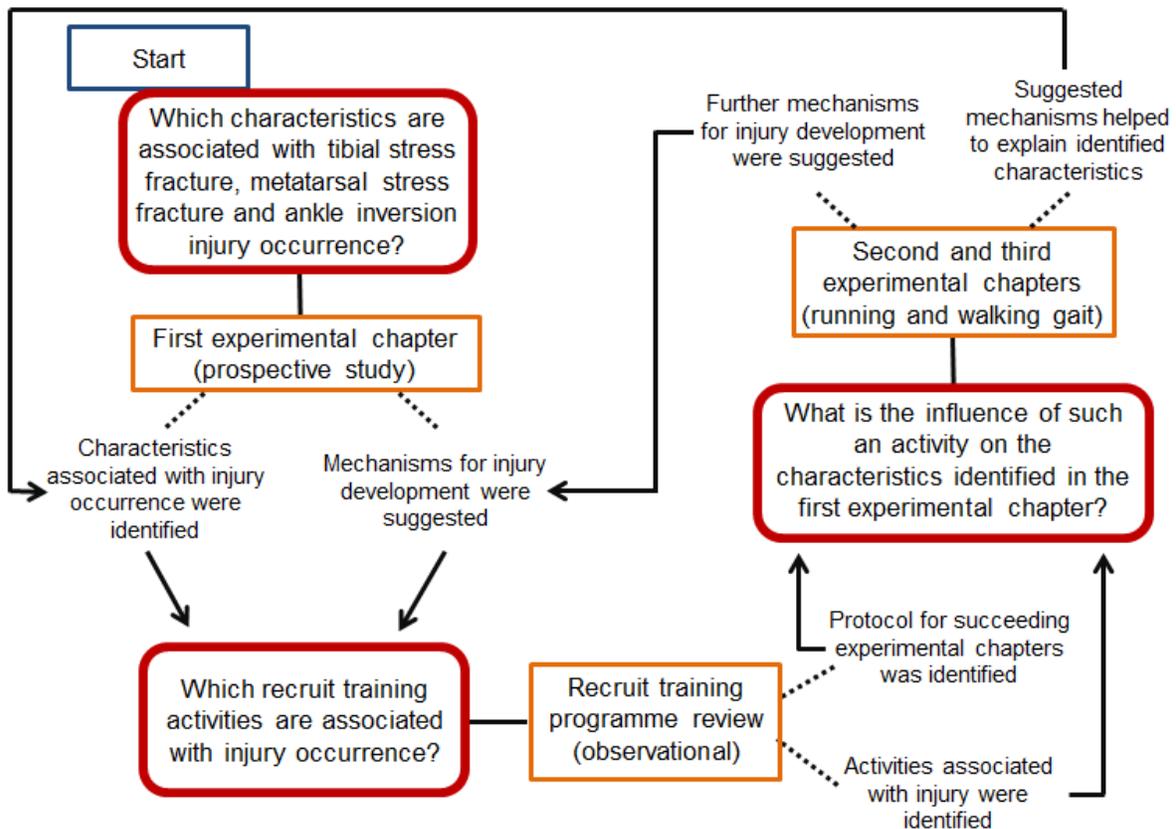


Figure 8.1: Schematic of the research questions addressed in this thesis

This section presents an overview of the thesis, including a concise summary of each study chapter. The purpose of this summary is to highlight the links between study chapters and to outline the progression of the thesis as a whole. For each study chapter, the rationale, the key findings and the key questions which arose are summarised.

Research questions addressed in this thesis

- 1) Which anthropometric and biomechanical variables may predispose recruits to tibial stress fractures, metatarsal stress fractures and ankle inversion injuries?
- 2) Which training variables are associated with high injury incidence during the Royal Marine recruit training programme?
- 3) How does gait change after completion of a prolonged load carriage training activity?
- 4) How does load carriage influence walking gait?

8.1.1 Summary of Chapter 4

What was the rationale for conducting the research presented in Chapter 4?

- Mechanisms for lower limb injury development in Royal Marine recruits were poorly understood. This study aimed to identify biomechanical and anthropometric characteristics associated with certain injuries in order to provide insight into mechanisms for their development.

What were the characteristics of recruits who sustained tibial stress fractures during training which differed from the characteristics of those who remained injury-free?

- Lower BMI
- Smaller calf girth
- Smaller bimalleolar breadth
- Greater lateral heel pressure during barefoot running
- Later peak eversion during barefoot running
- Reduced tibial internal rotation during barefoot running

What were the characteristics of recruits who sustained metatarsal stress fractures during training which differed from the characteristics of those who remained injury-free?

- Greater peak fourth metatarsal pressure during barefoot running

- Later peak first, second and third metatarsal pressure during barefoot running
- Later heel-off during barefoot running

What were the characteristics of recruits who sustained ankle inversion injuries during training which differed from the characteristics of those who remained injury-free?

- Smaller body mass
- Smaller BMI
- Smaller calf girth
- Smaller bimalleolar breadth
- Earlier peak fifth metatarsal pressure during barefoot running

What were the key questions which arose from the findings of Chapter 4?

- Why may these characteristics predispose recruits to these injuries? What is the mechanism by which that injury occurs?
- How are these characteristics influenced by completion of a military training activity?

8.1.2 Summary of Chapter 5

What was the rationale for conducting the research presented in Chapter 5?

- Specific training variables and activities which may be associated with injury occurrence during the recruit training programme were unknown.

What were the key findings from Chapter 5?

- Total distance covered on foot per training week was associated with increased injury occurrence.
- Mass of the total load carried on foot per training week was associated with increased injury occurrence.
- The combined effects of load carriage and prolonged distance coverage were associated with increased injury occurrence.

What were the key questions which arose from the findings of Chapter 5?

- Why are prolonged load carriage activities associated with increased injury occurrence?
- How does a prolonged load carriage training activity influence lower limb mechanics?

8.1.3 Summary of Chapter 6

What was the rationale for conducting the research presented in Chapter 6?

- Gait changes following a prolonged load carriage activity had not been previously investigated. The aim of this study was to investigate lower limb gait changes following an activity associated with injury occurrence, in order to provide insight into the mechanisms by which these injuries occur.

What were the key findings from Chapter 6?

Following a prolonged load carriage training activity there was:

- Reduced forefoot loading
- Increased rearfoot and midfoot loading
- Increased dorsiflexion range of motion
- Increased peak dorsiflexion angle
- Evidence of a reduced ability to transfer load from the rearfoot to the forefoot

What were the key questions which remained after completion of the study in Chapter 6?

- How does load independently influence gait characteristics?
- What is the influence of completing a prolonged load carriage activity on lower limb kinetic and EMG variables?
- What is the influence of completing a prolonged load carriage activity on walking gait?

8.1.4 Summary of Chapter 7

What was the rationale for conducting the research presented in Chapter 7?

- The influence of a prolonged load carriage activity on walking gait, and the independent influence of carrying load were poorly understood. The aim of this study was to assess the influence of load carriage, and of completing a prolonged load carriage activity on lower limb kinematics, kinetics and EMG variables during walking, in order to improve understanding of the mechanisms for injury occurrence suggested in Chapter 6.

What were the key findings from Chapter 7?

- Load carriage resulted in increased ankle dorsiflexion range of motion and peak knee flexion angle
- Load carriage resulted in increased plantar flexor and knee extensor moments
- Load carriage resulted in increased plantar flexor and knee extensor muscle activity
- Following completion of a prolonged load carriage activity, knee extensor moments were reduced
- Following completion of a prolonged load carriage activity, there was evidence of plantar flexor muscle fatigue

8.2 Mechanisms for injury development

Chapter 4 identified characteristics associated with the occurrence of common recruit training injuries, and Chapter 5 identified training activities associated with injury occurrence. The gait changes reported in Chapters 6 and 7 following such an activity, provided suggested mechanisms for the occurrence of these injuries.

8.2.1 Tibial stress fracture

Chapter 4 identified that recruits who sustained tibial stress fractures had a lower BMI, smaller calf girth, and smaller ankle width than recruits who completed training injury-free. Recruits with a smaller body composition are likely to be under

greater physical demand during the regular load carriage activities that occur throughout recruit training which may increase the risk of stress fracture. Recruits who sustained tibial stress fractures displayed greater heel loading than recruits who completed training injury-free (Chapter 4). Increased rearfoot loading, as a result of a reduced ability to transfer load from the rearfoot to the forefoot, was observed following a prolonged load carriage activity (Chapter 6). Increased rearfoot loading may increase forces applied to the tibia, thereby increasing the risk of stress fracture. As recruits who sustained tibial stress fractures demonstrated greater loading under the heel without having completed a prolonged load carriage activity (Chapter 4) this loading may have been further increased following completion of a prolonged load carriage activity. Bone loading may therefore exceed critical limits in these recruits, which may explain their predisposition to a tibial stress fracture.

During load carriage, recruits demonstrated an increase in plantar flexor moments (Chapter 7). This likely resulted in plantar flexor muscle fatigue following the prolonged load carriage activity. This fatigue would be greater than if the activity were performed without additional load, but load is unlikely to be the only contributor. Plantar flexor muscle fatigue may explain the reduced ability to transfer load from the rearfoot to the forefoot as identified in Chapter 6. Reduced plantar flexor muscle activity can result in increased tibial bending (Yang, et al., 2014) and increased tensile strain in the tibia (Milgrom, et al., 2007), exacerbating the risk of stress fracture (Pohl et al., 2008). Recruits with a smaller calf girth may be more susceptible to plantar flexor muscle fatigue, and this may explain why recruits with a smaller calf girth in Chapter 4 were predisposed to tibial stress fracture development. The gait changes observed in Chapter 6 and 7 therefore provide a suggested explanation for the association between load carriage activities and stress fracture occurrence, and also provide a suggestion as to why recruits with greater heel loading and a smaller calf girth are at increased risk of sustaining a tibial stress fracture.

8.2.2 Metatarsal stress fracture

Recruits who sustained metatarsal stress fractures during training displayed later peak metatarsal pressures during barefoot running than recruits who remained injury-free (Chapter 4). Later peak metatarsal pressures were also reported following completion of a prolonged load carriage activity (Chapter 6). The later peak metatarsal pressures following the prolonged load carriage activity occurred at a similar time to those reported in Chapter 4 in recruits who sustained third metatarsal stress fractures (Table 6.5, p.118). Later peak pressures following the activity were suggested to result from a reduced ability to push-off during stance, which was supported by the increased ankle dorsiflexion, increased rearfoot loading and corresponding decrease in forefoot loading (Chapter 6).

There was additional demand placed on the plantar flexor muscles when load was carried (Chapter 7) contributing to greater plantar flexor muscle fatigue than if no load was carried. This may explain the reduced ability to push off during stance reported in Chapter 6. Reduced plantar flexor muscle activity has been found to increase metatarsal bending (Arndt, et al., 2002; Sharkey, et al., 1995), suggesting an increased risk of stress fracture. The suggested mechanisms that link these findings with metatarsal stress fracture are similar to those for tibial stress fracture. Recruits who demonstrated later peak metatarsal pressures without having completed a prolonged load carriage activity (Chapter 4) may have a lower plantar flexor contribution to push-off than injury-free recruits.

Calf girth did not differ between recruits who sustained metatarsal stress fractures and injury-free recruits. Plantar flexor muscles which specifically plantar flex the foot and toes, such as the flexor digitorum longus, flexor hallucis longus, and flexor digitorum brevis may be more important in resisting metatarsal bending than calf plantar flexor muscles. The reduced loading under the hallux and toes following the prolonged load carriage activity (Chapter 6) is indicative of a reduced contribution of the hallux and toes to push-off. This may be the result of fatigued foot plantar flexor muscles. Foot plantar flexor muscles are reportedly protective against metatarsal stress fractures (Arndt, et al., 2002; Sharkey, et al., 1995). Muscular fatigue may reduce this protective effect. These mechanisms provide a suggested

explanation of the association between prolonged load carriage activities and metatarsal stress fractures, and may also explain why recruits who demonstrate later peak metatarsal pressures are predisposed to metatarsal stress fractures.

8.2.3 Ankle inversion injury

Recruits who sustained ankle inversion injuries during training had a smaller body mass, BMI, calf girth and bimalleolar breadth at baseline than those who remained injury-free (Chapter 4). A recruit with a smaller body mass will be subjected to relatively greater forces during load carriage activities and may be more susceptible to injury and fatigue. There was evidence of peroneus longus muscle fatigue following a load carriage activity (Chapter 7). This muscle is a subtalar evolver, therefore a fatigued peroneus longus muscle may have a reduced ability to counter excessive inversion, increasing the likelihood of ankle inversion injury. The acute nature of ankle inversion injuries means that mechanisms by which they occur are harder to identify than for overuse injuries. Furthermore, this injury occurs through motion in the frontal plane, unlike stress fractures, which are believed to be strongly associated with sagittal plane bending. There is lower repeatability (Appendix G) and greater within-recruit variability (Appendix D) of biomechanical variables measured in the frontal plane than in the sagittal plane. This may make it even more difficult to understand mechanisms for ankle inversion injuries compared with stress fractures. Despite these difficulties, the findings of this thesis provide an important contribution to the mechanistic understanding of ankle inversion injury occurrence in Royal Marine recruits.

8.3 Limitations

Prospective study is an effective study design for the understanding of characteristics associated with injury development. The major limitation is the risk of insufficient injury cases reported during the study period. More injury cases would have strengthened Chapter 4. The coefficients of variation (Appendix D) suggest high inter-individual variability for a number of biomechanical variables, increasing the risk of a type II error, whereby characteristics may exist which were not identified due to the number of injuries reported. However, if these

characteristics are highly variable within recruits, their identification may not be useful, as recruits at increased risk of injury may not be easily identified in future.

A limitation of working with the Royal Marine recruit population in injury-based research is the likely reluctance of recruits to report injuries for various reasons. It is unlikely that injuries were under-reported in Chapter 4 given the severity of injuries that were considered. Anecdotally, it is considered that it would be difficult for a recruit to complete the demanding training programme, including all the physical assessments and tests if they had sustained an unreported tibial stress fracture, metatarsal stress fracture or ankle inversion injury. Reluctance to report injuries may result in the development of symptoms of bone stress into a stress fracture.

An inclusion criterion throughout this thesis was that all volunteer recruits were injury-free at the time of data collection. It is possible that some participating recruits falsely claimed to be injury-free, which would mean that recorded gait characteristics were not a true representation of an injury-free gait. Investigators were aware of this risk and reminded recruits that any injuries or discomfort reported would remain confidential. The sample sizes used in each study, and the effect sizes of changes observed in Chapters 6 and 7 provide confidence that the findings were not unduly influenced by this factor.

This thesis includes two studies (Chapters 4 and 6) in which barefoot running gait was assessed, and a further study (Chapter 7) in which walking gait in military boots was assessed. The results in this thesis may have been strengthened if the mode of activity and footwear condition was consistent throughout. All three experimental studies were demanding on recruit time, within a busy training programme, thus it was not possible to record barefoot running and shod walking data in each study. Lengthy consideration was given to the design of each study and it is believed that the most appropriate condition was selected in each case. The strength of results and associations between the findings in each of the studies suggests this decision was justified. The studies were closely related through the use of the same data collection protocol in Chapters 4 and 6, and the

same prolonged protocol in Chapters 6 and 7. This ensured that the findings of each study facilitated the interpretation of the others.

The biomechanical models used to determine kinematics and kinetics throughout this thesis (Sections 3.4.6, 3.4.8) rely on accurate marker placement that is subject to error. Trained investigators positioned the markers on anatomical landmarks, but inaccuracies are unavoidable. In particular, the axes may not have been strictly perpendicular, and this would have introduced error. Differences that occurred in kinematic and kinetic variables between sessions, in which markers were repositioned, may have been the result of marker placement inaccuracies. However, it is likely that changes would have been in different directions between recruits, rather than a group mean change in the same direction, if the marker positioning resulted in random error. Therefore the fact that group mean changes were observed, suggests these changes were greater than any change that resulted from marker placement error.

Joint angles were adjusted for the offsets recorded during a standing trial. Recruits were asked to stand in a relaxed position, and were not asked to stand with knees as straight as possible. Conventionally, zero degrees of knee flexion would be considered to represent a straight leg, so that any negative value represents hyperextension of the knee. That was not the case in this thesis, where it is likely that a recruit contacted the ground with a knee that was more extended than during standing, therefore resulting in negative values at touchdown. In future, results may be clearer if recruits are asked to stand with their knees straight when collecting the standing trial.

Recruits were familiarised to the procedures by repeated practice runs or walks until they appeared to be comfortable with the process. It must be noted that running barefoot on an EVA runway is an activity the recruits are likely to be unfamiliar with, and as such the gait displayed may not be a true representation of their running gait. For true familiarisation, the recruits may have needed to run in this condition for several weeks. Different or additional variables may have been identified as being associated with injury occurrence, had a different protocol been used.

Studies which make assessments pre- and post- a certain protocol often include a control group to determine whether any observed changes would have occurred without the influence of the protocol. That was not deemed necessary in the studies in Chapters 6 and 7. This would have required a greater number of recruits to participate in the study, and this was considered unethical. It was assumed that gait changes that occurred as a result of the activity would not have been observed in a control group who did not complete the activity. Future studies of this nature would benefit from the inclusion of information regarding pain and discomfort following a prolonged activity.

8.4 Implications

Ultimately, the purpose of conducting research of this type is to reduce lower limb injury occurrence. It was believed that in order to achieve this in the future, an increased understanding of the mechanisms for injury development was required. Chapter 4 identified characteristics that differed between recruits who sustained tibial stress fractures, metatarsal stress fractures and ankle inversion injuries, and recruits who remained injury-free. Gait changes observed in Chapters 6 and 7 helped to establish associations between those characteristics and injury development. The anthropometric characteristics that were associated with injury occurrence (Chapter 4) could be used to inform entry criteria into Royal Marine recruit training, as these variables are relatively cost-effective and easy to measure reliably. In the case of BMI and calf girth, these variables could be identified and modified appropriately prior to a recruit commencing training. Identification of a minimum bimalleolar breadth for entry into the training programme could be considered. Additionally, it may be possible to identify recruits at increased injury risk based on these variables, and to introduce an intervention to minimise risk in those individuals.

The review of the recruit training programme identified training variables and activities associated with injury occurrence. Whilst it is tempting to suggest that the training programme should be altered to reduce injury occurrence, clearly the demanding nature of recruit training is essential in order for recruits to reach the required standards of a trained Royal Marine. Furthermore, the current recruit

training programme is completed by hundreds of recruits per year, indicating that it is not unduly demanding. With this in mind, it may not be appropriate to alter the training programme.

The findings of Chapters 6 and 7 built upon the findings of Chapter 4 to provide an improved understanding of the mechanisms by which tibial and metatarsal stress fractures, and to a lesser extent ankle inversion injuries occur. The findings were well supported by existing literature, providing confidence in their validity. In summarising the evidence, it appears that the key contributor to tibial and metatarsal stress fracture was a reduced ability to push-off during stance following a military load carriage activity, most likely as a result of plantar flexor muscle fatigue. These mechanisms could explain some of the characteristic differences observed in Chapter 4, providing further confidence in the validity of the findings.

The increased understanding of mechanisms for injury development can inform the assessment of interventions. Interventions that could be considered include footwear, orthotics, and physical training interventions. It is possible that footwear and orthotics could facilitate plantar flexion during the push-off phase of stance. However, a device to achieve this within this population would need to be developed. Orthotic or footwear interventions require thorough assessment as they may increase the risk of other injuries through altered gait. The findings presented in this thesis suggest that specific physical training that increases foot and ankle plantar flexor muscle strength and/or fatigue resistance may reduce the incidence of stress fractures and ankle inversion injury. Interventions to increase plantar flexor muscular endurance should be considered. Such interventions may be more beneficial to recruits who are at greater risk of sustaining a tibial stress fracture, metatarsal stress fracture, or ankle inversion injury than those considered to be at a lower risk. It would therefore be beneficial to establish limits for variables associated with injury occurrence, in order to identify those recruits at greatest risk.

Resistance training to increase plantar flexor muscular endurance is likely to result in muscle hypertrophy (Bird, Tarpinning, & Marino, 2005). This may increase calf girth and therefore reduce risk of those injuries with which a smaller calf girth was associated (tibial stress fracture and ankle inversion injury, Chapter 4). Plantar

flexor muscle training may also increase strength in these muscles. Recommendations to increase muscular endurance suggest combining concentric and eccentric activities, using 1-3 sets of 15-20 repetitions (Bird, Tarpenning, & Marino, 2005). The amount of load used should be the maximum load that the individual can lift for 15-20 repetitions whilst maintaining the correct technique. Muscular endurance is enhanced with relatively high repetitions and low resistance (Anderson & Kearney, 1982; Campos et al., 2002; Hass et al., 2001). It is recommended that there is 30-60 seconds of recovery time between each set and that training of this type takes place on 1-2 days per week (Bird, Tarpenning, & Marino, 2005). Calf raise activity when the foot can be lowered below the position of the lever (usually the forefoot) (Mafi et al., 2001) includes both a concentric and eccentric phase (Hébert-Losier et al., 2009). Resistance can be increased through the addition of backpacks, or using equipment designed for this purpose (Mafi, Lorentzon, & Alfredson, 2001). Single leg heel raises have been used as an indicator of ankle plantar flexor muscle fatigue, and ability to complete this activity has been inversely associated with overuse shin pain (Madeley, Munteanu, & Bonanno, 2007). The addition of calf raise activity to training may help to maintain the ability to push off during load carriage activities. Furthermore, this activity should develop both the foot and ankle plantar flexor muscles, which may therefore be beneficial in minimising risk of tibial stress fractures, metatarsal stress fractures and ankle inversion injuries. The timing of this within the programme should be carefully considered so that valuable recovery time is not lost. Physical training takes place on most training days within the programme, and this is often gym-based training, particularly in Phase-1 of training. These sessions may be an appropriate opportunity to include concentric and eccentric plantar flexor muscle training, so that overall volume of training is not increased. As with any intervention, there is a risk of detrimental outcomes, which should be assessed. This may particularly be the case if plantar flexor muscle training replaces another training activity. Intuitively it would be expected that there is a smaller risk of detrimental effects with this type of intervention than an orthotic/footwear intervention, as changes are likely to be more gradual, and more individualised. It is possible that calf girth increases throughout the training programme. This should

be assessed in future recruit populations in association with training success and injury occurrence. Furthermore, functional assessments such as the number of successive calf raises a recruit can do until exhaustion may provide an indication of fatigability, and this could help to identify recruits at increased risk of injury occurrence. The introduction of such a test at various stages throughout the training programme should be considered. Outcome in a test of this nature has previously been associated with medial tibial stress syndrome (Madeley, Munteanu, & Bonanno, 2007). An assessment of this nature could be conducted both with and without additional load.

Lower limb stress fractures are a problem for the wider athletic population, particularly runners. The mechanisms for stress fracture development presented in this thesis are likely to be specific to military populations and those who regularly carry load. However, reduced loading under the toes (Escamilla-Martínez, et al., 2013; Nagel, et al., 2008; Weist, Eils, & Rosenbaum, 2004; Willems, De Ridder, & Roosen, 2012) and increased heel loading (Escamilla-Martínez, et al., 2013; Weist, Eils, & Rosenbaum, 2004; Willems, De Ridder, & Roosen, 2012) as found following the load carriage activity (Chapter 6), have been consistently reported following running for various durations in populations at high risk of stress fracture. Some of the mechanisms for stress fracture development in these populations may therefore be the same as those found in this thesis. The characteristics that were associated with injury occurrence in Chapter 4 may also be relevant to non-military populations, particularly those who regularly carry load. This thesis included only male participants, and although it would be expected that similar mechanisms may be relevant to injury development in female military recruits, this requires investigation.

8.5 Future research

Based on the increased understanding of mechanisms provided by the present study, intervention studies should be conducted which address the following research questions:

- Can values be determined that identify recruits at increased risk of tibial stress fracture, metatarsal stress fracture and ankle inversion injury?
- Can increases in BMI and calf girth prior to entry reduce the risk of tibial stress fracture and ankle inversion injury in recruits at high risk?
- Can a test to measure plantar flexor muscular endurance throughout training identify recruits at greatest risk of injury?
- Does the inclusion of specific plantar flexor muscle training throughout the Royal Marine recruit training programme minimise gait changes following a prolonged load carriage activity?
- Does the inclusion of specific plantar flexor muscle training throughout the Royal Marine recruit training programme reduce plantar flexor muscle fatigue following a load carriage training activity?
- Does the inclusion of specific plantar flexor muscle training throughout the Royal Marine recruit training programme result in increased calf girth?
- Does the inclusion of specific plantar flexor muscle training throughout the Royal Marine recruit training programme reduce the incidence of tibial stress fracture, metatarsal stress fracture and ankle inversion injury?

8.6 Recommendations

In summary, the findings of this thesis led to the following recommendations:

- Entry criteria into the Royal Marine recruit training programme should be re-examined, with minimum values for BMI, calf circumference and bimalleolar breadth determined based on the baseline data of those who remained injury-free (Chapter 4).

- Interventions focusing on increasing calf girth, and reducing fatigability of foot and ankle plantar flexor muscles should be assessed.

8.7 Conclusions

The purpose of this thesis was to identify variables associated with tibial stress fractures, metatarsal stress fractures, and ankle inversion injuries in Royal Marine recruits, and to improve understanding of the mechanisms by which these injuries occur. These aims were achieved, with each successive study further improving the existing understanding of mechanisms for these injuries. Royal Marine recruits with a smaller body composition are likely to be at increased risk of sustaining an injury during training, due to the greater physical demand of their training, and their greater susceptibility to muscular fatigue as a consequence. Calf girth may be an important modifiable injury risk factor for Royal Marine recruits. Muscular training to increase calf girth and reduce plantar flexor muscle fatigability is recommended to reduce the risk of these common training injuries.

APPENDIX A: Letters confirming ethical approval for Chapters 4 and 6



science | innovation | technology

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Dr Joanne Fallowfield,

Ref: 0849/204

Environmental Medicine Unit,
Institute of Naval Medicine,
Alverstoke,
Gosport,
Hampshire PO12 2DL.

Dear Dr Fallowfield,

Re: Identification of Biomechanical Predictors of Lower Limb Stress Fracture Susceptibility (0849/204)

Thank you for submitting this interesting research protocol for ethical review and for attending the recent Research Ethics Committee meeting.

I am happy to confirm ethical approval on behalf of MoDREC and should be grateful if you would send me a copy of your final report on completion of the study. This approval is conditional upon adherence to the protocol – please let me know if any amendment becomes necessary.

I hope the work goes well.

Yours sincerely,

Dr Robert Linton

Chairman MoD Research Ethics Committee



MOD Research Ethics Committee (General)

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Dr Joanne Fallowfield,

Ref: 0849/204

Environmental Medicine Unit,
Institute of Naval Medicine,
Alverstoke,
Gosport,
Hampshire PO12 2DL.

15th April 2010

Dear Dr Fallowfield,

Re: Identification of Biomechanical Predictors of Lower Limb Stress Fracture Susceptibility (0849/204) – 1st amendment

Thank you for submitting details of this amendment.

I understand that you wish to include goniometer measurements of knee hyperextension and also to add two MSc students as investigators. It would be helpful if they could send me brief CVs in due course.

This letter confirms the ethical approval given on behalf of MODREC in my e-mail of 13th April. Please let me know if any further amendment becomes necessary.

Yours sincerely,

Dr Robert Linton

Chairman MOD Research Ethics Committee



MOD Research Ethics Committee (General)
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Dr Joanne Fallowfield
Head of Applied Physiology
Institute of Naval Medicine
Crescent Road
Alverstoke
Hampshire
PO12 2DL

Your ref: 150/127

Ref: 0849/204

27th January 2011

Dear Dr Fallowfield,

**Re: Identification of Biomechanical Predictors of Lower Limb Stress Fracture
Susceptibility (0849/204) – 2nd amendment**

Thank you for submitting details of this amendment.

This is to allow the addition of Ms Hannah Rice to the research team and for the data to be used to investigate a possible association between static and dynamic biomechanical measures and prevalence of ankle injuries in RM recruits.

I am happy to give ethical approval for this amendment on behalf of the MOD Research Ethics Committee (General).

Yours sincerely,

Dr Robert Linton

Chairman MOD Research Ethics Committee (General)

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Dr Joanne Fallowfield
Head of Applied Physiology
Institute of Naval Medicine
Crescent Road
Alverstoke
Hampshire
PO12 2DL

Your ref: 150/127

Ref: 0849/204

11th October 2011

Dear Dr Fallowfield,

**Re: Identification of Biomechanical Predictors of Lower Limb Stress Fracture
Susceptibility (0849/204) – 3rd amendment**

Thank you for submitting details of this amendment.

This is to allow the application of further markers in order to track lower limb movement during barefoot running.

I am happy to give ethical approval for this amendment on behalf of the MOD Research Ethics Committee (General).

Yours sincerely,

Dr Robert Linton

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Dr Joanne Fallowfield
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PO12 2DL

Your ref: 150/127

MODREC Ref: 0849/204

15th March 2013

Dear Dr Fallowfield,

**Re: Identification of Biomechanical Predictors of Lower Limb Stress Fracture
Susceptibility (0849/204) – 4th amendment**

Thank you for submitting details of this amendment.

This is to allow a further group of 45 RM recruits to be studied at week-20 of training before and after an 8 mile loaded march. I note that an Experimental Test Allowance of up to £48.42 will be paid.

I am happy to give ethical approval for this amendment on behalf of the MOD Research Ethics Committee (General).

Yours sincerely,

Dr Robert Linton

Chairman MOD Research Ethics Committee (General)

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APPENDIX B: Letter confirming ethical approval for Chapter 7

MOD Research Ethics Committee (General)



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Dr Joanne Fallowfield
Head of Applied Physiology
Institute of Naval Medicine
Alverstoke
Gosport
Hampshire PO12 2DL

Ref: 367/Gen/12

27th September 2011

Dear Dr Fallowfield,

Re: The effect of load carriage and fatigue during marching and running on biomechanical and anatomical measures in Royal Marine recruits – version 2.0

Thank you for attending the recent MODREC meeting and for subsequently making minor revisions to this protocol.

I am now happy to confirm ethical approval for this research on behalf of the MOD Research Ethics Committee (General) and should be grateful if you would send me a copy of your final report on completion of the study. Please would you also send me a brief interim report in one year's time if the study is still ongoing.

This approval is conditional upon adherence to the protocol – please let me know if any amendment becomes necessary.

Yours sincerely,

A handwritten signature in blue ink that reads 'Robert Linton'.

Dr Robert Linton
Chairman MOD Research Ethics Committee (General)

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APPENDIX C: Health History Questionnaire

CTC BIOMECHANICS STUDY – HEALTH HISTORY QUESTIONNAIRE

Surname: _____

First Names: _____

Service No. _____ DoB: _____ Date: _____

Ethnic origin: (please circle) White background Black Caribbean
Black African

Mixed Black Caribbean and White Mixed Black African and White Any Chinese Background
Mixed

Asian and White Other Ethnic Background, please state _____

Do you have a family history of heart disease or early death? Yes/No

Are both your parents still alive? Yes/No

If either is dead, at what age(s) did they die? Father _____ years; Mother _____ years

Do / did your parents, brothers or sisters suffer from asthma or wheezing in the chest? Yes/No

Do you suffer from, or have you ever suffered from:

chest pain	Yes/No
breathlessness on exertion	Yes/No
dizziness on exertion	Yes/No
collapse when exercising	Yes/No
palpitations	Yes/No
asthma/wheezing	Yes/No
heat illness	Yes/No
anaemia	Yes/No
cold injury (freezing or non-freezing)	Yes/No
poor circulation (“Raynaud’s”)	Yes/No

Yes/No

If yes to any, please give details:

Have you ever been admitted to hospital? Yes/No

If yes, please give details

Have you ever broken any bones? Yes/No

If yes, which bone(s) and when?

Do you take any medication regularly or to treat any condition? Yes/No

If yes, please give details

APPENDIX D: Coefficients of variation for anthropometric, plantar pressure, kinematic, kinetic and EMG variables

The relative coefficients of variation (CV) for a selection of variables calculated on a ratio scale were computed (standard deviation divided by the mean). This provided an indication of the amount of variability in relation to the mean, allowing comparison between variables of differing units.

Results

Table D1: Coefficients of variation for anthropometric variables

Variable	CV
Calf girth	0.05
Corrected calf girth	0.05
Ankle width	0.07
Mean	0.06

Table D2: Coefficient of variation for pressure variables

Variable	CV
Ground contact time	0.10
HL peak pressure	0.31
M1 peak pressure	0.36
M3 peak	0.29
M1 impulse	0.44
M3 impulse	0.30
Mean	0.28

HL: lateral heel; M1: first metatarsal; M3 third metatarsal

Table D3: Coefficient of variation for kinematic variables

Variable	CV
Dorsiflexion ROM	0.25
Time peak dorsiflexion	0.10
Tibial rotation ROM	0.52
Eversion ROM	0.51
Time peak eversion	0.19
Dorsiflexion rate	0.29
Eversion rate	0.45
Mean	0.33

ROM: range of motion

Table D4: Coefficient of variation for kinetic variables

Variable	CV
Peak plantar flexor moment	0.21
Peak knee extensor moment	0.28
Peak knee flexor moment	0.23
Time peak plantar flexor moment	0.02
Time peak knee extensor moment	0.21
Mean	0.24

Table D5: Coefficient of variation for EMG variables

Variable	CV
VL maximum amplitude	0.22
PL median frequency	0.26
PL mean frequency	0.16
GL iEMG	0.25
TA iEMG	0.29
Mean	0.24

APPENDIX E: Reliability of manual zone adjustment within RSscan software

Zone adjustment reliability:

Inter- and intra-observer reliability were assessed for the two investigators who manually adjusted zones for the data in this thesis. Both investigators were familiar with the software at the time of assessment. First, the automatic zone division was observed, and compared with the image of pressures acting under the foot (Figure E1).

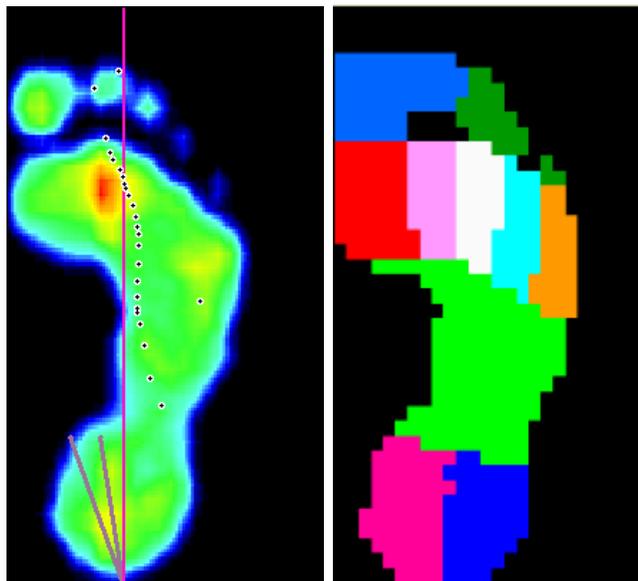


Figure E1: Sample image of pressures under foot (left) and accompanying automatically determined zones (right)

The adjustments to be made were agreed between investigators, with one demonstrating the procedure to the other. The following adjustments were made:

- 1) Position of the outline of the foot was altered to contain the foot (Figure E2). This can result in altered positioning of the metatarsal zones (Figure E3)

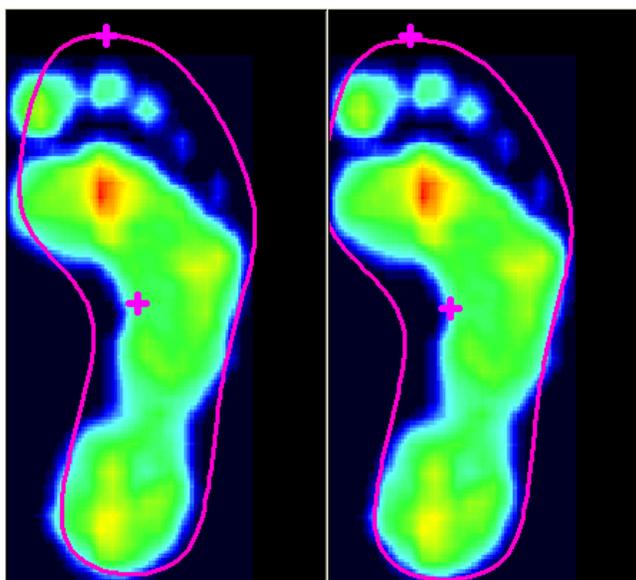


Figure E2: automatic position (left) and after adjustment (right)

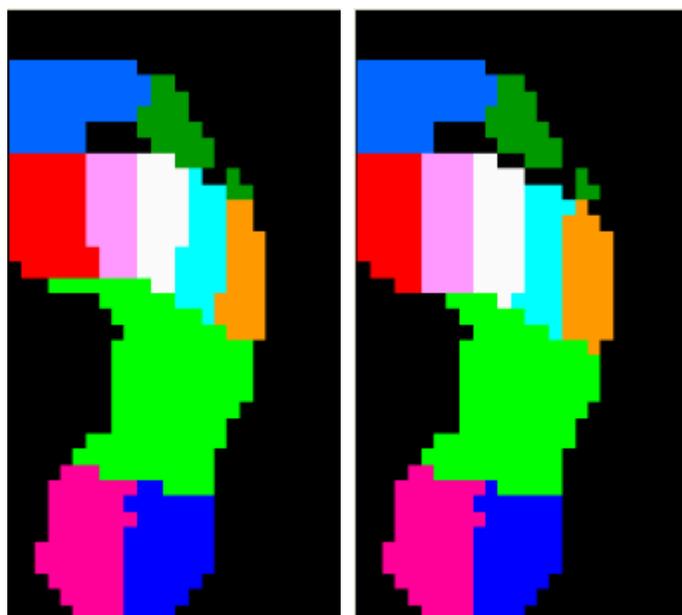


Figure E3: Position of the metatarsal zones by automatic division (left) and after movement of the foot outline (right)

- 2) Straight lines which represented the metatarsal zones were altered and pixels representing the hallux and lesser toes were deleted or added where appropriate (Figures E4 and E5). Investigators agreed that minimal alteration was preferable.

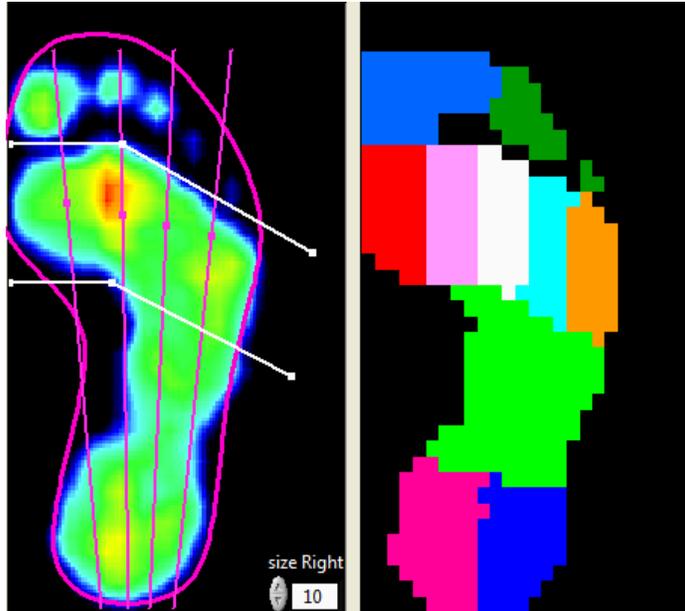


Figure E4: straight lines (left) representing the ends of the metatarsal zones (right) prior to manual adjustment

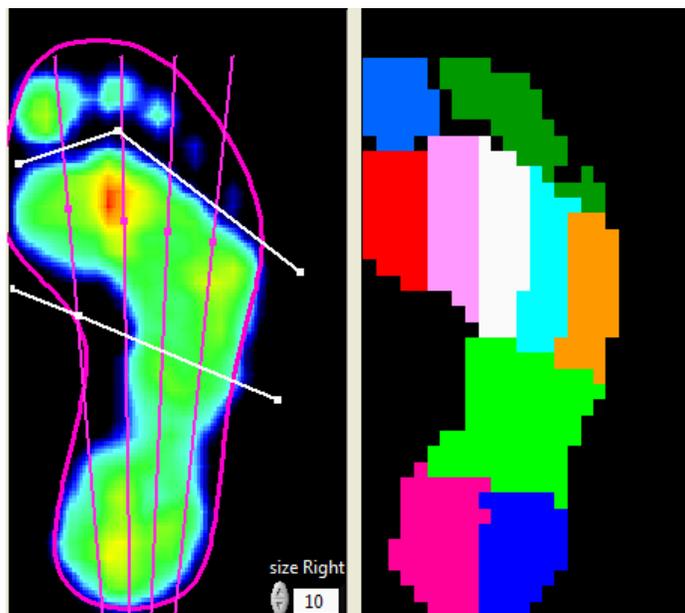


Figure E5: straight lines (left) representing the ends of the metatarsal zones (right) following manual adjustment

The two investigators each adjusted right foot zones according to these guidelines for barefoot running trials from ten randomly selected males. Each of the ten participants had recorded five running trials. Peak pressures and impulses from the five metatarsals and the medial and lateral heel were exported after this adjustment. Each investigator completed this task three times, on three different occasions. The intraclass correlation coefficient (ICC) was calculated for each variable using a single measures, two-way random effects model. Values were classified as fair ($0.4 < \text{ICC} \leq 0.6$), good ($0.6 < \text{ICC} \leq 0.8$) or excellent ($0.8 < \text{ICC} \leq 1$) (Landis, 1977). The percentage difference between repeats was also calculated. The mean of repeated exports were taken for each observer and compared between the two observers to give an indication of inter-observer reliability.

Results:

Intra-observer reliability: Peak pressures and impulses under each zone had values of $\text{ICC} \geq 0.995$ for both investigators ($P < 0.001$) indicating very high intra-observer reliability. Inter-observer reliability was very high ($\text{ICC} \geq 0.985$, $P < 0.001$) for peak pressure and impulse.

APPENDIX F: Within-recruit reliability of plantar pressure variables

The reliability of pressure measurements within-recruits was assessed from 12 recruits who had each completed five barefoot running trials at 3.6 m.s⁻¹. Each recruit's trials were conducted consecutively within the same data collection session. The data for the assessment of reliability were collected across two different days, and the pressure plate was recalibrated in between (8 recruits on first session, 4 recruits in second session). Data from both feet were included in the analyses (n = 24). The intraclass correlation coefficient (ICC) was calculated and classified as outlined in Appendix E (p.175). The variables selected were peak pressures and impulses (hallux, first metatarsal, third metatarsal, lateral heel), ground contact time, time of peak pressure (first, third and fifth metatarsals), and rearfoot and forefoot contact percentage and impulse. For the assessment of reliability of rearfoot and forefoot contact percentage and impulse, data from a randomly selected foot of ten recruits were used. ICC values, F values and p values are presented for each variable.

Results

Within-recruit reliability results are presented for peak pressure (Table F1), impulse (Table F2), temporal variables (Table F3) and contact area and impulse (Table F4). Reliability was excellent for peak pressure and impulse under the lateral heel. Peak pressure under the first metatarsal was poor. Temporal variables demonstrated mostly excellent reliability, with good reliability under the third metatarsal. Contact percentage and impulse under both the rearfoot and forefoot demonstrated excellent reliability.

Table F1: within-recruit reliability of peak pressure values

Peak Pressure	ICC	F	P
HX	0.573	2.326	0.002
M1	0.201	1.251	0.224
M3	0.650	2.928	< 0.001
HL	0.858	6.948	< 0.001

HX: hallux; M1: first metatarsal; M3: third metatarsal; HL: lateral heel

Table F2: within-recruit reliability of impulse values

Impulse	ICC	F	P
HX	0.719	3.490	< 0.001
M1	0.504	2.009	0.010
M3	0.581	2.380	0.002
HL	0.910	10.921	< 0.001

HX: hallux; M1: first metatarsal; M3: third metatarsal; HL: lateral heel

Table F3: within-recruit reliability of temporal pressure variables

Timing	ICC	F	P
Ground contact time	0.939	15.796	< 0.001
Time M1 peak pressure	0.836	5.971	< 0.001
Time M3 peak pressure	0.683	3.169	< 0.001
Time M5 peak pressure	0.866	7.540	< 0.001

M1: first metatarsal; M3: third metatarsal; M5: fifth metatarsal

Table F4: within-recruit reliability of contact area and impulse for rearfoot and forefoot regions

Contact area and impulse	ICC	F	P
Rearfoot percentage	0.900	10.097	< 0.001
Forefoot percentage	0.939	15.678	< 0.001
Rearfoot impulse	0.957	24.294	< 0.001
Forefoot impulse	0.955	23.599	< 0.001

APPENDIX G: Within-recruit reliability of kinematic and kinetic variables

Within-recruit reliability of kinematic and kinetic variables was assessed from 17 recruits who had each completed five walking trials at 1.4 m.s⁻¹. Four trials were selected from each recruit, to avoid issues of missing data. Each recruit's trials were conducted consecutively within the same data collection session. Data for reliability assessment were collected across four sessions. The Coda system was realigned between these sessions. Only data from the left leg were included in the analyses. The most commonly reported variables were considered. The intraclass correlation coefficient (ICC) was calculated and classified as described in Appendix E (p.175). ICC values, F values and p values are presented for each variable. ICC values were classified according to the Landis and Koch classification (Appendix E, (Landis, 1977)).

Results:

Sagittal plane kinematic variables demonstrated excellent within-recruit reliability (Table G1). Subtalar joint kinematics demonstrated good reliability. All kinetic variables demonstrated excellent within-recruit reliability.

Table G1: Within-recruit reliability of kinematic variables during walking

Kinematics	n	ICC	F	P
Dorsiflexion ROM	17	0.976	52.153	< 0.001
Peak dorsiflexion	17	0.989	112.516	< 0.001
Dorsiflexion rate	17	0.941	17.069	< 0.001
Knee flexion ROM	17	0.955	20.967	< 0.001
Peak knee flexion	17	0.984	74.260	< 0.001
Knee flexion rate	16	0.921	12.180	< 0.001
Eversion ROM	16	0.714	3.504	0.002
Eversion rate	16	0.700	3.257	0.003
Kinetics	n	ICC	F	P
Peak plantar flexor moment	17	0.967	28.783	< 0.001
Peak knee extensor moment	17	0.984	61.408	< 0.001

Note: ROM: range of motion

APPENDIX H: EMG sensor positioning

When positioning EMG sensors on the five muscles used in this thesis (vastus lateralis (VL), biceps femoris (BF), gastrocnemius longus (GL), tibialis anterior (TA) and peroneus longus (PL)), muscular actions were used to ensure correct sensor positioning. When testing the signal quality of the sensor positioned on each muscle, a given action should elicit muscle activity. The role of each of the five muscles, and the instruction given to recruits to check correct sensor positioning are provided in Table H1. This was used to provide confidence that the sensor was located in the correct position during data collection in Chapter 7.

Table H1: role of each muscle and the instruction given to each recruit when assessing signal quality of each EMG sensor

Muscle	Role	Instruction to recruit
VL	Knee extensor	1) Tense thigh muscles
BF	Knee flexor, hip extensor	1) Raise leg whilst keeping knee straight 2) Heel flick
GL	Plantar flexor, knee flexor	1) Stand on tiptoes 2) Heel flick
TA	Dorsiflexor, invertor	1) Pull toes towards shin 2) Roll ankle outwards
PL	Plantar flexor, evertor	1) Stand on tiptoes 2) Roll ankle inwards

APPENDIX J: Within- and between-day reliability of EMG variables

Within-recruit reliability was assessed both within- (five walking trials) and between-days (mean of five trials across two consecutive days). Seven active males conducted five walking trials at $1.4 \text{ m}\cdot\text{s}^{-1}$, whilst wearing self-selected, non-military footwear. The position of the sensor was marked with pen which was still visible the following day. The intraclass correlation coefficient (ICC) was calculated and classified as described in Appendix E (p.175).

Results:

Within-day reliability values are reported in tables J1 to J5 for the VL, BF, GL, TA and PL muscles respectively. Within-day reliability was good ($\text{ICC} > 0.7$) for all muscles and variables, with the exception of maximum PL amplitude which demonstrated poor reliability. Between-day reliability values are reported in tables J6 to J10 for the VL, BF, GL, TA and PL muscles respectively. Between-day reliability was poor in the BF and GL muscles. VL amplitude variables demonstrated excellent reliability ($\text{ICC} \geq 0.96$) whereas frequency variables demonstrated good reliability. TA reliability was good ($\text{ICC} > 0.69$) for all variables and PL reliability was good ($\text{ICC} > 0.7$) for all variables except for median frequency which demonstrated fair reliability.

Table J1: within-day reliability for the vastus lateralis (VL) muscle

VL	ICC	F	P
Median frequency	0.752	3.824	0.020
Mean frequency	0.820	6.827	0.002
Maximum amplitude	0.938	17.786	< 0.001
iEMG	0.980	52.248	< 0.001

Table J2: within-day reliability for the biceps femoris (BF) muscle

BF	ICC	F	P
Median frequency	0.856	6.439	0.002
Mean frequency	0.886	8.347	0.001
Maximum amplitude	0.786	4.891	0.007
iEMG	0.806	5.283	0.005

Table J3: within-day reliability for the gastrocnemius lateralis (GL) muscle

GL	ICC	F	P
Median frequency	0.861	6.469	0.002
Mean frequency	0.901	9.114	< 0.001
Maximum amplitude	0.973	38.894	< 0.001
iEMG	0.962	26.044	< 0.001

Table J4: within-day reliability for the tibialis anterior (TA) muscle

TA	ICC	F	P
Median frequency	0.837	6.170	0.001
Mean frequency	0.910	10.595	< 0.001
Maximum amplitude	0.947	20.480	< 0.001
iEMG	0.903	9.317	0.008

Table J5: within-day reliability for the peroneus longus (PL) muscle

PL	ICC	F	P
Median frequency	0.729	3.427	0.020
Mean frequency	0.811	4.735	0.005
Maximum amplitude	0.421	1.961	0.125
iEMG	0.878	7.300	0.009

Table J6: between-day reliability for the vastus lateralis (VL) muscle

VL	ICC	F	P
Median frequency	0.462	1.990	0.212
Mean frequency	0.539	2.028	0.205
Maximum amplitude	0.960	31.551	0.001
iEMG	0.985	86.528	< 0.001

Table J7: between-day reliability for the biceps femoris (BF) muscle

BF	ICC	F	P
Median frequency	-8.477	0.181	0.981
Mean frequency	-0.364	0.754	0.640
Maximum amplitude	0.257	1.415	0.329
iEMG	0.572	2.208	0.159

Table J8: between-day reliability for the gastrocnemius lateralis (GL) muscle

GL	ICC	F	P
Median frequency	0.145	1.173	0.419
Mean frequency	-0.187	0.807	0.608
Maximum amplitude	0.103	1.122	0.442
iEMG	0.232	1.305	0.367

Table J9: between-day reliability for the tibialis anterior (TA) muscle

TA	ICC	F	P
Median frequency	0.692	3.144	0.117
Mean frequency	0.796	4.990	0.036
Maximum amplitude	0.847	5.838	0.016
iEMG	0.705	3.156	0.076

Table J10: between-day reliability for the peroneus longus (PL) muscle

PL	ICC	F	P
Median frequency	0.445	1.746	0.240
Mean frequency	0.741	4.580	0.031
Maximum amplitude	0.903	12.760	0.002
iEMG	0.806	5.353	0.030

APPENDIX K: Determination of the number of injury-free recruits required for analysis (Chapter 4)

The prospective study in this thesis (Chapter 4) involved data collection from 1065 recruits. Data from those who sustained an injury were compared with those who remained injury-free. 419 recruits remained injury-free. It was deemed unnecessary to analyse all kinematic and plantar pressure data for these recruits. To determine the required sample size, a cumulative means analysis was conducted.

Cumulative means analysis

Cumulative means analysis is a method for determining sample size based on methods suggested by Bates et al., (1983). The mean value from 150 recruits for a number of anthropometric, plantar pressure and kinematic variables used in Chapter 4 were obtained. These values were used as a stable representation of the mean values of recruits who completed training injury-free. Existing prospective studies examining gait variables have typically used smaller samples.

The mean value obtained from 150 recruits was the criterion mean. The criterion difference was one quarter of the standard deviation of this value. Cumulative means were then obtained from a random selection of these 150 recruits, increasing from one up to 150. The difference between the cumulative mean and the criterion mean was obtained until this difference was less than the criterion difference. This point indicated the minimum sample required, with the inclusion of additional recruits unlikely to alter the group mean.

For the variables included, 101 injury-free recruits was the maximum required to achieve stability. The variable which elicited this number was passive hip range of motion which was a variable included in Nunns' thesis (Nunns, 2014). For many variables, fewer than 70 recruits were required, suggesting that 100 was a conservative number. Data from 120 injury-free recruits were analysed for Nunns' thesis, to ensure a conservative sample size. It was logical to use all of these recruits in the analyses for the study in Chapter 4 of this thesis.

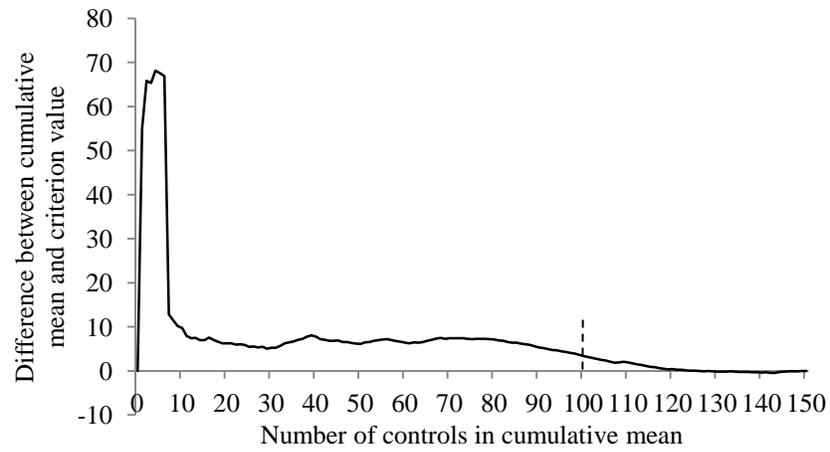


Figure K1: Cumulative means analysis for hip range of motion, obtained from Nunns (2014) with permission. The dashed line shows the point at which the cumulative mean consistently passes within one quarter of the standard deviation of the mean of 150 cases (n=101).

BIBLIOGRAPHY

- Ahmed, A. A. (2013). Estimation of stature using lower limb measurements in Sudanese Arabs. *Journal of Forensic and Legal Medicine*, 20(5), 483-488.
- Almeida, S. A., Williams, K., Shaffer, R. A., & Brodine, S. K. (1999). Epidemiological patterns of musculoskeletal injuries and physical training. *Medicine & Science in Sports & Exercise*, 31(8), 1176.
- Altman, D. G. (1980). Statistics and ethics in medical research: III How large a sample? *British Medical Journal*, 281(6251), 1336-1338.
- Anderson, T., & Kearney, J. T. (1982). Effects of three resistance training programs on muscular strength and absolute and relative endurance. *Research Quarterly for Exercise and Sport*, 53(1), 1-7.
- Arendt, E. A. (2000). Stress fractures and the female athlete. *Clinical Orthopaedics and Related Research*, 372, 131.
- Arndt, A., Ekenman, I., Westblad, P., & Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *Journal of Biomechanics*, 35(5), 621-628.
- Arnold, J. B., Causby, R., Pod, G. D., & Jones, S. (2010). The impact of increasing body mass on peak and mean plantar pressure in asymptomatic adult subjects during walking. *Diabetic Foot & Ankle*, 1.
- Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine*, 39(6), 324-329.
- Bates, B., Osternig, L., Sawhill, J., & James, S. (1983). An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. *Journal of Biomechanics*, 16(3), 181-191.
- Beck, B. R. (1998). Tibial stress injuries. *Sports Medicine*, 26(4), 265-279.
- Beck, B. R. (2000). *Stress Fractures* ACSM Current Comment. Michigan: ACSM
- Beck, T. J., Ruff, C. B., Mourtada, F. A., Shaffer, R. A., Maxwell-Williams, K., Kao, G. L., et al. (1996). Dual-energy X-ray absorptiometry derived structural geometry for stress fracture prediction in male US Marine Corps recruits. *Journal of Bone and Mineral Research*, 11(5), 645-653.

- Beck, T. J., Ruff, C. B., Shaffer, R. A., Betsinger, K., Trone, D. W., & Brodine, S. K. (2000). Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors. *Bone*, 27(3), 437-444.
- Bennell, K., Malcolm, S., Wark, J., & Brukner, P. (1996). Models for the pathogenesis of stress fractures in athletes. *British Journal of Sports Medicine*, 30(3), 200-204.
- Bennell, K., Matheson, G., Meeuwisse, W., & Brukner, P. (1999). Risk factors for stress fractures. *Sports Medicine*, 28(2), 91-122.
- Betker, A. L., Szturm, T., & Moussavi, Z. M. (2009). Estimation of 2-D center of mass movement during trunk flexion–extension movements using body accelerations. *IEE Transaction on Neural Systems and Rehabilitation Engineering*, 17(6), 553-559.
- Beynnon, B. D., Murphy, D. F., & Alosa, D. M. (2002). Predictive factors for lateral ankle sprains: a literature review. *Journal of Athletic Training*, 37(4), 376.
- Bilodeau, M., Schindler-Ivens, S., Williams, D., Chandran, R., & Sharma, S. (2003). EMG frequency content changes with increasing force and during fatigue in the quadriceps femoris muscle of men and women. *Journal of Electromyography and Kinesiology*, 13(1), 83-92.
- Bird, S. P., Tarpenning, K. M., & Marino, F. E. (2005). Designing resistance training programmes to enhance muscular fitness. *Sports Medicine*, 35(10), 841-851.
- Birrell, S. A., Hooper, R. H., & Haslam, R. A. (2007). The effect of military load carriage on ground reaction forces. *Gait & Posture*, 26(4), 611-614.
- Bisiaux, M., & Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait & Posture*, 28(4), 693-698.
- Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*, 39(13), 2438-2444.
- Blacker, S. D., Wilkinson, D. M., Bilzon, J. L. J., & Rayson, M. P. (2008). Risk factors for training injuries among British Army recruits. *Military Medicine*, 173(3), 278-286.
- Bloomfield, S. A. (1997). Changes in musculoskeletal structure and function with prolonged bed rest. *Medicine & Science in Sports & Exercise*, 29(2), 197-206.

- Brukner, P., Bennel, K., & Matheson, G. (1999). *Stress fractures*: John Wiley & Sons.
- Brukner, P. D., & Bennell, K. L. (2001). Stress Fractures. In F. O'Connor & R. Wilder (Eds.), *The textbook of running medicine* (pp. 227-256). New York: McGraw-Hill.
- Bullock, S. H., Jones, B. H., Gilchrist, J., & Marshall, S. W. (2010). Prevention of physical training-related injuries: recommendations for the military and other active populations based on expedited systematic reviews. *American Journal of Preventive Medicine*, 38(1), S156-S181.
- Campos, G., Luecke, T., Wendeln, H., Toma, K., Hagerman, F., Murray, T., et al. (2002). Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *European Journal of Applied Physiology* 88(1-2), 50-60.
- Carter, D. R., Caler, W. E., Spengler, D. M., & Frankel, V. H. (1981). Fatigue behavior of adult cortical bone: the influence of mean strain and strain range. *Acta Orthopaedica*, 52(5), 481-490.
- Cavanagh, P., Morag, E., Boulton, A., Young, M., Deffner, K., & Pammer, S. (1997). The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics*, 30(3), 243-250.
- Chan, K., Yuan, Y., Li, C., Chien, P., & Tsang, G. (1993). Sports causing most injuries in Hong Kong. *British Journal of Sports Medicine*, 27(4), 263-267.
- Clark, M. L., S.; National Academy of Sports Medicine. (2009). *NASM Essentials of Sports Performance Training*: Lippincott Williams & Wilkins,.
- Cohen, J. (1988a). The Analysis of Variance *Statistical Power Analysis for the Behavioral Sciences (Second Edition)* (pp. 148-150): Lawrence Erlbaum Associates.
- Cohen, J. (1988b). Multiple Regression and Correlation Analysis *Statistical Power Analysis for the Behavioural Sciences (Second Edition)* (pp. 407-444): Lawrence Erlbaum Associates.
- Cowin, S., & Hegedus, D. (1976). Bone remodeling I: theory of adaptive elasticity. *Journal of Elasticity*, 6(3), 313-326.
- Creaby, M. W., & Dixon, S. J. (2008). External frontal plane loads may be associated with tibial stress fracture. *Medicine & Science in Sports & Exercise*, 40(9), 1669.

- Dancey, C., & Reidy, J. (2007). Bivariate correlations *Statistics Without Maths for Psychology* (pp. 169-195): Pearson Education Limited 2007.
- Davey, T. (2013). *Nutritional influences on bone health, stress fracture risk and training progression in Royal Marine recruits*. Thesis. University of Surrey.
- Davey, T., Delves, S., Lanham-New, S., Allsopp, A., & Fallowfield, J. (2011). Body composition of Royal Marine recruits during 32 weeks of military training. *Proceedings of the Nutrition Society, 70*(OCE4), E150.
- De Cock, A., De Clercq, D., Willems, T., & Witvrouw, E. (2005). Temporal characteristics of foot roll-over during barefoot jogging: reference data for young adults. *Gait & Posture, 21*(4), 432-439.
- De Luca, C. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Critical reviews in biomedical engineering, 11*(4), 251-279.
- Dick, F. W. (2007). *Sports Training Principles* (5th ed.). London: A & C Black.
- Dierks, T. A., & Davis, I. (2007). Discrete and continuous joint coupling relationships in uninjured recreational runners. *Clinical Biomechanics, 22*(5), 581-591.
- Dixon, S. J., Creaby, M. W., & Allsopp, A. J. (2006). Comparison of static and dynamic biomechanical measures in military recruits with and without a history of third metatarsal stress fracture. *Clinical Biomechanics, 21*(4), 412-419.
- Escamilla-Martínez, E., Martínez-Nova, A., Gómez-Martín, B., Sánchez-Rodríguez, R., & Fernández-Seguín, L. M. (2013). The effect of moderate running on foot posture index and plantar pressure distribution in male recreational runners. *Journal of the American Podiatric Medical Association, 103*(2), 121-125.
- Evans, G. (1982). Stress fractures at Commando Training Centre Royal Marines, Lympstone--a retrospective survey (September 1979-October 1981). *Journal of the Royal Naval Medical Service, 68*(2), 77.
- Ferris, L., Sharkey, N. A., Smith, T. S., & Matthews, D. K. (1995). Influence of extrinsic plantar flexors on forefoot loading during heel rise. *Foot & Ankle International, 16*(8), 464-473.
- Field, A. (2005). Repeated measures designs *Discovering Statistics Using SPSS* (pp. 457-505). Thousand Oaks, CA: Sage.

- Franklyn-Miller, A., Bilzon, J., Wilson, C., & McCrory, P. (2014). Can RSScan footscan ® D3D™ software predict injury in a military population following plantar pressure assessment? A prospective cohort study. *The Foot*, 24(1), 6-10.
- Frost, H. M. (1994). Wolff's Law and bone's structural adaptations to mechanical usage: an overview for clinicians. *The Angle Orthodontist*, 64(3), 175-188.
- Gefen, A. (2002). Biomechanical analysis of fatigue-related foot injury mechanisms in athletes and recruits during intensive marching. *Medical and Biological Engineering and Computing*, 40(3), 302-310.
- Gerdle, B., Larsson, B., & Karlsson, S. (2000). Criterion validation of surface EMG variables as fatigue indicators using peak torque: a study of repetitive maximum isokinetic knee extensions. *Journal of Electromyography and Kinesiology*, 10(4), 225-232.
- Giladi, M., Milgrom, C., Simkin, A., Stein, M., Kashtan, H., Margulies, J., et al. (1987). Stress fractures and tibial bone width. A risk factor. *Journal of Bone & Joint Surgery, British Volume*, 69(2), 326-329.
- Giladi, M., Milgrom, C., & Stein, M. (1985). The low arch, a protective factor in stress fractures. A prospective study of 295 military recruits. *Orthopaedic Review*, 14(11), 709-712.
- Godi, M., Turcato, A. M., Schieppati, M., & Nardone, A. (2014). Test-retest reliability of an insole plantar pressure system to assess gait along linear and curved trajectories. *Journal of Neuroengineering and Rehabilitation*, 11(95).
- González, A., Hayashibe, M., Demircan, E., & Fraise, P. (2013). *Center of Mass Estimation for Rehabilitation in a Multi-contact Environment: a Simulation Study*. Paper presented at the Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on.
- Grood, E. S., & Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *Journal of Biomechanical Engineering*, 105(2), 136-144.
- Gross, T., & Bunch, R. (1989). A mechanical model of metatarsal stress fracture during distance running. *The American Journal of Sports Medicine*, 17(5), 669-674.

- Hägg, G. M., Luttmann, A., & Jäger, M. (2000). Methodologies for evaluating electromyographic field data in ergonomics. *Journal of Electromyography and Kinesiology*, 10(5), 301-312.
- Haniff, J., Appannah, G., Nor, M., Safiza, N., Wong, N., Kee, C. C., et al. (2008). Reliability and technical error of calf circumference and mid-half arm Span measurements for nutritional status assessment of elderly persons in Malaysia. *Malaysian Journal of Nutrition*, 14(2), 137-150.
- Hardin, E. C., van den Bogert, A. J., & Hamill, J. (2004). Kinematic adaptations during running: effects of footwear, surface, and duration. *Medicine & Science in Sports & Exercise*, 36(5), 838-844.
- Haris Phuah, A., Schache, A. G., Crossley, K. M., Wrigley, T. V., & Creaby, M. W. (2010). Sagittal plane bending moments acting on the lower leg during running. *Gait & Posture*, 31(2), 218-222.
- Harman, E. (2000). *The effects of backpack weight on the biomechanics of load carriage*: DTIC Document
- Hass, C. J., Feigenbaum, M. S., & Franklin, B. A. (2001). Prescription of resistance training for healthy populations. *Sports Medicine*, 31(14), 953-964.
- Headlee, D. L., Leonard, J. L., Hart, J. M., Ingersoll, C. D., & Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, 18(3), 420-425.
- Hébert-Losier, K., Newsham-West, R. J., Schneiders, A. G., & Sullivan, S. J. (2009). Raising the standards of the calf-raise test: a systematic review. *Journal of Science and Medicine in Sport*, 12(6), 594-602.
- Heir, T., & Glomsaker, P. (1996). Epidemiology of musculoskeletal injuries among Norwegian conscripts undergoing basic military training. *Scandinavian Journal of Medicine & Science in Sports*, 6(3), 186-191.
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., et al. (1999). *European recommendations for surface electromyography*: Roessingh Research and Development The Netherlands.
- Horita, T., Komi, P., Nicol, C., & Kyröläinen, H. (1999). Effect of exhausting stretch-shortening cycle exercise on the time course of mechanical behaviour in the drop jump: possible role of muscle damage. *European Journal of Applied Physiology and Occupational Physiology*, 79(2), 160-167.

- House, C., Reece, A., & Roiz de Sa, D. (2013). Shock-absorbing insoles reduced the incidence of lower limb overuse injuries sustained during Royal Marine training. *Military Medicine*, 178(6), 683-689.
- Hughes, L. (1985). Biomechanical analysis of the foot and ankle for predisposition to developing stress fractures. *The Journal of Orthopaedic and Sports Physical Therapy*, 7(3), 96.
- Hunt, A. E., Smith, R. M., & Torode, M. (2001). Extrinsic muscle activity, foot motion and ankle joint moments during the stance phase of walking. *Foot & Ankle International*, 22(1), 31-41.
- Jackson, D. (1978). Shin splints: an update. *The Physician and Sportsmedicine*, 6, 55-61.
- Jacob, H. (2001). Forces acting in the forefoot during normal gait—an estimate. *Clinical Biomechanics*, 16(9), 783-792.
- Jones, B., Cowan, D., & Knapik, J. (1994). Exercise, training and injuries. *Sports Medicine (Auckland, NZ)*, 18(3), 202.
- Jones, B. H. (1993). *Epidemiology of injuries associated with physical training among young men in the army*: DTIC Document
- Jones, B. H., Bovee, M. W., Harris, J. M., & Cowan, D. N. (1993a). Intrinsic risk factors for exercise-related injuries among male and female army trainees. *The American Journal of Sports Medicine*, 21(5), 705-710.
- Jones, B. H., Cowan, D. N., Tomlinson, J. P., Robinson, J. R., Polly, D. W., & Frykman, P. N. (1993b). Epidemiology of injuries associated with physical training among young men in the army. *Medicine & Science in Sports & Exercise*, 25(2), 197-203.
- Kallenberg, L. A., Schulte, E., Disselhorst-Klug, C., & Hermens, H. J. (2007). Myoelectric manifestations of fatigue at low contraction levels in subjects with and without chronic pain. *Journal of Electromyography and Kinesiology*, 17(3), 264-274.
- Kaufman, K. R., Brodine, S., & Shaffer, R. (2000). Military training-related injuries: surveillance, research, and prevention. *American Journal of Preventive Medicine*, 18(3), 54-63.
- Kaufman, K. R., Brodine, S. K., Shaffer, R. A., Johnson, C. W., & Cullison, T. R. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *The American Journal of Sports Medicine*, 27(5), 585.

- Kenny, P., & Campbell, J. D. (1968). Fracture toughness an examination of the concept in predicting the failure of materials. *Progress in Materials Science*, 13, 135-181.
- Kepple, T. M., Siegel, K. L., & Stanhope, S. J. (1997). Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait & Posture*, 6(1), 1-8.
- Kibler, W., Chandler, T., & Stracener, E. S. (1992). Musculoskeletal adaptations and injuries due to overtraining. *Exercise and Sport Sciences Reviews*, 20(1), 99.
- Kinoshita, H. (1985). Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait. *Ergonomics*, 28(9), 1347-1362.
- Knapik, J., Reynolds, K., Staab, J., Vogel, J., & Jones, B. (1992). Injuries associated with strenuous road marching. *Military Medicine*, 157(2), 64.
- Knapik, J. J., Reynolds, K. L., & Harman, E. (2004). Soldier load carriage: historical, physiological, biomechanical, and medical aspects. *Military Medicine*, 169(1), 45-56.
- Knechtle, B., Barandun, U., Knechtle, P., Zingg, M. A., Rosemann, T., & Rüst, C. A. (2014). Prediction of half-marathon race time in recreational female and male runners. *SpringerPlus*, 3(1), 248.
- Knobloch, K., Yoon, U., & Vogt, P. M. (2008). Acute and overuse injuries correlated to hours of training in master running athletes. *Foot & Ankle International*, 29(7), 671-676.
- Konrad, P. (2006). The ABC of EMG. A Practical Introduction to Kinesiological Electromyography. Retrieved 05 July, 2014, from <http://www.noraxon.com/docs/education/abc-of-emg.pdf>
- Korpelainen, R., Orava, S., Karpakka, J., Siira, P., & Hulkko, A. (2001). Risk factors for recurrent stress fractures in athletes *The American Journal of Sports Medicine*, 29(3), 304-310.
- Kumar, S., Amell, T., Narayan, Y., & Prasad, N. (2002). *Indices of Muscle Fatigue*. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.
- Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159.

- Lindner, T., Schulze, C., Woitge, S., Finze, S., Mittelmeier, W., & Bader, R. (2012). The effect of the weight of equipment on muscle activity of the lower extremity in soldiers. *The Scientific World Journal*, 2012.
- Lundgren, P., Nester, C., Liu, A., Arndt, A., Jones, R., Stacoff, A., et al. (2008). Invasive in vivo measurement of rear-, mid-and forefoot motion during walking. *Gait & Posture*, 28(1), 93-100.
- Lunsford, B. R., & Perry, J. (1995). The standing heel-rise test for ankle plantar flexion: criterion for normal. *Physical therapy*, 75(8), 694-698.
- Madeley, L. T., Munteanu, S. E., & Bonanno, D. R. (2007). Endurance of the ankle joint plantar flexor muscles in athletes with medial tibial stress syndrome: a case-control study. *Journal of Science and Medicine in Sport*, 10(6), 356-362.
- Mafi, N., Lorentzon, R., & Alfredson, H. (2001). Superior short-term results with eccentric calf muscle training compared to concentric training in a randomized prospective multicenter study on patients with chronic Achilles tendinosis. *Knee Surgery, Sports Traumatology, Arthroscopy*, 9(1), 42-47.
- Mann, R. A., Moran, G. T., & Dougherty, S. E. (1986). Comparative electromyography of the lower extremity in jogging, running, and sprinting. *The American Journal of Sports Medicine*, 14(6), 501-510.
- Martin, A., Spenst, L., Drinkwater, D., & Clarys, J. (1990). Anthropometric estimation of muscle mass in men. *Medicine & Science in Sports & Exercise*, 22(5), 729-733.
- Maynard, V., Bakheit, A., Oldham, J., & Freeman, J. (2003). Intra-rater and inter-rater reliability of gait measurements with CODA mpx30 motion analysis system. *Gait & Posture*, 17(1), 59-67.
- McDowell, M. A. (2008). *Anthropometric reference data for children and adults: United States, 2003-2006*: US Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics.
- McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: a systematic review. *Gait & Posture*, 29(3), 360-369.
- McNair, P. J., & Marshall, R. N. (1994). Kinematic and kinetic parameters associated with running in different shoes. *British Journal of Sports Medicine*, 28(4), 256-260.

- Meinders, M., Gitter, A., & Czerniecki, J. (1998). The role of ankle plantar flexor muscle work during walking. *Scandinavian Journal of Rehabilitation Medicine*, 30(1), 39-46.
- Melton, L. J., Kan, S. H., Frye, M. A., Wahner, H. W., O'Fallon, W. M., & Riggs, B. L. (1989). Epidemiology of vertebral fractures in women. *American Journal of Epidemiology*, 129(5), 1000-1011.
- Merletti, R., Knaflitz, M., & De Luca, C. (1990). Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions. *Journal of Applied Physiology*, 69(5), 1810-1820.
- Merletti, R., Lo Conte, L., & Orizio, C. (1991). Indices of muscle fatigue. *Journal of Electromyography and Kinesiology*, 1(1), 20-33.
- Merletti, R., Sabbahi, M. A., & De Luca, C. J. (1984). Median frequency of the myoelectric signal. Effects of muscle ischemia and cooling. *European Journal of Applied Physiology and Occupational Physiology*, 52(3), 258-265.
- Milgrom, C., Giladi, M., Stein, M., Kashtan, H., Margulies, J., Chisin, R., et al. (1985). Stress fractures in military recruits. A prospective study showing an unusually high incidence. *Journal of Bone & Joint Surgery, British Volume*, 67(5), 732-735.
- Milgrom, C., Radeva-Petrova, D., Finestone, A., Nyska, M., Mendelson, S., Benjuya, N., et al. (2007). The effects of muscle fatigue on in vivo tibial strains. *Journal of Biomechanics*, 40(4), 845-850.
- Milgrom, C., Shlamkovitch, N., Finestone, A., Eldad, A., Laor, A., Danon, Y., et al. (1991). Risk factors for lateral ankle sprain: a prospective study among military recruits. *Foot & Ankle*, 12(1), 26.
- Monaghan, K., Delahunt, E., & Caulfield, B. (2007). Increasing the number of gait trial recordings maximises intra-rater reliability of the CODA motion analysis system. *Gait & Posture*, 25(2), 303-315.
- Morag, E., & Cavanagh, P. (1999). Structural and functional predictors of regional peak pressures under the foot during walking. *Journal of Biomechanics*, 32(4), 359-370.
- Moritani, T., & Muro, M. (1987). Motor unit activity and surface electromyogram power spectrum during increasing force of contraction. *European Journal of Applied Physiology and Occupational Physiology*, 56(3), 260-265.

- Mubarak, S. J., Gould, R. N., Lee, Y. F., Schmidt, D. A., & Hargens, A. R. (1982). The medial tibial stress syndrome. *The American Journal of Sports Medicine*, 10(4), 201-205.
- Mullineaux, D. R., Milner, C. E., Davis, I. S., & Hamill, J. (2006). Normalization of ground reaction forces. *Journal of Applied Biomechanics*, 22(3), 230-233.
- Munnoch, K. (2008). *The psychological impact of physical injury on recovery in Royal Marines' recruit training*. Thesis. University of Southampton.
- Munnoch, K., & Bridger, R. S. (2007). Smoking and injury in Royal Marines' training. *Occupational Medicine*, 57(3), 214-216.
- Murphy, D., Connolly, D., & Beynon, B. (2003). Risk factors for lower extremity injury: a review of the literature. *British Journal of Sports Medicine*, 37(1), 13.
- Murray, M., Mollinger, L., Gardner, G., & Sepic, S. (1984). Kinematic and EMG patterns during slow, free, and fast walking. *Journal of Orthopaedic Research*, 2(3), 272-280.
- Naeije, M., & Zorn, H. (1982). Relation between EMG power spectrum shifts and muscle fibre action potential conduction velocity changes during local muscular fatigue in man. *European Journal of Applied Physiology and Occupational Physiology*, 50(1), 23-33.
- Nagel, A., Fernholz, F., Kibele, C., & Rosenbaum, D. (2008). Long distance running increases plantar pressures beneath the metatarsal heads: a barefoot walking investigation of 200 marathon runners. *Gait & Posture*, 27(1), 152-155.
- Neely, F. G. (1998). Biomechanical risk factors for exercise-related lower limb injuries. *Sports Medicine*, 26(6), 395-413.
- Nielsen, A. B., & Yde, J. (1989). Epidemiology and traumatology of injuries in soccer. *The American Journal of Sports Medicine*, 17(6), 803-807.
- Nunns, M. (2014). *Biomechanical variables associated with tibial and third metatarsal stress fractures in Royal Marines recruits*. Thesis. University of Exeter.
- Olds, T., Stewart, A., Carter, L., Marfell-Jones, M., & A., S. (2006). *International Standards for Anthropometric Assessment*. International Society for the Advancement of Kinanthropometry.

- Orr, R. M., Pope, R., Johnston, V., & Coyle, J. (2014). Soldier occupational load carriage: a narrative review of associated injuries. *International Journal of Injury Control and Safety Promotion*, 21(4), 388-396.
- Parijat, P., & Lockhart, T. E. (2008). Effects of quadriceps fatigue on the biomechanics of gait and slip propensity. *Gait & Posture*, 28(4), 568-573.
- Peck, R., Olsen, C., & Devore, J. (2012). Summarizing Bivariate Data *Introduction to Statistics and Data Analysis* (pp. 223-318). Boston, MA: Brooks/Cole.
- Phinyomark, A., Thongpanja, S., Hu, H., Phukpattaranont, P., & Limsakul, C. (2012). The Usefulness of Mean and Median Frequencies in Electromyography Analysis *EMG Methods for Evaluation Muscle and Nerve Function* (pp. 107-132).
- Pohl, M. B., Mullineaux, D. R., Milner, C. E., Hamill, J., & Davis, I. S. (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics*, 41(6), 1160-1165.
- Pope, R. P. (1999). Prevention of pelvic stress fractures in female army recruits. *Military Medicine*, 164(5), 370-373.
- Quesada, P. M., Mengelkoch, L. J., Hale, R. C., & Simon, S. R. (2000). Biomechanical and metabolic effects of varying backpack loading on simulated marching. *Ergonomics*, 43(3), 293-309.
- Rauh, M. J., Macera, C. A., Trone, D. W., Shaffer, R. A., & Brodine, S. K. (2006). *Epidemiology of stress fracture and lower extremity overuse injury in female recruits*: DTIC Document
- Reinking, M. F. (2007). Exercise related leg pain (ERLP): a review of the literature. *North American Journal of Sports Physical Therapy*, 2(3), 170.
- Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2013). Musculoskeletal Modelling *Research Methods in Biomechanics, 2nd Edition* (pp. 247-275). Champaign, IL: Human Kinetics.
- Rolland, Y., Lauwers-Cances, V., Cournot, M., Nourhashémi, F., Reynish, W., Rivière, D., et al. (2003). Sarcopenia, calf circumference, and physical function of elderly women: a cross-sectional study. *Journal of the American Geriatrics Society*, 51(8), 1120-1124.
- Rose, W. (2011). EMG (electromyogram) analysis. *Mathematic and Signal Processing for Biomechanics* Retrieved 3 July, 2014, from <http://www.udel.edu/biology/rosewc/kaap686/notes/EMG%20analysis.pdf>

- Ross, R. A., & Allsopp, A. (2002). Stress fractures in Royal Marines recruits. *Military Medicine*, 167(7), 560-565.
- Roub, L. W., Gumerman, L. W., Hanley, E. N., Clark, M. W., Goodman, M., & Herbert, D. L. (1979). Bone stress: a radionuclide imaging perspective. *Radiology*, 132(2), 431-438.
- Schaffler, M., Radin, E., & Burr, D. (1989). Mechanical and morphological effects of strain rate on fatigue of compact bone. *Bone*, 10(3), 207-214.
- SENIAM. Preparation of the skin. Retrieved 17 July, 2014, from <http://www.seniam.org/>
- Shan, G., & Bohn, C. (2003). Anthropometrical data and coefficients of regression related to gender and race. *Applied Ergonomics*, 34(4), 327-337.
- Sharkey, N., Ferris, L., Smith, T., & Matthews, D. (1995). Strain and loading of the second metatarsals during heel-lift. *Journal of Bone & Joint Surgery, American Volume*, 77(7), 1050-1057.
- Simkin, A., Leichter, I., Giladi, M., Stein, M., & Milgrom, C. (1989). Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot & Ankle International*, 10(1), 25-29.
- Sinclair, J., & Taylor, P. J. (2014). Influence of new military footwear on the kinetics and kinematics of running in relation to army boots. *Journal of Strength and Conditioning Research*, 28(10), 2900-2908.
- Smoliga, J. M., Myers, J. B., Redfern, M. S., & Lephart, S. M. (2010). Reliability and precision of EMG in leg, torso, and arm muscles during running. *Journal of Electromyography & Kinesiology*, 20(1), e1-9.
- Soutas-Little, R. W., Beavis, G. C., Verstraete, M. C., & Markus, T. L. (1987). Analysis of foot motion during running using a joint co-ordinate system. *Medicine & Science in Sports & Exercise*, 19(3), 285-293.
- Spink, M. J., Fotoohabadi, M. R., & Menz, H. B. (2010). Foot and ankle strength assessment using hand-held dynamometry: reliability and age-related differences. *Gerontology*, 56(6), 525-532.
- Stefanyshyn, D. J., & Nigg, B. M. (1997). Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. *Journal of Biomechanics*, 30(11), 1081-1085.

- Steinhaus, A. H. (1933). Chronic effects of exercise. *Physiological Reviews*, 13, 103-130.
- Stolwijk, N. M., Duysens, J., Louwerens, J., & Keijsers, N. (2010). Plantar pressure changes after long-distance walking. *Medicine & Science in Sports & Exercise*, 42(12), 2264-2272.
- Surve, I., Schwellnus, M. P., Noakes, T., & Lombard, C. (1994). A fivefold reduction in the incidence of recurrent ankle sprains in soccer players using the Sport-Stirrup orthosis. *The American Journal of Sports Medicine*, 22(5), 601.
- Taylor, D., O'Reilly, P., Vallet, L., & Lee, T. (2003). The fatigue strength of compact bone in torsion. *Journal of Biomechanics*, 36(8), 1103-1109.
- Teague, D. C. (2009). Stress Fractures. In M. D. Bucholz, J. D. Heckman, C. M. Court-Brown & P. Tornetta (Eds.), *Fractures in Adults* (Vol. 2). Philadelphia: Wolters Kluwer Health.
- Tsai, L. C., Sigward, S. M., Pollard, C. D., Fletcher, M. J., & Powers, C. M. (2009). Effects of fatigue and recovery on knee mechanics during side-step cutting. *Medicine & Science in Sports & Exercise*, 41(10), 1952.
- Umberger, B. R., & Martin, P. E. (2007). Mechanical power and efficiency of level walking with different stride rates. *Journal of Experimental Biology*, 210, 3255-3265.
- Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods*, 74(2), 219-227.
- Wang, H., Frame, J., Ozimek, E., Leib, D., & Dugan, E. L. (2013). The effects of load carriage and muscle fatigue on lower-extremity joint mechanics. *Research Quarterly for Exercise and Sport*, 84(3), 305-312.
- Wang, L., Hong, Y., & Li, J. X. (2012). Durability of running shoes with ethylene vinyl acetate or polyurethane midsoles. *Journal of Sports Sciences*, 30(16), 1787-1792.
- Warden, S. J., Burr, D. B., & Brukner, P. D. (2006). Stress fractures: pathophysiology, epidemiology, and risk factors. *Current Osteoporosis Reports*, 4(3), 103-109.
- Weist, R., Eils, E., & Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the

incidence of metatarsal stress fractures. *The American Journal of Sports Medicine*, 32(8), 1893-1898.

Wentz, L., Liu, P.-Y., Haymes, E., & Ilich, J. Z. (2011). Females have a greater incidence of stress fractures than males in both military and athletic populations: a systemic review. *Military Medicine*, 176(4), 420-430.

Willems, T., Witvrouw, E., Delbaere, K., De Cock, A., & De Clercq, D. (2005). Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait & Posture*, 21(4), 379-387.

Willems, T. M., De Clercq, D., Delbaere, K., Vanderstraeten, G., De Cock, A., & Witvrouw, E. (2006). A prospective study of gait related risk factors for exercise-related lower leg pain. *Gait & Posture*, 23(1), 91-98.

Willems, T. M., De Ridder, R., & Roosen, P. (2012). The effect of a long-distance run on plantar pressure distribution during running. *Gait & Posture*, 35(3), 405-409.

Willems, T. M., Witvrouw, E., De Cock, A., & De Clercq, D. (2007). Gait-related risk factors for exercise-related lower-leg pain during shod running. *Medicine & Science in Sports & Exercise*, 39(2), 330.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons Inc.

Wit, A., & Czaplicki, A. (2008). Inverse dynamics and artificial neural network applications in gait analysis of the disabled subjects. *Human Movement*, 9(2), 93-102.

Wood, A., Hales, R., Keenan, A., Moss, A., Chapman, M., Davey, T., et al. (2014). Incidence and time to return to training for stress fractures during military basic training. *Journal of Sports Medicine*, 2014.

Yang, P.-F., Sanno, M., Ganse, B., Koy, T., Brüggemann, G.-P., Müller, L. P., et al. (2014). Torsion and antero-posterior bending in the in vivo human tibia loading regimes during walking and running. *PloS One*, 9(4), e94525.

Yeung, M., Chan, K.-M., So, C., & Yuan, W. (1994). An epidemiological survey on ankle sprain. *British Journal of Sports Medicine*, 28(2), 112-116.

Yoshikawa, T., Mori, S., Santiesteban, A., Sun, T., Hafstad, E., Chen, J., et al. (1994). The effects of muscle fatigue on bone strain. *The Journal of Experimental Biology*, 188(1), 217-233.

Zatsiorsky, V. (2002). Joint torques and forces: The inverse problem of dynamics
Kinetics of Human Motion.