A Biomechanical Analysis of British Army Foot-Drill: Implications of Lower-Extremity Musculoskeletal Injury in Age-matched Civilian Men and Women

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DECLARATION

I hereby declare that the composition of the present thesis and all the information contained within is entirely my own work. The present thesis has not been submitted for any other degree or professional qualification.

Signature:

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ABSTRACT

British Army foot-drill may be a risk factor for musculoskeletal (MSK) injury. However, limited empirical research exists quantifying lower-extremity risk factors of foot-drill in men and women. To better understand and provide greater insight into the potential risk of injury of foot-drill, the aim of this thesis was to conduct a series of studies analysing measures of reliability on foot-drill vertical ground reaction force (vGRF) data (study 1), the effects of in-service footwear on magnitudes of loading across foot-drill (study 2), compare sex-specific kinetic/kinematic characteristics of foot-drill (study 3), and quantify predictors of injury risk following a bout of foot-drill training in age-matched civilian men and women. Study 1: A single familiarisation session and a total of eight-trials demonstrated accurate and stable measures of foot-drill performance for the vGRF variable (Intraclass correlation (ICC)>.075, coefficient of variation of the typical error ($CV_{te\%}$) <10)). However, poor reliability was reported for vertical rate of force development (vRFD). Nevertheless, these data were used to inform further studies. Study 2: In comparison with the combat boot (CB) and ammunition (drill) boot (AB), the training shoe (TR) demonstrated significant reductions in peak vGRF and vRFD (i.e., potential force mitigating strategy), and greater time to peak force (TTP), demonstrating a reduced rapid rise in vertical force. Study 3: Significant kinetic/kinematic, GRF, and temporal characteristic differences were apparent between sex, whereby greater frontal plane lower-extremity motion was observed for women, with greater GRF, temporal, and sagittal plane motion observed for men across foot-drill. Study 4: Women demonstrated significant alterations in ankle proprioceptive sensibility and static and dynamic postural stability following a bout of foot-drill training, suggesting that the integrity of neuromuscular control mechanisms may be compromised following foot-drill training. In conclusion, foot-drill represents a substantial mechanical load on the lower-extremity MSK system and may be a contributing risk factor of lower-extremity MSK injury in men and women.

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1.0 Chapter 1: Introduction

1.1 Introduction

Physical training has long been an essential requirement in the physical preparation of military personnel within the British Army for the continual rigorous physical demands of military duty (Knapik *et al.,* 2003). Mission completion and overall success are significantly dependent on developing and maintaining high levels of physical robustness. Therefore, Army recruits engage in a rigorous exercise-training program during their initial months of military training, defined as basic military training (BMT) or Phase one. However, the arduous physical demands of BMT are not without risk, with empirical research and Ministry of Defence (MOD) annual medical discharge reports demonstrating high injury rates of training-related lower-extremity MSK injuries/disorders for male and female recruits (Bullock *et al.,* 2010; MOD, 2015; Popovich *et al.,* 2000; Sinclair and Taylor, 2014). For the purpose of this thesis, male and female recruits are defined as untrained entry-level (novice) army personnel, who have yet to complete and pass BMT, whereas, men and women soldiers are defined as trained personnel who have completed and passed BMT.

The primary objective of BMT is to transform civilians into trained soldiers (Carden *et al.,* 2015). However, this process is usually hindered by the rigorous physical demands of physical training, poor initial physical fitness levels, and the occurrence of lower-extremity MSK injuries associated with the arduous physical demands of certain occupational training-related activities and tasks (Blacker *et al*., 2008). British Army foot-drill is a fundamental military occupational activity, routinely practiced by recruits during the initial weeks of BMT and throughout their military careers (Carden *et al*., 2015). The defining performance characteristics of British Army foot-drill involve repetitively and forcefully impacting the ground with an exaggerated heel-strike, and landing with the knee in an extended (straight-leg) position. Despite limited research focused on potential MSK injury risk factors of foot-drill, researchers have quantified selective GRF and temporal parameters within civilian and military, trained and untrained personnel (Carden *et al.,* 2015; Connaboy *et al.,* 2011). These biomechanical studies demonstrated that specific GRF and temporal parameters of foot-drill are likely key contributory factors related to such MSK injuries as bone stress fractures (Carden *et al*., 2015). Furthermore, similar to the unique movement patterns of foot-drill, impacting the ground with the knee in an extended position has shown to increase the risk of bone-on-bone contact of the proximal tibia and distal femur, and depression of the proximal and distal tibial and femoral cartilage and meniscus, resulting in potential damage to MSK structures of lower-extremity joints (Makinejad *et al.,* 2013).

Certain physiological and anatomical factors inherently place the average women recruit/soldier at a disadvantage in most aspects of physical performance relative to their male counterparts (Epstein *et al.,* 2013). Women typically are shorter, possess lower body mass, bone mass, and have greater adipose tissue and less lean muscle mass than men (Greeves, 2015). Specific biomechanical risk factors that predispose women to greater risk of MSK injury involve greater pelvic width to femoral length ratio, which has been identified as one of the key factors in the anterior cruciate ligament (ACL) injury mechanism (Pollard *et al*., 2010). In addition, women exhibit significantly smaller knee flexion angles and a more erect landing posture during jump-landing activities when compared to men (Decker *et al*., 2003; Lephart *et al.,* 2001), indicating that women may feature weaker lower-limb musculature; resulting in stiffer landing kinematics and a reduced capacity to attenuate the magnitude of kinetic energy at ground contact (Paterno *et al.,* 2010; Wikstrom *et al*., 2006).

A number of these biomechanical factors can be modulated through training equipment, such as footwear. The use of a greater shock absorbing footwear has been identified as one potential method for reducing the risk of lower-extremity MSK injuries in athletic and military populations (Dixon *et al.,* 2003; Sinclair and Taylor, 2014). However, standard issue military footwear has succumbed to scrutiny regarding its functionality and capacity to provide military personnel with the necessary shock absorbency required to withstand the demands of occupational training-related activities (Sinclair and Taylor, 2014). More specifically, the black leather combat boot (CB), worn by British Army cadets and recruits upon enlistment may have implications for greater risk of lower-extremity MSK injury (Geary *et al.,* 2002) when performing such cyclic, impact loading activities as running, marching and foot-drill. However, to date research has failed to determine the influence of different military footwear on the high impact loading forces of foot-drill, and whether a specific type of footwear already in circulation could be utilised to marginally reduce the magnitude of impact loading forces experienced by recruits during the initial weeks of BMT.

Carden *et al.,* (2015) and Connaboy *et al.,* (2011) both demonstrated that the magnitude of vGRF and derivatives (rate of force development) are analogous to those produced during high level plyometric exercises, most notably, 30cm, 60cm, and 90cm drop landings (Wallace *et al*., 2010), a training modality programmed in accordance with a periodised model of training and more commonly associated with highly conditioned athletes (Connaboy *et al.*, 2011) due to the inherent risk of MSK injury associated with plyometrics (Baechle and Earle, 2008). Twist *et al*., (2008) reported a latent impairment in neuromuscular function proceeding an acute bout of plyometric training; concluding that transient adaptations in neuromuscular acuity and proprioceptive sensibility may further exacerbate lower-extremity MSK injury risk (Deshpande *et al.,* 2003). Given the magnitude of GRF parameters (Carden *et al.,* 2015; Connaboy *et al.*, 2011) coupled with the rigorous scheduling of foot-drill (40min to two-hour sessions per day) (Williams, 2005), coupled with a lack of knowledge pertaining to the current frequency, duration, and total number of impacts of high force foot-drills, most notably, halt, stand-at-attention, and stand-at-ease (peak vGRF range: 1.3-4.6bw) (Carden *et al.*, 2015; Connaboy *et al.*, 2011); suggests that the cyclic high impact loading forces of foot-drill may alter and/or impair lower-extremity neuromuscular function and joint proprioception of recruit populations.

Although recent biomechanical foot-drill laboratory analyses have identified lower-extremity MSK injury risk factors associated with individual foot-drills for both trained and untrained men and women, (Carden *et al.*, 2015; Connaboy *et al.*, 2011), prospective research is yet to determine the real-time accumulative effect of these regimented manoeuvres, typical of a recruit foot-drill training session on predictors of lower-extremity MSK injury risk, namely, non-linear measures (sample entropy) of static postural stability, dynamic postural stability using the dynamic postural stability index (DPSI), and ankle joint positional sense.

The aetiology of occupational training-related lower-extremity MSK injuries/disorders are multi-factorial, making the task of reducing the incidence rates of injuries within military populations extremely difficult. Therefore, as a means of tackling the MSK injury epidemic within military recruit populations, we propose a concept referred to as the *aggregation of marginal losses*, whereby the accumulation/aggregation of marginal reductions in potentially injurious loads may act to reduce the risk of injury among a number of military occupational activities. Incorporating an interdisciplinary approach, whereby practices and policies seek to systematically act to reduce (marginally) the loads experienced across multiple activities could accumulate to significantly reduce the high incidence rates of lower-extremity MSK injuries/disorders, most notably, stress fractures, sprains, and lower-limb joint pain, potentially reducing the heavy financial burden associated with these types of injuries whilst improving the training and operational readiness of the British Army recruit populations.

1.2 Thesis Rationale, research aims, and study hypotheses

Only two biomechanical studies (Carden *et al*., 2015; Connaboy *et al*., 2011) have quantified the impact forces, loading rates, and tibial accelerations of British Army foot-drill. These studies have failed to determine the specific number of trials required to accurately assess reliable measures of biomechanical variables of British Army foot-drill. In addition, the total number of trials chosen in these studies were selected arbitrarily, with no justification regarding the need of any familiarisation sessions and/or trials prior to data collection, along with no rationale for the mean number of trials used to represent the biomechanical variables studied. The stability and reproducibility of mean values could be questioned as the magnitude and influence of variability within previous foot-drill was not calculated. Therefore, it is important that the reliability of measures of foot-drill performance be the initial focus of this thesis as using too few trials may not reliably represent the individual's true performance, whilst having a potential negative influence on future foot-drill studies.

The research aims of this thesis are categorised into their respective experimental chapters. The aims of experimental chapter one are three fold: (i) determine the magnitude of any systematic bias among British Army foot-drill session(s) and between trial(s), (ii) establish the within-subject variation of such biomechanical variables as vGRF and vertical RFD; and (iii) analyse the test-retest reliability to determine the number of sessions and/or trials required to maximise the possibility of identifying changes in the vGRF and vertical RFD (vRFD) of British Army foot-drill between different conditions, and over time. It was hypothesised that several trials would be necessary to achieve high levels of performance stability during British Army foot-drill, and that familiarisation sessions and/or trials would be required prior to collecting stable foot-drill biomechanical data. Similar to that of Hunter *et al.*, (2004), it was further hypothesized that as random error decreased, test-retest correlation scores would increase when using the average of multiple trials, providing important information regarding the necessary number of trials/familiarisation session(s) needed for further foot-drill research.

Due to the magnitude of mechanical loading identified in experimental chapter 1, and the lack of evidence-based load reduction strategies (i.e., shock absorbing footwear) aimed at mitigating the high impact loading forces of foot-drill in age-matched civilian men, it was suggested that the use of a specific type of in-service footwear may act to reduce the intensity of mechanical loading specific to foot-drill. Therefore, the main focus of experimental chapter two was to determine the influence of current in-service footwear has on GRF variables as a means of providing a potential strategy to reduce the mechanical loading of British Army foot-drill observed in study one. Therefore, following on from experimental study 1, the aims of this study are to compare the magnitude of the vGRF and temporal parameters of foot-drill, including peak vGRF, peak vRFD, and TTP across three different types of standard issue British Army footwear, namely the CB, ammunition (Drill) boot (AB), and Hi-Tech Silver Shadow training shoe (TR). This study hypothesised that foot-drill, when compared with the loading patterns of a normal walk, would produce greater peak vGRF, peak vRFD, and shorter TTP values; and that the TR would significantly attenuate peak vGRF, peak vRFD, and produce longer TTP values when compared with the CB and AB for all foot-drills.

Following on from experimental study 1 and 2, it was suggested that the regimental movement patterns of foot-drill, namely the exaggerated heel-strike of QM, and the forceful extended-knee landing of SaA, SaE and halt, may present sex-specific lower-extremity kinetic, kinematic, and temporal characteristics that may contribute to an increased risk of lower-extremity MSK injury. Therefore, the aims of study 3 – chapter 5 are to quantify differences in frontal and sagittal (hip, knee) and transverse (ankle) plane kinematics, kinetics (hip, knee, and ankle joint moments and GRF profiles) of specific British Army foot-drills; along with temporal occurrences of peak events of these parameters between age-matched civilian men and women. In consideration of the physiological and anatomical mechanistic differences reported between men and women during landing activities (Podroza *et al*., 2010; Pollard *et al*., 2010), it was hypothesised that men would produce significantly greater impact loading forces, greater sagittal plane hip and knee motion, and would produce significantly greater temporal magnitudes of the hip and knee when compared to women. In addition, significantly greater frontal plane knee motion during foot-drill was expected for women when compared to men.

Studies 1-3 – chapters 3-5 identified lower-extremity injury risk factors associated with the biomechanics of individual British Army foot-drills. As a result of these findings, this thesis investigated whether the accumulative mechanical loading representative of a single British Army foot-drill training session would impair specific neuromuscular control systems, thus providing key information regarding the potential risk of injury specifically related to foot-drill training. Therefore, the aims of experimental chapter 6 – study 4 were two-fold: (i) examine the potential pre-post adaptations and/or impairments in static and dynamic postural stability, and (ii) quantify the potential differences in ankle joint proprioception pre-post an acute bout of British Army foot-drill training in age-matched civilian women. Twist *et al*., (2008) reported a latent impairment in neuromuscular function post an acute bout of plyometric training – a training modality similar to that of foot-drill. Based on these results and those of this thesis, it was hypothesised that age-matched civilian women would demonstrate altered and/or impaired ankle joint proprioception, and dynamic and static postural stability following a bout of foot-drill training when compared to baseline and pre-test values.

2.0 Chapter 2: Literature Review

2.1 Literature Review

The overall purpose of this chapter is to provide the reader with a relevant and informative review of the existing literature regarding the most relevant topics related to the aims and objectives of each experimental study of this thesis. The overall aim of the thesis was to investigate and quantify potential lower-extremity MSK injury risk factors and predictors of injury risk in male and female recruits associated with the arduous physical demands of British Army foot-drill. However, to fully understand the potential implications of injury associated with the rigors of British Army foot-drill, it is critical to encapsulate variables that directly and/or indirectly influence the development of recommendations that may propose changes in training practices and/or policies that have been structured within military training programmes for decades. As such, literature surrounding the efficacy of military training programmes (domestic and international), policies relating to the inclusion of women into ground close combat roles, standard operating procedures designed to safe guard recruits from injury and potential medical discharge, injury prevention strategies and/or interventions that may or may not have been implemented into service, and the distinct physiological, biomechanical, and anatomical differences affecting physical performance between men and women are considered.

To achieve such a task, a review of relevant scientific literature was conducted using the PubMed-Medline database, available through Edinburgh Napier University (ENU). This database was consulted up to February 2018 using key search items relating to policy, sex-differences, medical discharges, musculoskeletal lower-extremity overuse injuries associated with training-related maximal - submaximal cyclic impact loading activities, along with the anatomical sites at which these injuries occurred. Information detailing the key performance markers of British Army foot-drill was acquired from the British Army Drill Instructor Manual.

The majority of information specific to the rates of medical discharge per financial year was acquired from GOV.UK – a UK public sector information website created by government digital services that house twenty-four ministerial departments. It should be noted that despite efforts to obtain the most up to date and relevant literature surrounding the British Armed Forces via the freedom of information act, the thesis was somewhat limited in terms of access to information as this was a self-funded, non-MoD sanctioned PhD.

The literature review begins (2.1.1) with a comprehensive description of the various types of occupational physical training activities and tasks performed by untrained men and women, along with the physiological adaptations associated with the arduous physical demands of BMT. The following section (2.1.2) focuses on published rates of common lower-extremity MSK injuries during BMT, coupled with training-related injury risk factors linked to injury, back trooping and subsequent medical discharge. In addition, specific physiological, anatomical and biomechanical differences between men and women were identified and reported, whereby section 2.1.3 provided more specific information relating to the physiological, anatomical, and biomechanical differences between sex and how these differences significantly increase the risk of injury in women and are part-responsible for the disparity in sex-specific rates of training related lower-extremity MSK injury within the British Army.

As a result of limited empirical study investigating the potential intrinsic and extrinsic injury risk factors of foot-drill, section 2.1.4 focused on studies identifying factors of injury risk during athletic activities similar to that of foot-drill, namely, traditional and extended-knee jump-landing activities, along with a detailed review of the history and defining purpose of British Army foot-drill within today's military. Section 2.1.5 considers the existing literature surrounding British Army foot-drill as a potential injury risk factor and comparing factors with other sports-related high impact loading activities and tasks. Lastly, section 2.1.6 identified athletic and military specific training-related injury prevention and/or reduction strategies/interventions aimed at targeting more than one injury or group of injuries, compared to studies focused specifically on one relevant injury to a group (recruits).

2.1.1 The efficacy of basic military training programmes in recruit populations

Physical training has long been an essential requirement in the physical preparation of soldiers within the British Army for the continual rigorous physical demands of military duty (Knapik *et al.*, 2003). All British Army recruits and soldiers are expected to maintain a state of physical readiness, optimising their ability to perform in any tactical and/or operational environment. Mission completion and overall success of missions are significantly dependent on developing and maintaining high levels of physical robustness. For example, military personnel must engage in numerous physically demanding activities and tasks throughout their military careers, namely, carrying heavy loads over long distances and on uneven terrain; and shorter more intense activities, such as sprinting and traversing obstacles in rural and urban terrain (Harman *et al.*, 2008).

The efficiency of operation and effectiveness of outcome heavily depends on the physical attributes of the recruit and/or soldier, as the speed at which tasks are performed can have a considerable impact on their fighting effectiveness and survivability. Therefore, British Army recruits engage in a rigorous initial exercise physical training program known as BMT or more commonly termed Phase one. The length of the Phase one course depends on whether the civilian enlists as a junior entry (JE) recruit, standard entry (SE) recruit, officer cadet (OFC), infantry (INF) recruit, or a Royal Marine Commando. Juniors (<18yrs old) complete their Phase one training at the Army Foundation College, Harrogate (AFC(H)) lasting 49-weeks and trained for the infantry, Royal Armoured Corps/Household Cavalry, Royal Artillery, and some

Royal Logistics Corps roles. Standard entry recruits either complete Phase one at the Army Training Centre, Pirbright (ATC(P)) or the Army Training Regiment, Winchester (ATR(W)), with both training units employing a 14-week Phase one course known as the Common Military Syllabus (CMS). The CMS trains SE recruits for such roles as Army Air Corps, Army Medical Services, Corps of Royal Electrical and Mechanical Engineers, Corps of Royal Engineers, Corps of Army Music, Royal Armoured Corps, Royal Regiment of Artillery, Royal Corps of Signals, Royal Logistic Corps, Adjutant General's Corps, and the Intelligence Corps. Officer cadets train at the Royal Military Academy Sandhurst (RMAS), undertaking 44-weeks of physical and leadership training. In addition to JE and SE, the British Army provides several other intensive physical training courses designed to prepare novice recruits for ground close combat roles. For example, the Combat Infantryman's Course (CIC) at the Infantry Training Centre, Cattrick (ITC(C)), and the Royal Marines Commando basic training course at the Commando Training Centre, Royal Marines in Lympstone are both considered the most physical demanding and arduous training courses lasting approximately 26 (Phase one) and 32 weeks, respectively. Despite differences in training units/programmes, the primary objective of Phase one is to ensure that recruited civilians are both mentally and physically equipped to meet and manage the demands of modern warfare, and in doing so, acquire the ability to fight and succeed in combat (Geary *et al.*, 2002).

For many newly enlisted recruits, the frequency, duration, intensity, and the overall physical load of Phase one is considerably greater than that experienced prior to enlistment (Sharma *et al.*, 2015), whereby failure to adapt and/or manage the large and rapid rise in physical load is believed to be attributable to an increased rate of lower-extremity MSK injury and subsequent medical discharge. An example of this was demonstrated from an internal Army Recruiting and Initial Training Command (ARITC) research project reporting the average daily distance (meters) for male and female recruits undergoing basic training at ATC(P). It was found that male and female recruits were completing an average daily distance of 13,284m (13.2km) and 11,858m (11.9km) respectively. It was further reported that one in five days for women and one in three days for men exceeded 15km. From this data it was recommended that the average daily distance, along with the mean increase in distance between weeks 1 and 2 (men:10,000m (10km) to >15,000m (15km); women: 6,000m (6km) to >12,000m (12km)) of training be reduced and training intensity be modified and made more progressive in the early weeks of Phase one to attenuate the risk of MSK injury associated with the rapid rise in mechanical loading placed on the lower-extremity MSK.

It is well recognised that the pattern of injury between men and women differs considerably, reflecting the differences in the physiological and anatomical characteristics of men and women that may expose them to greater risk of injury, coupled with the demands of physical training and occupational tasks and activities (Greeves, 2015). Research has shown there to be a mismatch between the level of physical fitness of recruits and the rigorous physical demands imposed on them (Blacker *et al.,* 2009). A large variance exists in the level of physical fitness between recruits entering Phase one, whereby it is clear that not all recruits have the physical ability to progress through training and/or adapt to the physical training stimuli at the same rate (Richmond *et al.,* 2012). This reported mismatch, coupled with the apparent lack of progressive overload of demanding military activities during Phase one, has been linked to high attrition rates and associated medical discharges, commonly reported for less-fit recruits reporting MSK injuries of the lower-extremities (Blacker *et al.,* 2009; Richmond *et al.,* 2012).

Despite the increased automation and mechanisation in military equipment, high levels of physical and tactical fitness are an essential requirement for recruits and soldiers to perform their jobs effectively without sustaining injury and/or overtraining (Rayson, 1999). In a military context, physical fitness has been defined as the capacity to meet the physical demands of occupational military tasks and unit missions (Rayson *et al.,* 1999). As described by Williams, (2005), Phase one consists of sports, circuit training, battle training, endurance training, agility, swimming, material and weapon handling, field exercises, and fitness assessments. The Phase one programme also involves other modalities of occupational activities; prolonged marching with and without additional load while on military exercise, and numerous periods of foot-drill training; ranging between 40-180-minute (min) periods per day for regular recruits, and two 2-hour periods (on training days) during the initial 4-weeks for reserve recruits. High aerobic fitness, low percentage body fat, high levels of muscle strength, and fat-free mass are desirable physical fitness characteristics (Williams, 2005) correlated with such military tasks as marching, load carriage (Knapik *et al*., 1996; Rayson *et al.,* 2000), stretcher carrying (Rayson *et al.,* 2000), and repetitive submaximal and maximal box lifting (Mello *et al.,* 1995).

Research has reported significant improvements in a variety of physiological characteristics during Phase one, such as maximal oxygen uptake (Knapik *et al*., 1980; Williams *et al*., 1999), favourable changes in percentage body fat and fat-free mass (Legg and Duggan, 1996). However, relatively small to moderate improvements in muscle strength and task performance (Drain *et al.,* 2015: Rayson 1999; Richmond *et al.,* 2012) have been observed. Accordingly, Rayson (1999) investigated the effectiveness of the Commissioning Course (CC) to develop and maintain standards of physical fitness whilst determining the relationship between fitness and risk of injury in 106 British Army male and female officer cadets. Although the CC was determined as an effective programme from which officer cadets gained improvements in the majority of fitness components specific to the rigors of military performance, these improvements were considered modest and equivocal, whereby male and female officer cadets demonstrated marginal improvements in material handling muscle strength tests (5-9%). Despite these modest gains in fitness components, the majority of officer cadets passed their respective military tasks, namely, a single lift, a carry, a repetitive lift, and a loaded march. However, it should be noted that although no significant differences in the incidence rates of injury was observed between male and female officer cadets, a considerable proportion of female cadets failed to meet the physical fitness standards of the CC, demonstrating a decline in physical fitness levels during the later stages of the training course.

Similarly, Williams *et al*., (1999) evaluated the efficacy of British Army basic training in improving material handling (MH) performance, whereby male and female recruits performed a series of MH tests involving a maximal lift, repetitive lift, and a loaded-march. Results of the effects of Phase one resulted in significant reductions in body fat, improved predicted Vo2max, and greater estimated fat-free mass between weeks-1 and 11 of training. The major finding from this study was determined by the inconsistency of the basic training programme to improve MH ability in recruits, whereby only two (repetitive 22kg lift, $\Delta\%$ +29.5, $p<.001$, and a loaded 2mile 25kg march, $\Delta\%$ -15.7, $p<.001$) of the six muscle strength tests demonstrated a statistically significant improvement, suggesting that performances on the MH tasks most dependant on muscle strength may not have been reflective of an effective resistance training element within the Phase one programme.

Interestingly, Genaidy *et al*., (1994) reported a 60% increase in maximal box lift of complex design in sixteen recruits (12 males, 4 females) following only 4-weeks of training designed specifically for the demands of maximal box lifting. However, Genaidy did not quantify any learning effect with respect to MH tasks, thus the rapid increase in max box lift capability may be a result of a learning effect given the short period of time that such an increase in capability was reported. In addition, Williams *et al*., (1999) reported a lack of quantification of any learning effect on performance data with respect to MH tasks, whereby adequate familiarisation and quantification of learning effects using a control group and pre-training tests enabling recruits to practice and learn complex MH tasks could mitigate any potential learning effects and improve the internal validity of the study. For example, Knapik *et al*., (1997) quantified the influence of physical fitness training on MH capability in women, reporting a cumulative 52% increase in MH performance following 14 weeks of physical training. The major methodological difference between this study and others (Williams *et al*., 1999; Genaidy *et al*., 1994) was that Knapik (1997) reserved the initial two-weeks for familiarisation and instruction focusing on form and lifting technique, and the training programme consisted of a greater strength to aerobic physical training ratio (3:2/week x 14-weeks = 42:28), whereas Williams *et al*., (1999) reported mainly aerobic physical training, with MH periods consisting mainly of tuition in recommended safe technique. Given the importance and relevance of strength training for specific and adequate muscle strength adaptation for military occupational tasks and activities, the modest improvements in strength associated with basic training programmes reported by Williams *et al*., (1999) is surprising, as high levels of muscle strength represent many of the tasks and physical employment standards (PES) British Army military personnel encounter during their careers.

It is well recognised that physical capacity and the ability to manage and cope with the rigorous of military training and/or operations are critical attributes for employment within the military. As a means of upholding the safety of the recruit and/or soldier, formal assessments of physical performance with predetermined minimum standards ensures that recruits can perform requisite tasks safely and effectively for specific job roles (Drain *et al*., 2015; Rayson *et al*., 2000). The box lift and place (BLP) (or equivalent) is a key PES utilised as a validated means of assessing the ability of the recruit to perform essential military specific muscle strength tasks related to a series of job roles. A key training component related to the success of the BLP is muscle strength, thus BMT programmes must provide male and female recruits with sufficient muscle strength training to enable them to achieve and maintain the baseline PES for BLP, along with other PES tasks such as loaded march and repetitive lift and carry. However, the effectiveness of BMT programmes to provide recruits with adequate stimulus to enhance measures of muscle strength and endurance relative to the requirements of PES is reportedly poor. For instance, Drain *et al*., (2015) quantified the adaptive profile of BMT to develop muscle strength to meet the BLP standard upon completion of week-8 of a 12-week basic training programme in Australian Army recruits. It was determined that both male (Week1: 44.3kg vs Week8: 46.5kg, Δ%=4.7%) and female (Week1: 21.9kg vs Week8: 24.9kg, Δ=12%) recruits exhibited modest improvements in maximal BLP performance, yet when compared between sex, female recruits demonstrated a greater training response than male recruits, exhibiting an 8.2% increase (men: 6.5% vs women: 14.7%) in relative gains in muscle strength. However, male recruits were on average 2-fold stronger than females at baseline BLP at the commencement of BMT (men: 44.3kg vs women: 21.9kg, Δ=51%), explaining, in part, the greater relative response to the strength training stimulus observed in female recruits. The disparity in baseline muscle strength explains why only 20% of female recruits were able to achieve the minimum 25kg BLP standard at week 1 of BMT, providing evidence to suggest that female recruits are more reliant on basic training to develop requisite levels of muscle strength necessary for employment into the Australian Army. However, Drain reported 30% of the female cohort failed to meet the BLP standard after 8-weeks of training, suggesting that the strength training element of BMT requires improvement with respect to its effectiveness, and that baseline measures of absolute muscle strength are greater prior to week 1 of BMT.

It is suggested that the lack of emphasis of strength training, i.e., the frequency and duration of strength training sessions in comparison to other training modalities (i.e., aerobic training) is a key aetiological factor linked with the modest and equivocal muscle strength improvements observed for several military nations (Drain *et al.*, 2015; Rayson, 1999; Williams *et al.*, 1999). As such, it has been suggested that augmented muscle strength would likely increase training stimulus, along with a potential increase in the number of recruits capable of achieving higher MH standards for more physically demanding employment categories. However, increasing the total number and duration of strength training sessions in an already rigorously demanding training programme is likely to negatively impact on the recruit's ability to effectively adapt to the military training stimulus, thereby increasing the risk of overtraining and subsequent lower-extremity MSK overuse injury.

In accordance with basic physical training principles, the lack of muscle strength improvement may not directly be linked to a deficiency in the magnitude (i.e., frequency and duration) of strength training within basic training programmes. Rather, the model by which strength training and other military specific training modalities has and/or is programmed within the CMS, and whether this specific training modality is effectively structured and implemented in accordance with a periodised model of training, taking into consideration factors such as type of exercise/activity (i.e., closed, open kinetic exercises, field or gym based), repetitions (i.e., 1-3=maximal strength, 5-8=sub-max strength, 8-12=strength/muscular endurance), equipment, sets, and recovery times (Baechle and Earle, 2008) as a means of eliciting optimal adaptation and transfer of physical fitness outcomes to the demands of military occupational activities/tasks with minimal risk of injury and/or overtraining. As such, military organisations have investigated and implemented change in the design of BMT programmes, examining and comparing the efficacy of modified physical training programmes against current programmes for the purpose of reducing the risk of lower-extremity MSK overuse injuries, increasing first time pass rates during basic training, whilst maintaining high levels of combat physical fitness and/or enhancing specific physical and physiological parameters associated with specific military occupational tasks and activities. For instance, Brown *et al.*, (2010) quantified the effectiveness of a modified physical training programme designed to enhance specific physical and physiological parameters associated with improved loaded marching performance in sixty-five British Army infantry recruits undertaking the CIC at ITC(C). The modified physical training programme consisted of 13 additional high intensity interval training sessions, and 15 additional field-based resistance training sessions, whereby measures of 2.4km loaded march performance, 2.4km run time, static strength, dynamic strength, and body composition were examined at week 1, 11 and 21. At baseline, no significant differences in performance measures were observed between the traditional and modified training groups. This study found a lack of significant performance improvements observed at the end of training (week 21) for 2.4km loaded march (13.6 vs 13.9min, Diff=0.3min), Vo2max (4.1 vs 4.0 L/min^{-1}, Diff=< .1), 2.4km run time (9.4 vs 9.6min, Diff=0.2min), or static lift strength (121.9 vs 126.8kg, Diff=4.9kg) when compared to the traditional physical training programme. In response to the lack of difference in physical and physiological performance enhancement between the modified and traditional physical training programme, it was suggested that the inadequate differentiation in the frequency and intensity of training stimuli between the two programmes was a key factor linked to the lack of performance adaptation following the modified programme.

Research highlights the importance and effectiveness of periodisation of specific training principles within BMT programmes and that of specific military occupational activities and tasks that involve high impact cyclic lower-extremity loading such as running, tabbing, marching, and British Army foot-drill. However, the practical considerations of applying periodised planning to training programmes for both male and female recruit populations poses a unique challenge for the Army, primarily due to (but not limited to) the distinct physiological, anatomical, biomechanical, and level of initial physical fitness on enlistment of male and female recruits, coupled with Phase one training demands (both classroom and physical), manning and whilst promoting the reduction in the incidence of lower-extremity MSK injury.

Continuing the line of research of the previous study conducted by Williams *et al.,* (1999), whereby it was concluded that the basic training programme (at that time) failed to increase levels of strength and MH ability, along with improvements in simulated military task performance whilst having minimal impact on reducing training-related MSK overuse injuries, Williams *et al.,* (2002) evaluated the efficacy of a modified 12-week British Army basic military training programme compared with the existing training programme. The modified programme involved a resistance training element that conformed to a periodised model of training, whereby such training principles as specificity were utilised to ensure that strength exercises performed in training correlated with those MH tasks performed in the field. Additionally, progressive overload, individualisation (i.e., relative training loads), and a period of familiarisation that optimised the transfer of key technical points whilst providing a baseline of ability to execute such strength training exercises as the pull-up, bench press, shoulder press, deadlift, and upright row was included. When compared to the existing training programme, the modified programme demonstrated significantly greater improvements in physical and physiological parameters for several MH occupational tasks, most notably, maximal box lift (12.4% vs 1.7%,), 3.2-km 15-kg-loaded march (8.9% vs 3.6%), estimated fat-free mass (4.2% vs 1.5%), predicted maximum oxygen consumption (9.3% vs 4.1%) and 1.45 meter dynamic lift (15.5% vs 0.2%).

In contrast with others (Brown *et al*., 2010; Drain *et al*., 2015; Williams *et al*., 1999) the modified programme demonstrated a significant improvement in MH ability associated with the implementation of a periodised strength training element, which represent key physical and physiological performance attributes for many of the task’s male and female recruits and soldiers undertake during their military careers. In addition, effective periodisation resulting in higher levels of upper and lower-extremity muscle strength as shown by Williams *et al.*, (2002) resulted in significant reductions in percentage bodyfat and increases in fat-free mass (FFM) (i.e., muscle). Greater muscle size and strength is said to assist in the attenuation of high impact loading forces exhibited at the foot-ground interface (Coventry *et al*., 2006). Therefore, the 3.6% (d =0.3) and 8.2% (d =0.9) greater FFM observed for male and female recruits respectively, after 11-weeks of modified basic training may have provided more effective shock attenuating capabilities against potentially injurious lower-extremity loading. In addition, the significantly larger effect size observed for female recruits in comparison to the moderate effect size in men, suggests that the 8.2% increase in FFM post training may be more clinically meaningful in relation to performance and injury risk for female recruits.

A key study that supports the outcomes of previous research (Williams *et* al., 2002) conducted by the U.S Army Physical Fitness School proposed major modifications to U.S Army physical training in 2001/02, developing a new physical training programme known as Physical Readiness Training (PRT). The development of the PRT programme was a joint effort between researchers and military staff, namely, drill instructors and physical training commanders/instructors, and was developed using a three phased approach; (i) train-the-trainer, (ii) pilot phase, and (iii) the test phase, whereby daily observations and focus groups during the pilot phase resulted in further PRT modifications designed to reduce the incidence of injury whilst maintaining high success rates of Army Physical Fitness Tests (APFTs) (Knapik *et al.,* (2002). The PRT differed from traditional US Army training programmes, in that it de-emphasised running mileage, incorporated greater variation of full-body exercises, and utilised certain training principles similar to that of Williams *et al*., (2002), namely, progressive overload and specificity in the strategic management of newly integrated physical training activities and tasks. Although the total number of training sessions were similar for both the traditional (control group (CG)) and PRT (experimental group (EG)) programmes, the CG had more than double the formation running mileage of the EG, had considerably more emphasis on basic calisthenics (i.e., variations of the push up and sit up), along with aerobic based training (mainly running). Whereas, the EG focused more on dumbbell and movement drills, high intensity interval training and flexibility. Furthermore, a key difference between the EG and CG was that in week 3 of PRT, the calisthenics were supplemented with timed-sets of push ups and sit ups, demonstrating progressive overload of the training stimulus, thus reducing the risk of overtraining and subsequent injury. Following 9-weeks of physical training, the EG demonstrated favourable injury and fitness outcomes in comparison to the CG. In addition, the relative risk of any overuse injury was found to be 52% higher for the CG in men (adjusted relative risk: EG=1.00 vs CG=1.52), and 46% higher for the CG in women (adjusted relative risk: EG=1.00 vs CG=1.46) when compared to men and women of the EG.

In terms of physical fitness outcomes as measured by Army Physical Fitness Tests (APFTs), the EG demonstrated higher pass rates on the final APFTs when compared to the CG in both male (85% vs 81%) and female (80% vs 70%) recruits, coupled with fewer failures in EG for women (EG: 1.6% vs CG: 4.6%). It is likely that the PRT programme enhanced other physical performance measures, namely, strength, flexibility and dynamic coordination due to the strategic implementation of training components whilst minimising excessive aerobic training. However, APFTs are not designed to capture enhancements in other training components, rather the APFTs only determine changes in aerobic and muscle endurance capacity from push-up, sit-up and a 2-mile run pre-post basic training. The results from the PRT programme are somewhat similar to those reported by Wilkinson *et al.*, (2008), whereby significant reductions in medical discharge rates (14.4% to 5.1%) and increased first time (35% to 40%) and overall (43% to 58%) pass rates were observed from adopting a more progressive and structured approach to physical training of the 24-week British Army CIC Parachute Regiment physical training course. Based on the results of the aforementioned studies, a progressive and evidence-based approach to the development and modification of military training programmes (Dada *et al*., 2017; Knapik *et al*., 2002; Wilkinson *et al*., 2008; Rudzki *et al.,* 1999) illustrates a trend towards reduced rates and risk of overuse and time loss injuries, higher first-time pass rates, and lower rates of APFT failure when compared to traditional physical training programmes.

Over the years there have been numerous modifications to how male and female recruits are physical trained and assessed within the British Army (Williams *et al*., 2010). In 1997, the introduction of Physical Selection Standards for Recruits (PSS(R)) coupled with gender-free physical training for the CMS in 2006 resulted in male and female recruits being trained and assessed together to a common standard (Rayson *et al*., 2012). Initially, women were trained to a lower standard of physical fitness, however it was recognised that as the number of career choices expanded, numerous female recruits were not physically capable of performing effectively within their selected role (Gemmell *et al*., 2002). Thus, women were exposed to equally demanding levels of physical training to that of men. However, it became apparent that gender-free training was significantly impacting on the total intake of female recruits into the British Army (9% reduction) and exposed women to greater risk of lower-extremity MSK overuse injuries (4.7% to 11.1%) and associated medical discharge. For instance, Rudzki and Cunningham, (1999) conducted a retrospective, uncontrolled observational analysis comparing rates of injury pre-post changes to the standard Australian Army physical training programme.

The inclusion and modification of different aspects of the standard physical training programme involved cessation of road runs as a formed body, resulting in a 26.5-km reduction in running mileage, the integration of interval training on grassed surfaces (400m – 800m sprints), reduced test run distances from 5-km to 2.4-km, standardised route marches, and the inclusion of deep water running which was deliberately programmed after 12-km road marches.

These changes resulted in a 46.6% reduction in the total incidence rate of injury presentation, whereby men demonstrated a reduction in medical discharge from 81.1 to 47 per 1000 recruits, resulting in a significant reduction in medical discharge of 33.1 per 1,000 recruits. Despite women demonstrating a significantly reduced incidence rate of injury presentation (35.1 to 22.7 per 1000 recruits, Diff=12.4) over the same period, female recruits demonstrated significantly greater medical discharges from 45.5 to 164.2 per 1,000 recruits, resulting in an overall increase in medical discharge of 57.7%. In consideration of the large disparity in medical discharge rates between men and women recruits reported by Rudzki and Cunningham (1999), the increase in female medical discharges in the presence of declining injury rates indicates that the injuries sustained by women were generally more debilitating, resulting in greater rehabilitation time (>8 weeks) and thus, greater risk of medical discharge. These results call into question the efficacy of gender-integrated physical training systems of men and women, and likely require re-evaluation of the current concepts of integrated recruit physical training, taking in consideration the poorer initial physical fitness levels prior to enlistment, and factors relating to the physiological and anatomical factors that inherently challenge women in most aspects of physical performance (Greeves, 2015). However, similar to research (Brown *et al*., 2010; Dana *et al.*, 2017; Gemmell *et al*., 2002; Williams *et al*., 2002; Williams *et al*., 2010), Rudzki *et al.*, (1999) reported that the single most effective strategy in reducing incidence rates of injury and medical discharge was the strategic reduction in the volume and frequency of repetitive loading activity (running and marching), coupled with the reduction in total 'junk miles' which represents the additional work conducted out-with timetabled physical training.

Despite obvious reductions over the years in lower-extremity MSK injury and medical discharge rates in recruit populations, the existing magnitude of injury rates, injury severity, and medical discharge remain to have a significant financial and personnel impact on the

British Army. Therefore, it is suggested that to achieve and maintain adequately trained strength (i.e., total serving recruits/soldiers) whilst reducing the incidence and severity of injury in recruits during Phase one, it is vital that British Army BMT programmes, such as the new 2018/19 CMS and CIC, along with occupational activities and tasks (i.e., tabbing, load carriage, foot-drill) be strategically monitored and periodically evaluated in collaboration with senior medical advisors and subject matter experts to ensure programme efficacy, appropriateness, legal defensibility, and risk of injury to recruits.

2.1.2 Rates of medical discharge, musculoskeletal injury incidence, and anatomical locations of injuries in recruits.

Injury, most notably lower-extremity MSK injuries are undisputedly the single most significant medical impediment to the physical health of the recruit, possessing a heavy financial burden due to medical dismissal of seriously injured recruits, medical care costs, lost and/or limited training days, and extensive rehabilitation time (Molloy *et al.*, 2012). According to the 2018 annual medical discharge report (MoD, 2018), lower- extremity MSK injuries and disorders are the principal cause of medical discharge across all three services (Army, Navy, Airforce) accounting for nearly 60% of all medical discharges in the British Army (MoD, 2018).

In agreement with previous MoD annual medical discharge reports (MoD, 2018), the knee, lower-back, and the shank (i.e., shin, ankle and foot combined) are the most common anatomical sites of MSK injury. Wilkinson *et al.*, (2011) indicated that 71% of all MSK injuries sustained by trained soldiers during pre-deployment training were located in the lower-back and lower-extremities. Similarly, medical discharge (81%) and remedial instructor (RI) referral (55%) for British Army recruits were associated with injuries sustained to the lower-extremities (Blacker *et al.*, 2008). Over a 12-month study period, Wilkinson *et al.*, (2011) reported that

386 British infantry soldiers sustained one or more injuries during pre-deployment training, resulting in a cumulative injury incidence of 58.8%, with 24 soldiers (3.6%) non-deployable due to reductions in medical status. It was further reported that 75% of all injuries reported were sustained during working hours, with physical training (30%) and military operations and exercises (15%) defined as the most common activities associated with injury. The percentage of injuries, medical discharges, and remedial fitness reported by Blacker *et al*., (2008) may be linked with the specific design of the pre-deployment training programme. However, little is known with regards to the training programme and no comparisons between pre-deployment training programmes was undertaken.

Between April 2016-March 2017, the MoD reported 1,932 medical discharges for the British Army during Phase one training (22.2 per 1,000 personnel), with 1,079 (59%) of those medical discharges linked directly to injuries of the knee joint (n=221, 12%), knee pain (n=83, 8%), low-back pain (n=86, 5%), and injuries to the foot/ankle (n=107, 6%). The Navy (n=446, 13.7 per 1000 personnel) and Royal Air force (RAF) (n=148, 4.4 per 1,000 personnel) demonstrated considerably lower magnitudes of medical discharge when compared to the British Army, however, similar incidences related to medical discharge were reported for Naval service personnel (including Royal Marines): knee joint (n=69, 15%), knee pain (n=35, 5%), low-back pain (n=38, 9%) and injuries to the foot/ankle (n=24, 5%); and RAF: knee joint (n=10, 7%), knee pain (n=5, 3%), low-back pain (n=9, 6%) and injuries to the foot/ankle (n=≤5, 3%). In addition, significantly greater rates of medical discharge for the Army, Navy and RAF were identified for specific demographic groups, most notably, personnel aged under 25 years, women, and recruit (i.e., untrained) personnel. These specific demographics that displayed higher rates of medical discharge were found to be consistent with the results observed in the recovery pathway, whereby greater proportions of female personnel, recruits, and those ≤ 25 years were undergoing rehabilitation.

In a study conducted by Jones *et al.*, (1993), significantly higher rates of female trainees self-reported having sustained an MSK injury when compared to men, reflecting the higher percentage of MSK injuries reported for women (88%) when compared to men (77%) of the lower-extremities. In addition, the order of frequency of the most commonly diagnosed MSK injuries during basic training were different between men and women, whereby low back pain (7.3%), tendinitis (6.5%), and joint sprains (4.8%) were most commonly reported for men, whereas muscle strains (15.6%), pelvic and lower-extremity stress fractures (12.3%), and overuse knee complaints (2.1%) were most commonly reported for female trainees. Similar to data reported for British and US Army populations, the most frequently reported MSK injuries for Norwegian Air Force recruits were Achilles tendinitis, compartment syndrome, overuse knee injuries, and joint or ligament sprains. It was further reported that 74% of injuries were related to military service activities, whereby 38% of those injuries were associated with the rigors of marching and other repetitive weight-bearing military activities (Heir *et al.*, 1996).

Specific to the British Army, significant differences were observed during the 2016/17 reporting period between male and female, and between trained (i.e., soldiers) and recruit personnel, whereby medical discharge incidence rates for women (26 per 1000 recruits) in comparison to men (21.9 per 1000 recruits) were 15.8% greater for women, and 75.5% higher for untrained (70.7 per 1000 recruits) when compared to trained personnel (17.3 per 1000 recruits). In addition, higher incidence rates of medical discharge were also observed for British Army personnel aged ≤ 20 years when compared to ages ranging from 20 to ≥ 50 years (mean rate per 1000 recruits: 18.7). The majority of recruits aged ≤ 20 years are entry-level recruits, thus the higher incidence rate of medical discharge observed for younger age-groups is said to be associated with the high incidence of medical discharges for untrained personnel (MoD, 2017).

In a study conducted by Blacker *et al.*, (2008), risk factors for training-related injuries resulting in remedial instructor (RI) referral or medical discharge (MD) in British Army recruits were recorded during basic training. Similar to recent MoD reports, women exhibited higher incidence rates of RI referral (0.173 per 100 days) and medical discharge (0.033 per 100 days) when compared to men (RI: 0.061 per 100 days, Δ=64.7%; MD: 0.018 per 100 days, Δ=45.5%) and that poorer levels of aerobic fitness were the primary cause for the greater incidence of injury during Phase one training, not sex. These results are in agreement with those reported by Bell *et al*., (2000) and others (Billings, 2002; Knapik *et al*., 2001; Pope *et al*., 1999), whereby female Army trainees entered the Army with significantly lower-levels of aerobic fitness, experiencing twice as many injuries as male trainees (relative risk [RR]: 2.1), and were 2.5 times more likely than men to experience time-loss injuries (RR: 2.4). It has also been discovered that a highly significant inverse relationship exists between the level of initial physical fitness and the incidence of MSK injury, suggesting that low levels of initial physical fitness (primarily aerobic) are attributable to the development of one or more MSK injuries in recruit populations (Rosendale *et al.,* 2003).

Medical surveillance data from the British Army were collected during a 26-wk basic training programme for two consecutive years, investigating MSK injury incidence and duration of rehabilitation of 6,608 British Army recruits (Sharma *et al.*, 2015). During this study period the overall incidence of MSK injuries was 48.7%, with the greatest rate of MSK injury reported during week two of basic training. The timing of these injuries resembles those reported in previous studies, whereby higher injury incidence rates were observed during the opening 4-wks of basic training (Almeida *et al.*, 1999; Brushoj *et al*., 2008). Furthermore, significantly greater MSK injuries were reported for basic training (n=2,242) when compared to phase two (n=984). These results are not surprising when one considers two key factors, (i) phase one training is considered significantly more physically demanding than phase two training and,

(ii) the majority of entry-level recruits enter the British Army with inadequate levels of physical fitness – a well-recognised risk factor associated with MSK injury and early medical discharge (Bell *et al*., 2000; Blacker *et al*., 2008; Knapik *et al*., 2001).

According to the MoD, higher rates of medical discharge reported for untrained personnel are thought to reflect the intensive physical rigor of initial military training, coupled with the demanding physical entry standards of the Field Army. In agreement with research (Bell *et al* ., 2000; Blacker *et al.*, 2008; Sharma *et al*., 2015), the majority of entry-level recruits (mainly women) begin initial military training with inadequate levels of physical fitness, recognised as a key contributing factor associated with failed physical testing and early medical discharge. Nevertheless, the MoD suggests that women, when compared to men, are more likely to approach healthcare services with complaints of pain and/or health issues, resulting in higher rates of reporting and potential medical discharge.

Several investigations focused on reducing the risk and incidence rate of MSK injuries of recruits during initial training have mostly been ineffective (Brushoj *et al*., 2008; Knapik *et al*., 2002; Popovich *et al*., 2000), whereby the capacity to affect change is suggested to be linked with the generic nature of these interventions, designed to target more than one injury or group of injuries rather than focusing specifically on one relevant injury to that military organisation and/or group (i.e., recruits) (Sharma *et al*., 2015). For instance, Brushoj *et al.*, (2008) conducted a randomised control trial investigating the effectiveness of an injury prevention training programme aimed at reducing the incidence rates of overuse knee injuries and medial tibial stress syndrome in 1,020 soldiers. Following comparison between the intervention and placebo group, no significant differences in the incidence rates of injury were observed (per 100 recruits: 0.22 vs 0.19; RR=1.2), however, the intervention group demonstrated significantly greater running distance in the 12-min run test when compared to the placebo group (82m vs

43m improvement, *p*=.037), indicating that the injury prevention programme concurrent with an increase in physical activity may have positively impacted on factors relating to improved running economy. Nevertheless, >200 recruits sustained an MSK injury, with just under 100 of those injuries' fulling the criteria for overuse knee injuries and medial tibial stress syndrome.

A possible explanation for the lack of injury prevention reported by Brushoj *et al* (2008) may be linked to the cumulative magnitude and frequency of mechanical loading on lower-extremity MSK structures, whereby the rapid rise in physical activity associated with basic training, combined with an additional injury prevention programme is likely to increase the magnitude of mechanical load considerably. Therefore, the increase in mechanical load may have prevented any potential change the injury prevention programme could have had on the incidence rates of overuse knee injuries and medial tibial stress syndrome in soldiers during BMT. Additional research attempted to reduce the overall incidence of running-related MSK injuries from increasing the duration and frequency of recovery during the initial 1 to 4 weeks of an 8 week US basic training programme (Popovich *et al*., 2000). Similar to that of Brushoj *et al*., (2008), Popovich *et al*., (2000) observed no evidence of a protective effect and/or reduction in overuse injuries from resting from running for 1-week during the initial weeks of basic training. Among the 1,357 male recruits who participated, 17% of all injuries were classified as MSK overuse and 11% traumatic, resulting 535 clinical visits and a total of 1,927 training days lost. It was concluded that the magnitude and frequency of other training modalities, namely marching, circuit training and loaded marching may have hindered the potential positive effects of the injury prevention strategy in US Army recruits.

Modifiable risk factors have been identified throughout the literature suggesting that overuse and other training-related lower-extremity MSK injuries can be decreased with evidence-based interventions that are supported by robust surveillance systems that capture the incidence of injuries with reliability and accuracy. For example, Finestone and Milgrom, (2008) reported a 60% reduction in the incidence of stress fractures of basic infantry recruits using two primary targeted interventions, (i) enforcement of a minimum sleep regimen whereby recruits were given a minimum of 6-hours sleep each night during basic training, and (ii) lowering the cumulative marching/running from approximately 900-kilometres to 380-kilometres over 13-weeks of basic training. These modifications specifically reduced the magnitude of mechanical loading experienced by recruits during basic training. As a consequence of these targeted modifications in basic training, the overall incidence of stress fractures specific to the tibia was reduced from 56.1% to 35.7%, resulting in a total reduction of 36.4% in the incidence of tibial stress fractures of recruits whilst improving and maintaining adequate levels of combat readiness. Given the extent of the injury problem within military organisations, it is recommended that a systematic process of prevention be utilised with routine surveillance to identify high-risk populations and most debilitating injuries for the purpose of prioritising the line of research (Kaufman *et al*., 2000).

Injury is undisputedly the leading health and readiness threat to the Armed forces, as such, research suggests that targeted interventions and/or strategies focused on specific injuries and their respective risk factors are likely to be superior in terms of their effectiveness to reduce the severity and incidence of lower-extremity MSK overuse injuries in recruits during basic military training. Published research indicates that preventative strategies be specifically directed by the primary factors that contribute to the risk of MSK injury, namely the magnitude and intensity of physical training, levels of initial physical fitness, and the influence and/or inability of specific equipment (i.e., footwear) (Kaufman *et al*., 2000). These strategies must be supported and directed by 2* military commanders to ensure effectiveness of implementation and to provide the recruit and soldier with adequate protection against injury whilst supporting operational readiness and ensuring maximal deployability.

In an effort to reduce the incidence of foot and metatarsal stress fractures in recruits, Finestone and Milgrom (2008) hypothesised that training with shoe gear that had improved shock absorbing capabilities would contribute to a lower incidence of lower-extremity stress fracture. As such, a modified basketball shoe with superior shock absorbing properties was worn by 187 recruits and was compared against 203 recruits wearing the standard combat assault boot (CB). Throughout 14-weeks of basic training, statistically significant differences in stress fracture incidence was observed between the modified footwear (experimental group (EG)) and CB (control group (CG)), specifically recruits wearing the modified basketball shoe reported zero metatarsal stress fractures, whereas 3.4% of recruits wearing the CB sustained metatarsal stress fractures (p=.03). Additionally, recruits wearing the modified basketball shoe reported significantly less soft tissue injuries of the foot when compared to recruits wearing the CB (n=29, 15.5% vs n=59, 29.1%, p<.01). However, the EG reported higher femoral (n=22, 11.8%) and tibial stress fractures (n=34, 18.2%) when compared to the CG (n=16,7.9%, n=33, 16.3% respectively), suggesting that the modified basketball shoe may provide the recruit with limited protection against high cyclic loading forces specific to the metatarsals. In addition, no significant differences were observed between the EG and CG for the overall incidence of overuse injuries in recruits during 14-weeks of basic training.

The CB remain a key factor for lower extremity MSK injury in recruit populations as demonstrated by Nunns *et al.*, (2012), quantifying the influence standard issue Royal Marine CB on specific foot and ankle biomechanics associated with the incidence of third metatarsal (MT3) stress fractures. Previous reports indicated that Royal Marines are exposed to one of the most physically demanding training courses in the British Armed Forces and sustain an unusually high proportion of MT3 stress fractures, accounting for 38% of all lower-extremity stress fractures (Ross and Allsopp, 2002). Based on in-shoe plantar pressure and 2-dimensional biomechanical analysis, Nunns *et al.*, (2012) reported significantly greater peak plantar pressures, impulse, loading rate, and ankle stiffness when running in the CB, providing evidence that the CB may have implications for MT3 stress fracture in Royal Marine personnel. In addition, as part of a government lead strategy to reduce the rates of MSK injuries, attrition, and increase the trained strength of the British Army, in 2012 the British Armed Forces signed a contract worth £80million that provided each serving soldier and recruit with a new range of brown combat boots replacing the old CB on the basis that the CB increased the risk of sustaining one or more lower-extremity MSK overuse injuries (Nunns *et al*., 2012; Sinclair and Taylor, 2014) and did not provide recruits/soldiers with adequate support and/or protection required when operating in a variety of different environments, especially for females as the CB were designed based on the normative foot dimensions of the male soldier with no alternative or adjustments provided for the female soldier.

Many of the studies considered within this literature review have explored interventions and/or strategies to reduce the incidence of MSK overuse injuries during basic military training programmes due to the significant financial and medical burden of injuries to male and female recruits. Despite many studies demonstrating modest and/or a lack of significant reduction in the incidence rates of lower-extremity MSK overuse injuries, Scott *et al*., (2012) implemented a multiple-intervention strategy aimed at reducing one of the most significant overuse injuries in terms of financial cost and rehabilitation - femoral neck stress fractures (FNSF). Arguably, femoral neck stress fractures are one of the most devastating bone injuries reported during basic training, with many cases requiring invasive surgical procedure. These specific bone injuries are responsible for only 5-10% of all bone injuries, but impact the US department of defence significantly, with an estimated $100,000 per FNSF. It was hypothesised that an evidence-based injury prevention strategy, involving such key sub-strategies as leadership education, leadership enforcement of proven methods, and a robust injury surveillance and reporting system would result in a reduction in the incidence of FNSF, along with other severe overuse injuries during US Army basic training. As a result, the total number of FNSF cases significantly reduced from 20 cases/10,000 recruits in 2008 to 8 cases/10,000 recruits in 2010 for men, and 41 cases/10,000 recruits in 2008 to 18 cases/10,000 recruits in 2010 for women, demonstrating a significant positive effect on the incidence rate of FNSF in male and female US Army recruits.

Despite these reductions in FNSF in male and female recruits, women demonstrated a considerably greater case load of FNSF in 2008 (>21 cases) and 2010 (>10 cases) when compared to men. It should be noted that during this reporting period, male and female recruits underwent basic training in integrated gender-free platoons. Inherent biological differences between sexes require women to work harder when undertaking the same tasks as men, and is reflected in part, by the greater risk of MSK injury observed during integrated training (Greeves, 2015). Thus, the physiological and anatomical differences between male and female recruits must be understood when re-designing or implemented novel military training tasks and activities for maximum operational readiness and retention of female soldiers.

2.1.3 Physiological differences and anatomical lower-extremity musculoskeletal injury risk factors of male and female military personnel

Basic training and subsequent regular physical training forms an integral part of military life and is crucial for the optimisation of operational effectiveness. However, initial military training programmes are not without risk, with high injury incidence and medical discharge rates reported across military organisations (Blacker *et al.*, 2008; Knapik *et al.*, 2001; Molloy *et al.*, 2012; Wilkinson *et al.*, 2011). Due to differences in recruit characteristics, Phase one training regimes, coupled with diverse environmental factors, the type and most common injuries reported, along with training-related injury risk factors are likely to differ across different military nations. However, the burden of lower-extremity MSK injuries is a global problem in terms of its impact on operational trained strength, deployability and cost. Furthermore, as risk of injury is a time dependent measure, it is difficult to directly compare injury with other studies of different durations, whereby training programmes of longer duration and/or intensity (British Army basic training = 14-weeks vs Combat Infantryman's Course (CIC) = 26-weeks)) may expose male and female recruits to substantially greater risk of injury (Hopkins *et al*., 2007).

For the majority of military organisations the aetiology, magnitude, and severity of MSK injuries sustained by recruits during initial military training programmes have been identified and reduced from using a strategic 'control process' involving, (i) surveillance research to determine the magnitude of the injury problem, (ii) empirical studies to determine the aetiology and risk factors for specific injuries, (iii) validation of intervention studies focused on reducing risk of injury, (iv) successful implementation of effective injury reduction interventions and, (v) empirical follow-up studies to monitor whether injury reduction and/or performance optimisation interventions retain their effectiveness throughout their implementation (Jones and Knapik, 1999).

Various basic training programmes have reported similar types of risk factors for both male and female recruit populations, including low levels of aerobic fitness (Bell *et al*., 2000; Blacker *et al*., 2008; Knapik *et al*., 2001), body mass index (<17-20 – 25-28) (Blacker *et al.,* 2008), history of previous injury (Kaufman *et al*., 2000), smoking (Knapik *et al.,* 2001; Altarac *et al.,* 2000), sex (Jones and Knapik, 1999), race (Knapik *et al*., 2007), age (<18yrs, 23-35yrs (Blacker *et al*., 2008; Murphy *et al*., 2003; Knapik *et al*., 2001), specific military training activities (i.e., loaded marching, running and drilling) (Jones and Knapik, 1999; Carden *et al.,* 2015), muscle strength (Williams *et al.,* 1999), training equipment (i.e., footwear) (Bennell *et* al., 1999; Sinclair and Taylor, 2014), and sex-specific physiological and anatomical factors such as sex hormones, menstrual disturbances, calorie intake, notch width, and posterior tibial slope (Greeves, 2015; Alentorn-Geli *et al*., 2009).

Several of these risk factors are directly linked to the risk and occurrence of a number of MSK injuries reported for basic training recruits. For instance, it is well-recognised that a low (<17) and high (>25) body mass index (BMI) and reductions in fat-free mass, coupled with low-levels of initial physical fitness are key factors associated with the occurrence of morbidity from injury, and are considered detrimental to successful performance of military occupational activities/tasks (Jones *et al*., 1993). In addition, Army Personnel Research Centre and the Defence Evaluation and Research Agency investigated lower-extremity injuries in British Army recruits. It was reported that 37% of recruits self-reported past history of MSK injury, with 88% of those with previous injury were medically discharged from training with knee complications (Box, 1989).

Other risk factors that have received considerable investigation include the relationship between sex hormones to ligament and bone stress fractures; more specifically the role of oestrogen on growth and maturation of bone, regulation of bone turnover, and laxity of ligamentous tissues, the demands of specific occupational activity (i.e., marching and foot-drill), along with shock absorbent footwear (Carden *et al*., 2014; Sinclair and Taylor, 2014; Nunns *et al*., 2012).

Utilising the control process as a guide, several studies have identified a number of lower-extremity injury risk factors during BMT programmes associated with such MSK training-related injuries as iliotibial band syndrome, medial tibia stress syndrome, ankle sprain, lower-back pain, anterior knee pain, Achilles tendinopathy, anterior cruciate ligament (ACL) injury, and stress fractures of the lower-extremity (Blacker *et al.,* 2008; Knapik *et al.,* 2001; Sharma *et al*., 2015; Wilkinson *et al*., 2011). Blacker *et al.,* (2008) quantified injury rates and identified risk factors associated with the development of both acute and overuse training-related injuries during 12-weeks of basic training. Rates of injuries, remedial instructor (RI) referral, and medical discharges were reported for over 13,000 male and female British Army recruits during basic training. It was reported that female recruits demonstrated significantly greater rates of RI referral and medical discharge when compared to male recruits. These results are consistent with those reported by Bell *et al.,* (2000) whereby crude injury rates indicated that female recruits were at a higher risk of injury when compared to male recruits.

The findings of Bell *et al*., (2000) and Blacker *et al.,* (2008) agree with those reported for the Australian and US Army (Rudzki and Cunningham, 1999; Knapik *et al.*, 2001) and Royal Navy (Allsopp *et al.,* 2003), whereby female recruits consistently demonstrate significantly greater injury incidence and medical discharge rates during basic training, leaving many to believe that sex is an independent risk factor for injury (Jones *et al.*, 1993). However, based on multivariate Cox regression analysis for RI referral and medical discharge (Blacker *et al*., 2008), whereby sex was not present within the model, along with fitness-adjusted injury rates calculated by Bell *et al*., (2000), indicated that female sex alone is not a significant risk factor for injury or medical discharge, rather the underlying lack of initial physical fitness reported for female recruits upon commencement of initial military training explains, in part, the sex-specific excess in MSK injury (Bell *et al.*, 2000; Blacker *et al*., 2008; Jones *et al.*, 1988). Additionally, a limitation of these studies is that sex hormones were not considered as part of the risk factor analysis. It is well recognised that sex hormones such as oestrogen and progesterone, menstrual disturbances caused by imbalances and/or deficiencies in energy intake to expenditure, chronic administration of oral contraceptives resulting in altered hormonal regulation, and the effects of oligomenorrhea and amenorrhea are key factors associated with increased risk of ligament injury (Alentorn-Geli *et al*., 2009) and bone stress fractures in female recruit and athletic populations (Wentz *et al*., 2011; Ruffing *et al*., 2007). From the literature, a general consensus exists indicating that women, due to the surge in oestrogen levels during the pre-ovulatory phase of the menstrual cycle, are at an increased risk of ACL/knee ligament injury and bone stress fracture due to greater laxity of connective tissues and irregularities in the bone turnover/remodelling process (Hewett *et al.*, 2007).

Rationalising the importance of aerobic fitness in determining risk of injury in recruits is likely to be that individuals with lower-levels of aerobic capacity will experience considerably greater overall physical strain and mechanical loading for any given military task, subsequently increasing their susceptibility to injury and potential medical discharge (Blacker *et al.*, 2008). However, anecdotally it has been suggested that poor levels of initial physical fitness observed on entry to the British Army may be linked to the effects of over training coupled with a lack of education, whereby recruits place themselves under extreme physical strain during the final weeks prior to enlistment with minimal recovery and/or structure, subsequently increasing the risk of overtraining and subsequent injury during the initial weeks of basic training.

It has long been recognised that women are at considerably greater risk of MSK injury in comparison to men, and that the distinct physiology and anatomy of the female recruit/athlete is attributable to the high incidence of lower-extremity MSK injury during basic training (Geary *et al.*, 2002). In accordance with Greeves (2015), and recent MoD scientific reviews focused on the exclusion of women in ground close combat roles (GCC), it has become apparent that an increasing number of military occupations are now available to women, following a comprehensive review of women in GCC roles (MoD, 2016), supported by recommendations from the Chief of General Staff. Following these events, the ban on women serving in GCC roles was lifted in July 2016 based on the Women in GCC Interim report (2016) on the health risks to women in GCC roles.

As injury and other factors (i.e., mental health) linked to downgrading and subsequent medical discharge were expected to present a similar, if not greater risk for women serving in GCC roles due to the significantly higher demands of preparing for, and operating in theatre alongside men, four specific mitigation strategies were recommended; (i) development of validated and defensible PES, (ii) implementation of optimal physical training strategies, (iii) interventions for injury prevention, and (iv) mental health first aid. Furthermore, the inclusion of women, coupled with the physical rigors of these new GCC roles, present new challenges for the physical preparation and protection of women in the British Army (Greeves, 2015). For instance, acquiring the physical capacity to carry, lift, and perform load carriage tasks for long durations is critical for physical training and when operating in theatre - forming the basis of a number of PES specific to GCC and non-GCC roles within the British Army (Greeves, 2015; Women in GCC Interim report 2016).

Despite the fact that female recruits and athletes are more likely to self-report injury and illness in comparison to their male counterparts (MOD, 2016/17), the specific aetiology and/or mechanisms associated with the significantly greater rates of RI referral and medical discharge observed for female recruits undergoing basic training is a diverse and multifactorial problem. Many military and epidemiological injury risk factor analyses have identified numerous physiological, anatomical, and training-related injury risk factors including (but not limited to) reduced strength and muscle endurance, greater pelvic width to femoral length ratio, reduced bone mineral density, shorter stature, over-striding when marching, smaller cross-sectional area and narrower cortex of bone, and hormonal factors such as menstrual irregularities, and the effects of amenorrhea or oligomenorrhea on bone health (Bell *et al.,* 2000; Evans *et al*., 2008; Ferber *et al.* Knapik *et al*., 2001; Lauder *et al.,* 2000; Wentz *et al*., 2011).

Studies directly comparing the incidence of stress fractures between sexes during basic training indicate a 2 to 12-fold greater risk of stress fracture in females when compared to males (Finestone *et al*., 2008; Greeves, 2015; Izard and Greeves, 2017; Jones *et al*., 1993; Matilla *et al*., 2007). It is well recognised that women, when compared to men, have smaller 'slender' bones significantly increasing the risk of stress fracture during such cyclic high impact loading activities as marching, running, load carriage, and potentially foot-drill (Carden et al. 2016; Greeves, 2015; Izard and Greeves, 2017). According to recent MoD research (Izard and Greeves, 2017), women are three times more likely to suffer a tibial stress fracture during basic training when compared to their male counterparts. Although physical activity confers beneficial effects on bone by improving its structure and architecture, the inhibitory effects of oestrogen on periosteal growth has been defined as a preventative factor for appropriate skeletal adaptation in women during basic military training (Izard *et al*., 2017).

In terms of overall muscular strength and size, women typically have 30-50% and 70% of the upper-body and lower-body strength of that of men (Bergman and Miller, 2001) respectively. Similarly, Nindl *et al*., (2000) reported that women, in comparison to men, have 30% less muscle in the lower-extremities and approximately 50% less in the upper-extremities, most notably of the arms. Due to higher concentrations of testosterone (Greeves, 2015), higher ratios of fast-twitch to slow-twitch muscle fibres are found in men when compared to women, resulting in superior levels of muscular strength and power (Miller *et al.*, 1993). The ability to carry heavy loads over long distances and over uneven terrain has been shown to be correlated with an individual's absolute strength and body mass (Scott and Ramabhai, 2000). Generally, the heavier the individual in terms of muscle mass, the greater the absolute strength that person will be able to express (Haff and Triplett, 2016). For instance, in a study conducted by Patterson *et al*., (2005) female soldiers who successfully completed a 15-km march at a pace of 5.5-km/hour carrying 35-kg were taller, heavier, stronger, and were recorded as having marginally greater aerobic capacity when compared to females who failed to complete the march. Similarly, Pandorf *et al*., (2002) indicated that larger females in terms of stature and muscle mass, were able to complete a loaded (mean weight: 40.6-kg) 3.2-km march faster when compared to females who were smaller in stature and obtained less lean muscle mass and more fat mass.

As a consequence of smaller muscle size, and a greater proportion of slow-twitch muscle fibres, it has also been reported that women have approximately 40% less anaerobic power when compared to men (Miller *et al.,* 1993). In addition, women have smaller hearts and thus, lower circulating blood volume and lower levels of haemoglobin, resulting in an average of 15-30% lower maximum oxygen uptake when compared to men (Bergman and Miller, 2001). Differences in aerobic capacity as demonstrated by 2-km run times, Yanovich *et al.,* (2008) reported that only the highest 90th percentile of women overlapped the scores of the lowest 10th percentile of men during the initial testing phase of basic training.

In accordance with previous reports (Miller *et al.,* 1993) the overall capacity of muscle strength, endurance, and power has been shown to be 30-60% lower in women, with only 1% of women matching the mean level of these physical attributes of men (Bergman and Miller, 2001). These differences are known to disadvantage women in most aspects of physical performance, coupled with the rigors of military physical training are said to be responsible for the sex-related injury relationship and the significantly higher incidence rates of RI referral and medical discharge (approximately a 2-fold greater rate in women) when compared to men (Blacker *et al.,* 2008). Differences in performance outcome between men and women have been shown to reduce when adjusted for specific anthropometric factors (body mass and fat-free mass) and aerobic fitness (1.5-mile run) (Esptein *et al.,* 2013). However, adjusting for specific anthropometric factors for military selection and/or training tasks may be irrelevant, as female recruits are required to complete the same *absolute* workloads as men when operating in specialised occupations (Greeves, 2015).

As a consequence of an overall lower working capacity, women are required to operate at a higher relative intensity (25-30% more) in order to successfully complete the same military training and occupational tasks as men (Blacker *et al.,* 2009; Greeves, 2015). For example, during a 90-minute 6-mile loaded march carrying up to 20-kg, women reported this specific military activity as more physically demanding, demonstrated by a greater rate of perceived exertion and heart rate. Despite carrying the same load, women were carrying 14% more load than that of men when expressed relative to body weight. Furthermore, Gemmell, (2002) conducted a retrospective study that quantified the rates of medical discharge linked to MSK overuse injuries preceding and following the inclusion of physical selection standards between male and female British Army recruits, observing a 6.1% greater rate of medical discharge when compared to men. Similar to Epstein *et al.,* (2013), Blacker *et al.,* (2009), and Greeves, (2015), the disparity in rates of medical discharge between male and female British Army recruits was due to differences in muscle physiology (reduced muscle size and strength), bone architecture (slenderer and less dense bones) and body composition (greater % of adipose tissue and reduced fat-free mass).

These findings, along with those reported as part of a large prospective physical demands research study conducted at Army Training Centre, Pirbright (ATC(P)), has significantly contributed to the implementation of single-sex training, whereby men and women are physical trained to a common standard in single-sex platoons as a means of reducing the magnitude of injury risk and medical discharge in women whilst maintaining levels of physical fitness in line with PES and the rigorous demands of military occupational activities and tasks. From these studies, the evidence indicates that women, in comparison to men, operate closer to their maximum physical capacity more frequently in most, if not all physical training modalities during integrated physical training, thus supporting the concept and implementation of single-sex training due to an increased risk of overtraining, fatigue, and lower-extremity MSK injury associated with integrated physical training (Bergman and Miller, 2001; Rayson, 2002).

2.1.4 Anatomical and biomechanical injury risk factors associated with non-conventional landing manoeuvres.

It is well recognised that athletes and recruits are at significant risk of injury when performing physical activity. Specific lower-extremity biomechanics have been implicated as causative factors for MSK overuse injury in athletic and military personnel (Sell *et al.,* 2006). The current evidence suggests that reduced hip flexor/extensor strength (Powers, 2010), greater pelvic width to femoral length ratio (Kernozek *et al*., 2005), larger Q-angles (the relationship between the femoral axis relative to the tibial axis measured at the knee joint in the frontal plane) and limited joint range of motion exposes the athlete and/or recruit to a greater risk of lower-extremity MSK overuse injury (Neely, 1998). Despite these intrinsic injury risk factors, the magnitude of mechanical cyclic high impact loading reported for such activities as marching, running, and foot-drill, have been defined as contributory risk factors associated with the development of lower-extremity stress fractures (Carden *et al.,* 2016; Finestone *et al,* 2008; Popovich *et al.,* 2000).

Despite physical screening of recruits upon entry to the Armed Forces who are unable to reach the required physical performance standards, training-related lower-extremity MSK injuries remain a common problem amongst recruits (Geary *et al*., 2002). As previously demonstrated (MoD, 2017), the knee joint is one of the most common sites of MSK injury in the British Army. Determining the specific mechanisms and training-related factors responsible for knee MSK injuries in military recruits is difficult to quantify but have been suggested to be similar to the mechanism responsible for knee injuries in athletic populations (Sell *et al.,* 2010). To date, no research has investigated lower-extremity kinematics and kinetics of foot-drill in male and/or female recruits. British Army foot-drill involves similar regimental movement patterns to those observed for extended-knee landings, whereby both activities involve impacting the ground with the knee joint in an extended position while activity minimising sagittal plane motion of the hip and knee joint at impact. Based on the mechanical loads reported for foot-drill (Carden *et al.,* 2016; Connaboy *et al.,* 2011) and similarities in movement patterns with that of extended-knee landings, it is hypothesised that foot-drill may exhibit similar lower-extremity biomechanical risk factors when analysed from three-dimensional motion analysis. Furthermore, due to the regimental movement patterns of foot-drill, it is suggested that recruits and soldiers performing such foot-drills as SaA, SaE and halt, will produce high impact forces and loadings rates due to the vigorous 'stamping' and will not exceed hip and knee flexion angles >90°, as this would violate the method in which foot-drill is taught and practiced.

Previous epidemiological studies have linked several kinematic and kinetic variables associated with extended-knee landings to greater risk of non-contact MSK knee injury (Decker *et al.,* 2003; Hewett *et al*., 2005). In a study conducted by Pollard *et al.,* (2010), greater magnitudes of frontal plane knee motion was correlated with reduced lower-extremity joint flexion during the landing phase of a 36cm drop landing task. Further, Huston *et al.,* (2001) observed significant differences in knee flexion angles at peak vertical GRF during 60cm drop landings between men and women, whereby women exhibited significantly reduced sagittal plain knee motion (7°, p<.05) in comparison to men (16°, Δ= 9°), concluding that stiffer lower-extremity landing patterns are likely to increase the magnitude of strain experienced by the ligaments of the knee joint. Similar to that of Huston *et al*., (2001), Lephart *et al*., (2002) reported that during single-leg and forward hop landing tasks, women demonstrated significantly reduced sagittal plane knee motion when compared to males. Women also exhibited significantly less relative peak torque for the lower-extremity musculature when compared to men, suggesting that reduced lower-extremity muscle strength may be related to the abrupt stiffening of the knee joint during jump-landing activities.

Based on these findings and those of others (Hewett *et al*., 2005; Lephart *et al.*, 2002; Pollard *et al*., 2010) it has been suggested that individuals (mainly women) who land with a greater extended-knee may employ a strategy of reliance on passive restraints in the frontal plane – a strategy thought to manipulate and/or reduce the rate of deceleration of the body's centre of mass. However, the greater frontal plane knee motion observed during extended-knee landings, coupled with the high impact loading forces and loading rates are key contributory factors associated with knee ligament injury (Hewett *et al*., 2002). Although the exact mechanism responsible for non-contact knee ligament injury continues to be debated, female athletes reportedly sustain a two- to eightfold greater rate of non-contact ACL injury in comparison to their male counterparts (Boden *et al*., 2010), indicating that the specific injury mechanism(s) is/are, in part, dependant on the physiological and anatomical factors specific to sex. Many explanations for the increased risk of injury to females when compared to males have been proposed; including increased knee valgus or abductor moments, generalised joint laxity, knee recurvatum, and hormonal effects of oestrogen on ligament laxity (Alentorn-Geli *et al*., 2009; Boden *et al*., 2000; Chappell *et al*., 2007; Hewett *et al*., 2007; Podraza *et al*., 2010). In addition, training-related factors such as jump-landing strategies are directly linked to the development of ligament injuries of the knee, specifically extended-knee landings, whereby studies indicate that landing with a reduced flexion at ground contact exhibits greater compressive forces on the cartilage and meniscus, also referred to as axial impulsive forces (i.e., compressive forces applied in a very short period of time) (Boden *et al*., 2010).

Meyer *et al*., (2008) demonstrated that excessive joint compressive loads > 3,000 – 7,000 Newtons at a knee extension angle of 30 degrees can lead to complete ACL rupture in human cadaver knees. This was the first study *in vitro* to demonstrate that excessive joint compressive loads can lead to complete ACL rupture, and it was hypothesised that the dominant factor leading to ACL failure is a compressive force orientated on the posterior tibial slope, resulting in posterior displacement of the femoral condyle on the tibial plateau. Additionally, Podraza *et al*., (2010) observed significantly greater magnitudes of GRF *in vivo* for those participants identified as landing within a 0-25° and 25-50° maximum knee flexion angle range (mean knee flexion: 17.1°, 35.4°, respectively), suggesting that individuals who produce maximum knee flexion angles ≤50° are likely to experience a rapid change in kinetic energy at ground contact, yielding greater magnitudes of mechanical loading at the foot-ground interface. Unlike conventional landings, whereby the muscular system acts as the primary shock absorption mechanism due to greater degrees of knee and hip flexion, the reduced energy dissipation during extended-knee landings characterised by a more erect lower-extremity landing posture, results in considerably greater GRFs along with greater magnitudes of mechanical loading on the limited contact area of specific knee components (Hewett *et al.,* 2005). In addition, Makinejad *et al.,* (2013) conducted an experimental and finite element analysis of knee-joint structure during extended-knee landing. From a combination of inverse dynamic analysis and computed tomography scans, the magnitude of mechanical load exhibited on the MSK structures of the knee joint during extended-knee landings resulted in serious deformation of the meniscus and cartilage, increased the risk of bone-to-bone contact, and generated compressive fracture loads capable of bone stress fracture of the lower-extremities (Bennell *et al.,* 1999; Makinejad *et al.,* 2013).

Although more conventional flexed knee landings are likely to exhibit greater knee extensor moments, along with greater quadriceps overload induced ACL strain (key factors linked to the ACL injury mechanism (Podraza *et al.*, 2010)), the majority of non-contact MSK knee injuries occur at near full knee-extension, whereby the reduction in kinetic energy dissipation of the lower-extremity muscles results in greater GRFs, loading rates, and tibial impact accelerations being absorbed by the connective tissue (i.e., tendons, ligaments, cartilage and meniscus) and bones of the lower-extremities, subsequently exposing both athletic and military men and women to an increased risk of connective tissue damage and bone injury (Podraza *et al.*, 2010; Zhang *et al.*, 2000). Greater peak loading profiles are expected in landings that demonstrate reduced sagittal plane hip and knee motion, i.e., extended-knee landings. However, as a consequence of this review it has become apparent that the magnitude of differences in the vGRF variable between flexed and stiff-leg landings are somewhat similar. For instance, in comparison to Wallace *et al*., (2010), whereby flexed knee 30cm and 60cm drop jumps resulted in a mean peak vGRF of 2.87 BWs and 3.82 BWs respectively, Seegmiller and McCaw (2003) reported similar peak vGRF for extended-knee 30cm (approx. 2.76 BW) and 60cm (approx. 4.12 BW) gymnastic landings. In addition, Verniba *et al*., (2017) also demonstrated similar magnitudes of peak vGRF for low (22cm, 2.28 BW approx.) and high (44cm, 2.71 BW approx.) stiff-leg (mean 52.2°) drop landings when compared to Wallace *et al*., (2010).

In addition to the vGRF variable, RFD (a derivative of the vGRF variable) is commonly reported as a measure of impact-related landing intensity (Jensen and Ebben, 2007; Puddle and Maulder, 2013), whereby these studies have used RFD (amongst others, namely joint reaction force) as a means of estimating the magnitude of stress placed on involved muscles, connective tissues and joints of the lower-extremity. It is suggested that when GRFs (and derivatives) are too great, the MSK system is unable to effectively disperse these forces, thus increasing the potential of impact-related landing injury. For instance, Puddle and Maulder (2013) investigated differences in the magnitude of vGRF and RFD between Parkour and traditional drop landing techniques, concluding that Parkour precision landings (peak vGRF=3.2 BW, RFD=83.3 Bw/s) and Parkour roll landings (peak vGRF=2.9BW, RFD=64.1Bw/s) were found to be significantly safer in comparison to traditional landing techniques (peak vGRF=5.2 BW, RFD=154.3 Bw/s) due to the significantly reduced intensity MSK structures of the lower-extremity are exposed to during these types of landings. In addition, Jensen and Ebben (2007) analysed the magnitude of vGRF and RFD across a series of plyometric exercises, whereby mean vGRF and RFD values ranged between 2.93BW for a single-leg jump and 3.91BW for a 61cm drop jump, and 424Bw/s for a 30cm squat jump and 975Bw/s for a 61cm drop jump, respectively. The magnitude of loading intensity as described previously is similar to those reported for a fundamental occupational military activity, known as British Army foot-drill. Connaboy *et al.*, (2011) indicated that the loading forces of common foot-drill are similar and, in some cases, greater than those reported for high level plyometric exercises (61cm drop jump). With this in mind, taking in to consideration that loading variables such as peak vGRF and RFD are commonly utilised as a means of estimating bone loading and potential bone injury (i.e., stress fracture), it is important that the intensity (i.e., GRF and RFD) of these high impact loading activities are well understood in terms of their risk to MSK injury and programmed in accordance with a periodised model of training.

These specific mechanical loading variables such as vGRF and RFD are defined as non-invasive measures of lower-extremity bone loading and have previously been utilised to quantify the magnitude of impact loading forces of British Army foot-drill in both male and male recruits (Carden *et al.*, 2015; Connaboy *et al.*, 2011). As a consequence of reduced lower-extremity muscle strength, lower bone mineral density, more slender bones (Izard *et al.*, 2017), and larger Q-angle ratios (Hewett et al., 2005), women are at a significant anatomical and biomechanical disadvantage for the majority of jump-landing activities. A key component of the non-contact ACL injury mechanism is the significantly larger Q-angles (≥20°) (Horton and Hall, 1989) reported during various jump-landing activities (handball, basketball, and gymnastics) and tasks (unilateral and bilateral depth drop and drop-jump landings), whereby greater knee valgus, originating in part from a larger Q-angle, contributes to a 4 to 6-fold greater risk of a non-contact MSK knee injury in women when compared to men (Podraza *et al.*, 2010). Furthermore, relative to the lower-extremity structure of women, research has refuted the notion that women have a wider pelvis than men (Ferber *et al.*, 2003), rather a larger pelvic width to femoral length ratio, owing to greater hip adduction, subsequently increasing angulation of the femur and resulting in a greater static (e.g. standing) and dynamic (e.g. jump-landing activities) genu valgus (e.g. frontal plane knee motion).

These anatomical characteristics reported for women are a primary aetiology for the discrepancies in altered movement patterns between men and women. For instance, Kernozek *et al.*, (2005) analysed lower-extremity landing patterns between men and women and reported that women, in comparison to men, exhibited significantly greater frontal plane motion of the knee and ankle joint during 60cm drop landings. It was also observed that women who produced smaller degrees of knee-flexion displacement exhibited greater knee valgus displacement, along with greater GRFs and loading rates. This observation is particularly germane to the female athlete and/or recruit during landing activities and considered a significant performance risk factor associated with the ACL injury mechanism (Kernozek *et al.*, 2005).

The majority of biomechanical studies investigating the risk of lower-extremity MSK injury, coupled with anatomical factors on performance have mainly focused on such activities and/or tasks as running (Crowell *et al.*, 2010), jumping (Hewett *et al.*, 2005), change of direction (Alentorn *et al.*, 2009), marching (Reynolds *et al.*, 1999; Windle *et al.*, 1999), load carriage

(Blacker *et al.,* 2010; Sell *et al.,* 2010), and extended-knee landings (Makinejad *et al.,* 2013; Yeow *et al.,* 2010). This is due to the magnitude of internal and external mechanical loading, coupled with potentially injurious lower-extremity biomechanical profiles, and their association with the high incidence rates of overuse knee ligament injuries, medial tibial stress syndrome, and bone stress fractures of the metatarsals and tibia (Wentz *et al.,* 2011). To date, research investigating potential lower-extremity biomechanical injury risk factors associated with the regimental movement patterns of foot-drill are scant. Therefore, additional empirical study is required as preliminary findings indicate that foot-drill may be a key contributing risk factor associated with bone injury and subsequent fracture (Carden *et al.,* 2016).

Mechanistically, a stress fracture is a form of fatigue damage, commonly associated with cyclic skeletal loading, occurring primarily in the weight-bearing lower-extremities or pelvic girdle (Jones *et al.,* 1993). The aetiology of stress fractures is multifactorial, with many risk factors implicated. However, cyclic exposure to high magnitudes of bone strain and strain rate are key contributory factors associated with the development of bone micro-damage (Warden *et al*., 2006), coupled with a sudden increase in military training load (Greeves, 2015). Consequently, the combination of repetitive submaximal/maximal impact loading produced at the foot-ground interface during running, loaded march and more recently, British Army foot-drill (Carden *et al.,* 2016), is recognised as a potential aetiological factor for lower-extremity stress fracture in recruits and athletes (Carden *et al*., 2016; Warden *et al*., 2006). Peak vGRF, RFD and tibial impact accelerations are defined as non-invasive measures of lower-extremity bone loading and have been utilised extensively by researchers to quantify the potential for developing such MSK overuse injuries as metatarsal and tibial stress fractures (Bennel *et al.,* 1996; Carden *et al.,* 2016).

The anatomical characteristics identified for female athletes and recruits, are key factors associated with significantly greater risk of bone stress fracture when compared to men. For example, Wentz *et al*., (2011) determined that women have a higher incidence rate of stress fracture for both athletic (men ~6.5% and women ~9.7%) and military (men ~3% and women ~9.2%) personnel, and that the primary risk factors observed for women involve reduced bone mineral density, narrower cortex, reduced lean muscle mass, and menstrual disturbances (Izard *et al.*, 2017); resulting in an overall reduced capacity to attenuate the potential injurious impact loading forces of foot-drill and other cyclic high impact loading activities. Based on these results, it is hypothesised that the magnitude of mechanical loading and risk of bone stress fracture reported for foot-drill (Carden *et al.*, 2016) may expose women to a greater risk of foot-drill related MSK injury when compared to men. However, additional empirical study is required to verify such hypotheses.

2.1.5 British Army Foot-Drill as a potential aetiological factor linked to lower-extremity musculoskeletal injury.

British Army foot-drill is a fundamental occupational activity, routinely practiced by recruits during the initial weeks of military training and throughout their military careers (Carden *et al*., 2015). The volume and frequency of foot-drill, ranging from 40min to two-hour sessions per day (Williams, 2005) is markedly higher for recruits in comparison to soldiers; performing many hours of foot-drill training during formerly timetabled sessions and whilst transiting through camp. Similar to other cyclic high impact loading activities, most notably, plyometric training (Self and Pain, 2001) and gymnastics landings (Seegmiller and McCaw, 2003), the defining performance characteristics of British Army foot-drill involve repeatedly and forcefully impacting the ground with an exaggerated heel-strike, and/or landing with the knee in an extended (straight-leg) position (Carden *et al.*, 2015).

Despite limited empirical foot-drill investigation, and the fact that previous studies are limited to only a select number of biomechanical variables, two prospective studies have quantified specific GRF variables of popular British Army foot-drill in trained soldiers, untrained recruits and recreational aged-matched civilians (Carden *et al*., 2015; Connaboy *et al*., 2011). Data specific to untrained personnel exhibited vertical GRF (vGRF), vertical rate of force development (vRFD), and peak tibial impact accelerations in excess of 4.6 bodyweights (BW), 536 BW/second (s), and 207.2 meters/sec^2 (m/s^2), respectively. Due to the magnitude of these loading values, it was suggested that foot-drill may be a key aetiological factor associated with the high incidence rates of lower-extremity MSK injury in male and female recruits during the initial weeks of basic training. Further observations from these data indicated that trained men when compared to trained women and untrained men, exhibited significantly greater magnitudes of vGRF, vRFD and peak tibial impact accelerations across all foot-drill, excluding marching. However, the magnitude of impact loading forces reported for marching were found to be similar to running speeds of 3 and 3.5m/s, equivalent to 1.6BW and 1.3BW, respectively (Carden *et al.*, 2015; Munro *et al.*, 1987).

The magnitude of external mechanical loading of foot-drill are comparable with data apparent in high level plyometric drills (Jensen and Ebben, 2007), a training modality more commonly associated with more experienced and better conditioned athletes (Connaboy *et al.*, 2011). For example, Wallace *et al.*, (2010) reported peak vGRF ranging between 2.87– 5.39 BW for 30-90cm depth drop landings in trained collegiate men. Similarly, Donoghue *et al.*, (2011) investigated peak vGRF and RFD profiles for a variety of jump-landing tasks, reporting peak vGRF in excess of 6 BW, however significantly lower peak RFD values when compared to foot-drill (range: 69- 134 BW/s). Bauer *et al*., (2001) quantified the force magnitudes and average RFD from a 61cm drop landing task, reporting peak vGRF and average RFD values in excess of 5.6 BW and 470 BW/s. It was also observed that time to peak vGRF (TTPvGRF) occurred between 0.01 and 0.04 seconds (secs). These results are somewhat similar to those reported by Donoghue *et al.*, (2011) whereby TTPvGRF was achieved between 0.051- 0.054 secs, reporting that these impact forces and loading rates may contain passive force components due to the short time taken to achieve impact loads similar to those reported for foot-drill (>5 BW) (Carden *et al*., 2015; Connaboy *et al*., 2011). According to research (Seegmiller and McCaw, 2003), an inverse relationship generally exists between the magnitude of peak vGRF and TTPvGRF, in that athletes and/or recruits who exhibit reduced sagittal plane hip and knee motion, along with high impact forces and loading rates are likely to experience relative loads over a shorter period of time. According to research (Donoghue *et al*., 2011; Ferber *et al.*, 2003; Fowler *et al*., 1997), the lower-extremity neuromuscular system requires approximately 50-70ms to actively respond to the landing stimulus and moderate the kinetic energy associated with impact, otherwise, impact loading forces achieved below this threshold may not be under sufficient neuromuscular control (Donoghue *et al*., 2011).

There is evidence in the literature indicating that insufficient and/or altered neuromuscular control of the lower-extremities, in particular the knee joint during the execution of potential injurious landing activities and/or tasks is a significant contributor to the development of knee ligament injury, and considered a key factor associated with the ACL injury mechanism (Hewett *et al*., 2000; Hewett *et al*., 2002). Lower-extremity joint connective tissue is likely to experience potentially hazardous vertical and 3-dimensional (3D) forces associated with deficiencies in dynamic joint stability to reduce the magnitude of internal and external stressors exhibited at ground-contact. Twist *et al*., (2008) reported a latent impairment in lower-extremity neuromuscular function proceeding a bout of plyometric training, as measured by static single-leg postural stability, whereby the upright stance of a healthy human is known to be unstable and requires a complex system of neuromuscular control loops to maintain a balanced upright position. Based on these results, it was concluded that lower-extremity neuromuscular control was significantly impaired 24 hours proceeding an acute bout of cyclic high impact loading activity. Although the precise mechanism(s) responsible for impaired neuromuscular control could not be established, it was suggested, in accordance with other research (Brockett *et al.*, 1997; Saxton *et al.*, 1995) that peripheral mechanoreceptors located in the muscle spindles and Golgi tendon organs of lower-extremity joints may have become desensitised as a result of the effects of the mechanical loading of plyometric training. Given the importance of these intramuscular receptors in controlling joint movement, position, and awareness, it is plausible that the accumulative mechanical loading of plyometric exercise may be responsible for changes in afferent receptor activity (signalling), resulting in deterioration of balance performance, and that the transient adaptations in neuromuscular acuity and proprioceptive sensibility may further exacerbate the risk of sustaining lower-extremity MSK injury (Deshpande *et al.*, 2003).

As stated previously, British Army foot-drill produces similar, and in some cases greater magnitudes of regimental lower-extremity loading, along with similar biomechanical movement patterns as those observed for extended-knee landings (e.g., knee flexion <90°) and high-level plyometric exercises (e.g., 30- 90cm unilateral and bilateral drop jumps, respectively). In addition, given the rigorous scheduling of foot-drill, i.e., 40min to two-hour sessions per day during the initial 1-4 weeks of Phase one (Carden *et al.*, 2015; Williams, 2005), it is plausible that the cyclic high impact loading forces of foot-drill may alter and/or impair lower-extremity neuromuscular function and joint proprioception of recruit populations. Unfortunately, the magnitude of mechanical loading and the effects on neuromuscular control systems from a bout of foot-drill training is currently unknown and necessitates further empirical study to elucidate these hypotheses. Nevertheless, understanding how specific neuromuscular control factors are influenced in response to the mechanical loading of certain military occupational activities (i.e., foot-drill) is crucial in the prevention of injury during subsequent training, whilst offering the greatest potential for interventional development and application in high-injury risk populations, namely, British Army recruits.

2.1.6 Lower-extremity musculoskeletal injury prevention and performance optimisation strategies: Effectiveness of implementation for military personnel.

The magnitude and severity of risk factors associated with lower-extremity injury in recruits has prompted researchers to investigate the efficacy of specific types of preventative measures and/or injury reduction strategies. However, due to logistical and financial limitations, many potential injury reduction strategies and/or interventions have never actively been implemented, with many requiring further scientific investigation, review, and/or group consensus before being recommended to military services. For example, based on expedited systematic reviews regarding prevention of physical training-related injuries in the military (Bullock *et al.,* 2010), more than twenty intervention strategies could not be recommended and/or approved for implementation due to a lack of evidence, poor quality of studies, or a balance of conflicting evidence (lack of homogeneity). Interventions demonstrating the strongest evidence are those that prevent MSK injuries as a result of reducing and/or strategically manipulating the magnitude of cyclic high impact loading forces of running, marching and load carriage (Greeves, 2015; Hill *et al.*, 1996; Kelly *et al*., 2000; Windle *et al.,* 1999).

It is well recognised that the majority of preventable overuse and traumatic lower-extremity injuries sustained by military personnel are due to the accumulative effect of weight bearing training-related activities and tasks (Bullock *et al*., 2010; Knapik *et al.,* 2004). A number of anatomical and biomechanical training-related lower-extremity MSK injury risk factors associated with the mechanical loading exhibited at the foot-ground interface can be modulated through training equipment, namely orthotics, shock absorbing insoles, and various types of in-service footwear. Despite conflicting evidence between studies regarding the effectiveness of shock absorbing insoles and/or specific types of shock absorbent footwear to reduce injury in military populations (Withnall *et al*., 2006; Hamill and Bensel, 1996), Schwellnus *et al.,* (1990) reported reductions in the incidence of total overuse injuries and tibial stress syndrome during 9-weeks of basic training from the implementation of a neoprene insole (shock absorbing foot orthotic) (Schwellnus *et al*., 1990). In addition, Windle *et al*., (1999) investigated the capacity of various shock absorbing insoles whilst wearing military boots during running and marching activities. It was reported that peak plantar pressures at heel strike during running and marching were significantly reduced when compared to the 'no insole' condition, and that factors such as shock absorbing insoles may reduce the magnitude of stress transmitted to the bone, thus potentially reducing the risk of stress fracture and other MSK injuries associated with the loading forces and pressures of running and marching.

Similarly, Hinz *et al*., (2007) reported significant reductions in the magnitude of peak plantar pressures of the second and fifth metatarsal head, and that the shock absorbing insoles were superior in terms of their ability to reduce plantar pressure when compared to the conventional insoles of combat boots worn by German Armed forces. However, these results are in contrast to those reported by Nigg *et al*., (1998) whilst wearing running shoes. These results indicate that the addition of shock absorbing insoles in footwear that already have inherent shock absorbing properties are likely to be less effective (Windle *et al.,* 1999). However, footwear limited in their ability to provide the wearer with substantial shock absorbency (mainly military boots), the use of a shock absorbing insole is considered valuable in terms of attenuating peak pressures and forces at foot-strike. In agreement with research (Windle *et al.,* 1999), Hinz *et* *al.*, (2007) concluded that with respect to the reduction in mechanical load across the planar surface of the foot, shock absorbent footwear and/or modified insoles may reduce the incidence of stress fractures associated with cyclic impact loading forces of running and marching. In consideration of the high impact forces and loading rates reported for foot-drill (Carden *et al*., 2015; Connaboy *et al*., 2011), it is hypothesised that the shock absorbing capabilities of current in-service footwear may not be sufficient in the attenuation of impact forces and loading rates representative of British Army foot-drill. However, further research is required to elucidate these claims.

Late and current in-service standard issue military footwear has succumbed to scrutiny regarding its functionality and capacity to provide military personnel with the necessary shock absorbency required to withstand the demands of occupational training-related activities and tasks. The majority of military footwear is designed to enhance performance and protect military personnel not only from repetitive mechanical loading exhibited at the foot-ground interface, but also from rough and uneven terrain, hot and cold environments, and moisture (Kaufman *et al.,* 2000). Most commercially available footwear are not designed and/or developed for the purpose of military life, however, may incorporate materials and/or design concepts that, if proven to be beneficial in terms of military performance and lower-extremity health of the recruit and/or soldier, could be adapted to a military in-service training shoe or boot (Hamill and Bensel, 1996).

In-service British Army boots have frequently been cited as a potential mechanism to the high rates of lower-extremity MSK overuse injuries reported for recruits (House *et al*., 2002), in part, due to their inability to attenuate the magnitude of mechanical loading at ground contact, whilst increasing risk of injury from limiting and/or altering the natural relative locomotion of the wearer. For instance, Sinclair and Taylor, (2014) indicted that whilst running at 4.0m/s, the black leather Army CB exhibited significantly greater impact forces, loading rates, ankle eversion, and tibial internal rotation when compared to an in-service physical training shoe, suggesting that the CB may contribute to such lower-extremity MSK injury pathologies as plantar fasciitis, patellofemoral pain, knee ligament injury, and medial tibial stress syndrome (Hinz *et al.*, 2012; Whittle, 1999). Similarly, in comparison to a neutral gym trainer, Nunns *et al*., (2012) reported significantly greater peak plantar pressures, impulse, loading rates, and ankle stiffness at the third metatarsal head (MT3) whilst running at 3.6m/s in Royal Marine combat assault boots. These results support the conjecture proposed by other empirical studies (Hamill and Bensel, 1996; House *et al*., 2002) regarding the inadequate or lack of shock absorbency and restrictive structural characteristics of British Army boots during frequently performed military activities and tasks.

To date, no empirical study has determined whether the shock absorbing properties of current in-service footwear, namely combat boots, parade boots, and training shoes, influence the cyclic high impact forces and loading rates of British Army foot-drill, and whether a specific type of in-service footwear can be utilised as a preventative strategy of lower-extremity stress fracture risk linked to the high impact forces of foot-drill (Carden et al., 2015; Connaboy *et al*., 2011). Athletes and recruits depend on the structural and cushioning properties of footwear to enhance and/or support specific locomotive performance, whilst attenuating and/or distributing the potential injurious mechanical loading experienced at ground contact. Therefore, it is important that validated and reliable models of footwear assessment are conducted to determine the influence military footwear has on measures of lower-extremity mechanical loading, and the potential of injury associated with the structural and shock absorbing characteristics of current in-service footwear.

The use of a more shock absorbent footwear during cyclic high impact loading activities is a plausible preventive strategy aimed at reducing the mechanical load exhibited on lower-extremity MSK structures during foot-drill training. However, as mentioned previously, high-quality evidence of its effectiveness in reducing mechanical loading and preventing training-related lower-extremity MSK overuse injuries is limited (Yeung *et al.,* 2011). Therefore, an alternative approach to injury prevention is to modify and/or strategically manipulate the lower-extremity biomechanics of specific movement patterns linked to an increased risk of injury. For example, marching as a risk factor for lower-extremity MSK overuse injury has been well documented (Hill *et al.,* 1996; Kelly *et al.,* 2000; Nunns *et al.,* 2012; Windle *et al.,* 1999). In context, research indicates that individuals who are anatomically shorter than the average recruit were forced to over-stride when marching to keep up with their respective platoon, resulting in the accumulation of large shearing and/or tensile stresses exhibited on the pubic rami by the adductors and hamstring muscles; subsequently resulting in pelvic stress fracture (Kelly *et al.,* 2000). Hill *et al*., (1996) reported a significant reduction in the occurrence of pelvic stress fractures in British Army recruits in response to a reduced stride length from a 30inch stride, to a 27inch stride. Furthermore, previous running studies have suggested that changes in step rate (increases) reduce lower-extremity joint loading, thus reducing risk of injury (Heiderscheit et al. 2011).

From simply altering the magnitude of step rate, authors were able to develop and employ a robust force attenuation strategy aimed at reducing the magnitude of running-related injuries, with an understanding that movement strategies that lessen the propagation of reaction forces up the kinetic chain, may reduce and/or prevent pelvic and lower-extremity MSK injuries (Podroza and White, 2009). By now, it is well understood that the forceful extended-knee landing of British Army foot-drill represents a substantial mechanical load, and has been implicated in the potential development of pelvic and lower-extremity stress fractures (Carden *et al*., 2015; Connaboy *et al*., 2011). It is hypothesised that the forceful extended-knee landings observed during foot-drill are responsible for the magnitude of these mechanical loads. Therefore, as a means of reducing risk of foot-drill related lower-extremity MSK injury in recruits, and based on previous empirical studies shown to successfully reduce rates of injury from modifications in the biomechanical movement patterns of marching and running (Hill *et al.*, 1996; Kelly *et al.*, 2000), it is plausible that modifying and/or strategically manipulating the lower-extremity biomechanics of specific foot-drills may aid in a reduction in load exhibited on the MSK system, and thus reducing the potential risk of foot-drill related MSK injury. However, currently no such modifications in the biomechanics of foot-drill can be recommended and/or implemented within the British Army, as the present thesis is yet to conduct a comprehensive empirical study investigating the potential 3D lower-extremity biomechanical risk factors associated with the violent extended-knee landing of British Army foot-drill.

3.0 Experimental Chapter 3– Study 1

3.1: Reliability of the Vertical Ground Reaction Forces of British Army Foot-drill in Age-Matched Civilian Men

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Experimental Chapter 3 – study 1: Published (Appendix 3a)Rawcliffe AJ, Simpson RJ, Graham SM, Psycharakis SG, Moir GL, and Connaboy C. Reliability of the kinetics of British Army foot drill in untrained personnel. *J Strength Cond Res*, 31(2): 435–444, 2017

3.2 Introduction

British Army foot-drill is a fundamental military occupational activity, routinely practised by recruits during BMT, and utilised to enhance discipline, co-ordination, and body awareness (Chandler, 1994). Each foot-drill contains a number of key performance markers which define that particular foot-drill. For example, quick march (QM) requires marching at two paces per second whilst repeatedly impacting the ground with an exaggerated heel strike. Other regimented movements performed while marching involve impacting the ground with an exaggerated heel strike onto the surface of the ground. Foot-drills such as SaA, SaE and halt, involve flexing at the hip to 90° followed by an forceful stamping of the foot onto the ground, landing with the knee in an extended (straight-leg) position.

Selective British Army foot-drill has previously been shown to produce high impact loading forces in soldiers who have been trained in foot-drill (trained) (Carden *et al.*, 2015) and recruits who have not (untrained) (Carden *et al.*, 2015; Connaboy *et al.*, 2011). To date, only two biomechanical studies have quantified the impact loading forces of selected foot-drills in untrained personnel. Using the mean of 3 trials, Carden *et al.*, (2015) reported high vGRF for march, halt, SaA, and SaE; ranging from 1.3 BW to 4.4 BW, and high vRFD; ranging from 7 BW/s to 499 BW/s. Similarly, Connaboy *et al.*, (2011) reported mean vGRF (3.06 ± 1.16 BW) and vRFD (187.7 ± 94.2 BW/s) values for the same foot-drills using the mean of 5 trials. Both studies reported impact loading forces similar to those experienced during high level plyometric exercises; a training modality more commonly associated with highly trained athletic populations due to the high risk of lower-extremity injury associated with the cyclic high impact forces experienced by the MSK system (Baechle and Earle, 2008). Based on the high loading profiles of foot-drill, it was suggested that foot-drill may be a key aetiological factor associated with the high incidence rates of lower-extremity MSK injury in recruits.

Although Connaboy *et al.,* (2011) and Carden *et al.,* (2015) investigated the impact loading forces of foot-drill, the number of trials utilised to accurately assess GRF variables of foot-drill was selected arbitrarily, with no justification regarding the requirement for any familiarisation sessions and/or trials prior to data collection, and no rationale for the mean number of trials used to represent the forces achieved. Using too few trials to assess biomechanical variables of foot-drill may not reliably represent the individual's true performance. Consequently, the stability and reproducibility of mean values could be questioned as the magnitude and influence of variability within previous foot-drill data was not calculated. The sources of error that contribute to the overall reliability of the measure primarily consist of biological, and technological – with a reliable test characterised by low within-subject variation (CVte% <10) and high test-retest correlation (ICC >0.75) (Hopkins *et al.,* 2001). Analysing the magnitude of a systematic bias, within-subject variation, and test-retest correlation of foot-drill will provide valuable information that will better inform future biomechanical studies of foot-drill in terms of the number of trials required to obtain accurate and stable measures of foot-drill performance, along with the requirement of any familiarisation sessions and/or trials prior to analysing the impact loading forces of foot-drill within an age-matched civilian male population.

Therefore, the aims of the present study were three fold: (i) determine the magnitude of any systematic bias within session(s) and between trial(s), (ii) establish the within-subject variation of key biomechanical variables; and (iii) analyse the test-retest reliability to indicate the number of sessions and/or trials required to maximise the possibility of identifying changes in the GRFs of British Army foot-drill between different conditions, and over time. Similar to other locomotor and landing tasks, it was hypothesised that several trials would be necessary to achieve high levels of performance stability during British Army foot-drill, and that familiarisation sessions and/or trials would be required prior to collecting stable foot-drill biomechanical data. In addition, it was hypothesized that as random error decreased, test-retest correlation scores would increase when using the average of multiple trials.

3.3 Methods

3.3.1 *Sample size power analysis and participants*

Due to a lack of available resources and time it was not possible to collect pilot data prior to this study. Sample size was estimated using G*Power software (v3.1.9.2, Germany) for a series of repeated measures ANOVAs (within-interaction) to statistically determine systematic bias between sessions (3 levels) and determine any significant differences in the magnitude of peak vGRF and vRFD between foot-drills (5 levels). Only a standard G*Power function was used to determine sample size. With an estimated 20% probability (power=.80) of a type II error, an alpha level set at .05, and an estimated effect size of 0.3 (medium-to-large), it was estimated that a sample size of 20 male participants would be sufficient to detect differences between sessions, with only 15 male participants required to detect a significant difference from zero in GRF variables (vGRF and vRFD) between foot-drills. Only 15 participants were successfully recruited for this study, therefore when detecting differences between sessions (i.e., systematic bias), this part of the analysis was expected to be slightly underpowered.

Fifteen recreational active healthy males (mean ± SD; age 22.4 ± 1.7 years; height 1.77 ± 5.6m; body mass 83 ± 8.7kg) with no pathological lower-limb, hip or spinal conditions were recruited for this study. Study participants were recreationally active, taking part in moderate physical activity and/or sport a minimum of two-to-three times per week over the previous three years (Decker *et al.,* 2003). Ethical approval for the present study was gained from the Edinburgh Napier University ethics committee. Written informed consent was obtained from each participant prior to data collection. Study participants were defined as “novice drill performers” as they did not obtain previous experience of performing British Army foot-drill training prior to this study.

3.2.2 *Experimental Design*

A within-participant repeated-measures study design was employed to assess measures of reliability, establishing the requirement for familiarisation sessions and/or trials to determine within-subject variation and test-rest reliability.

3.2.3 *Experimental Procedures*

During three 90-min testing sessions, ten acceptable trials (James *et al.,* 2007) of five British Army foot-drills involving; SaA, SaE, QM, halt and a normal walking gait were collected from each participant (Appendix 1). Acceptable trials were those that conformed to the key performance markers as described in the British Army Drill Instructors Manual (BADIM, 2009). Furthermore, if obvious adjustments in foot-drill movements were identified, those trials were discarded and repeated. Ten trials of a normal walking gait were also collected on each day of testing as to compare with the GRF variables of QM. Foot-drill data were collected on three non-consecutive days, with 24-hours separating each data collection session. Twenty-four hours prior to each participant's first data collection session, a qualified British Army drill sergeant was recruited to teach and perform the key performance markers of the four specific British Army drills chosen for analysis. The lead researcher was also taught how to perform drill to monitor foot-drill performance of each participant throughout data collection. All three test sessions were conducted at the same time of day and performed under the guidance of the same instructor. Participants were asked to avoid practicing foot-drill throughout the testing period and to refrain from strenuous, high impact loading activity 24-hours prior to each test session.

Each participant was fitted with a size-specific pair of Hi-Tech Silver Shadow^{TM} training shoes (TR) to reduce the influence of different shock absorbing properties of different footwear on force plate data (Dixon and Stiles, 2003). Each participant performed a standardised 10-min warm up whilst wearing the TR, consisting of 5-min on a cycle ergometer (Monark Exercise AB, 824-E, Sweden), cycling between 60-70 revolutions per minute under a 1.5kg breaking force, followed by various dynamic lunging and squatting movements prior to each test session (Puddle and Maulder, 2013). Foot-drill and walk were performed on two embedded (side-by-side) Kistler force plates (Kistler Instruments AG, 9281CA, Switzerland), interfaced with BioWare 3.2.5 software to record and analyse the vGRF and vRFD of each foot-drill and walk. The force plate was set at a sampling frequency of 1000Hz with a 3-sec capture period (Ebben *et al.,* 2010). Force data were collected using an eight-channel 16-bit analogue to digital converter (Qualisys, 8128, Sweden). The vGRF values were normalised to bodyweight (BW) to enable direct comparison across participants and with other studies.

Representative of an entry-level recruit, foot-drill was a novel task for all participants prior to data collection. Therefore, during the initial testing session only, study participants were given 15-min to practice the five foot-drills prior to data collection and become familiar with the TR. Study participants were given a 3-sec countdown prior to the execution of each foot-drill (figure 3.0). Specific to QM, participants were instructed to QM with an exaggerated heel strike across the 10-m walkway. During the execution of SaA, SaE, and halt, study participants were instructed to flex their hip to 90° and land with an forceful stamp onto the surface of the force plate with the knee in an extended position. Study participants kept their head and eyes forward to minimise visual fixation (targeting) of the force plate during all foot-drill trials (Challis, 2001).

Figure 3.0 represents the orientation of the force plate relative to the location of the participant and the active limb impacting the force plate during a SaE foot-drill manoeuvre.

Active limb

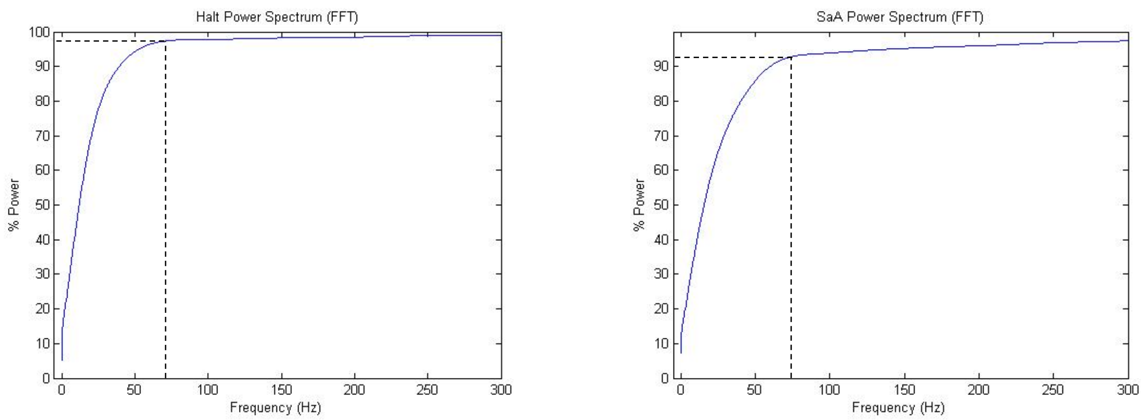
Active Kistler force plate

A 90-sec recovery period between each of the 10-trials and a 15-min recovery between foot-drills was employed to reduce the risk of fatigue on foot-drill performance (Baechle and Earle, 2008). Ten trials were collected for each of the five foot-drills during each of the three test sessions. A total of 30-trials were analysed for each of the five foot-drills over three test sessions. Accumulatively, data from 150 (acceptable) trials were collected and analysed per participant. To enhance the internal validity of the present study whilst minimising an order effect, foot-drill was counterbalanced using a randomised sort function in Excel for each participant across all three testing sessions. A comprehensive description of each foot-drill analysed within the present study can be found in the BADIM. The foot which strikes the force plate during each of the foot-drills is referred to as the active limb with the opposite limb referred to as the support limb.

Foot drill	from QM	from SaE	from SaA	active Limb
QM				*R*
Halt	*X*			*R*
SaA		*X*		*L*
SaE			*X*	*L*
Walk				*R*

Table 3.0 The regimented foot-drill manoeuvres completed from their respective foot-drill, identified by *X*. The active limb refers to the left (L) or right (R) limb that is used in each foot-drill (BADIM, 2009; Carden *et al*., 2015).

Walking, performed by each participant at their preferred speed, was measured in meters per second and was standardised for each individual participant using timing gates (Fusion sport, SmartSpeed, Australia) located at 0-m, 5-m and 10-m along the 10-m walkway. The velocity of walking was monitored across each test session and a maximum deviation of +/- 5% was allowed from each participants walking velocity (Rosendale *et al.*, 2003). Invariably, force plate analysis of impact related activity is subject to high frequency noise associated with vibrations at the foot-ground interface (Roewer *et al.*, 2014). Thus, based on power spectrum analyses from the Fast Fourier Transform (FFT) function, ensuring that 90% of the signal content was retained (Winter, 2009), vGRF (including vRFD) data were filtered with a low pass 4th order zero-lag (single bi-directional) Butterworth filter with a cut-off frequency (fc) ranging between 25hz (walk) and 70Hz (SaA, SaE, Halt, QM) (figure 3.1).



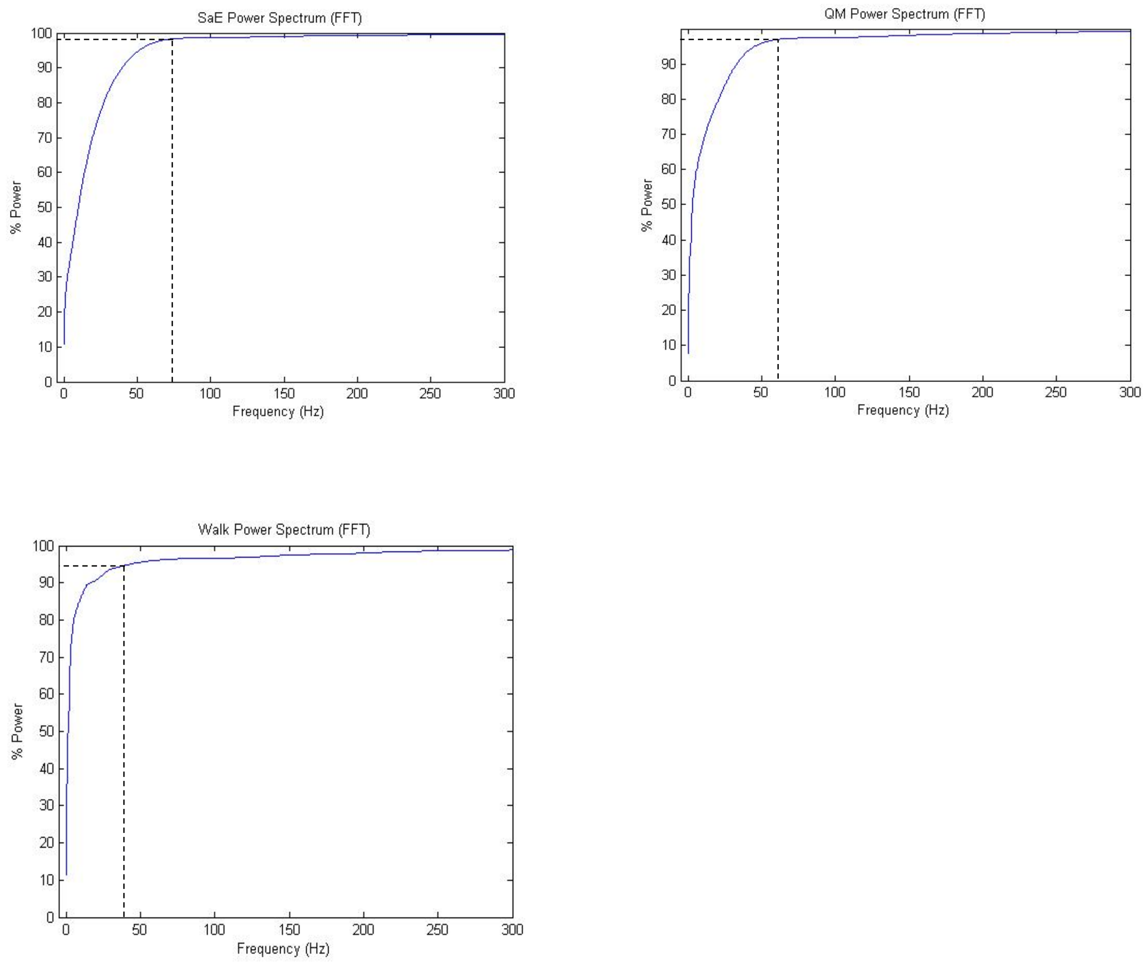


Figure 3.1: Exemplar power spectrum plots for each foot-drill illustrating respective fc. Depicts the (exemplar) frequency spectrums for each foot-drill as a function of FFT via Matlab. The respective fc for each foot-drill was determined as the point when the magnitude of the frequency content began to level out – illustrated by the intersection of the vertical and horizontal dashed line.

The BW normalized vGRF was calculated as,

$$BW_{Norm} = \frac{\mathrm{Fz}peak}{BW} \qquad \text{(Eq 3.1)}$$

where, BW_{Norm} is the normalized vGRF expressed in BW, Fz*peak* is the peak vertical ground reaction force measured in Newtons (N), and BW is the participant's bodyweight expressed in N determined from the force plate. The kinetic variables of interest were defined and calculated as follows: Fz_{peak} - defined as the highest (Peak) vertical ground reaction force (measured in N) of each foot-drill.

Time to Fz*peak* - defined as the time to reach Fzpeak expressed in milliseconds (ms).

$$Time\ to\ Fzpeak = \mathrm{t}max - \mathrm{t}min \qquad \text{(Eq 3.2)}$$

where, t*min* represents the time point of the initial onset of vGRF and t*max* represents the time point of Fz*peak*, measured in sec. The initial onset of vGRF was defined as when the vGRF component exceeded a threshold of 20N (Molloy *et al.*, 2012). The vRFD was calculated as;

$$RFD = \frac{\Delta F}{\Delta T} \qquad \text{(Eq 3.3)}$$

where, v*RFD* is the rate of force development measured in N per second (N/s), *ΔF* represents the change in force measured in N and, *ΔT* represents the change in time measured in sec.

vRFD was normalised relative to participant's BW calculated as,

$$Norm\ vRFD = \frac{RFD}{BW} \qquad \text{(Eq 3.4)}$$

where, *Norm vRFD* is the vRFD normalised to the participant's bodyweight, measured in N.

3.4 Statistical Analysis

Prior to calculating systematic bias, within-subject variation and, test-retest correlation, each of the biomechanical variables was examined for normality (Atkinson and Nevill, 1998). The vGRF and vRFD data violated the assumption of normality, thus a log transformation in SPSS 20 using 100x natural logarithm of the observed value was conducted (Atkinson and Nevill, 1998; Hopkins, 2000). Systematic bias and differences in vGRF and vRFD between foot-drills was determined using a repeated-measures analysis of variance (RM ANOVA) with Bonferroni adjusted multiple comparisons conducted for each of the predictor variables (vGRF and vRFD) for each of the foot-drills. This analysis was utilised as a means to determine whether the magnitude of difference among the mean values for each session (n = 3) and trial (n = 10) was statistically significant. Alpha (α) value was set at 0.05. To isolate the effects of the between-session and within-session systematic bias, data that demonstrated a systematic bias was removed from further reliability analysis, with the remaining data used in the subsequent reliability analyses (within-subject variation and test-retest correlations). The within-subject variation was calculated for the remaining foot-drill trials that did not contain any systematic bias. The within-subject variation was reported for the remaining trials as both the typical error and coefficient of variation of the typical error (CV_{te}). The within-subject variation was expressed as a percentage of the coefficient of variation of the typical error (CV_{te}%). The CV_{te}% was calculated using the methods proposed by Hopkins, (2000) and were calculated as:

$$CVte\% = \left(\frac{\mathrm{TE}n}{\mathrm{M}n}\right) X\ 100 \qquad \text{(Eq 3.5)}$$

where TE_n is the typical error of n trials and M_n is the mean value from the same n repeated trials.

Test-retest reliability was calculated for all acceptable trials for each foot-drill and evaluated using the ICC (Model 3,1) (Atkinson and Nevill, 1998; Hopkins *et al.*, 2000). The stability of the variation in each predictor variable was assessed using methods proposed by James *et al.*, (2007). Initial ICC was calculated for all data to establish maximum ICC values and 95% confidence intervals (CI). An iterative process was then conducted by which ICC values were calculated for the initial 3-trials up to the maximum number of acceptable trials per foot-drill (Hopkins *et al.*, 2001). To assess the stability of each predictor variable, the minimum number of trials required to achieve maximum levels of ICC were calculated. Furthermore, to determine the minimum number of trials necessary to achieve a stable representation of the variation within each predictor variable, the number of trials required to achieve an ICC value of 0.75, 0.80 and 0.85 were calculated.

3.5 Results

3.5.1 *Systematic Bias*

As only 15 participants were recruited for this study, a post hoc power calculation (G*Power) was conducted and indicated a power of 0.67, indicating that for detecting significant differences between sessions this part of the analysis was underpowered.

Statistically significant between-session differences were found for the vGRF and vRFD in the following foot-drills: vGRF SaA condition ($F_{2, 28} = 9.603$, $P = 0.001$, $\eta_p^2 = .407$), vRFD SaA condition ($F_{2, 28} = 7.152$, $P = .003$, $\eta_p^2 = .338$), vGRF SaE condition ($F_{2, 28} = 7.242$, $P = .003$, $\eta_p^2 = .341$), and the vRFD SaE condition ($F_{2, 28} = 9.615$, $P = .001$, $\eta_p^2 = .407$). Follow up Bonferroni adjusted comparisons indicated a systematic bias between session 1 and the two remaining testing sessions for the vGRF SaA and SaE, and vRFD SaE conditions, with the vRFD SaA condition illustrating a systematic bias between session 1 and 3 only (figure 3.2). No further statistically significant between-session systematic bias was observed for the remaining conditions and may be attributed to the insufficient power of the study.

Statistically significant within-session (between-trial) differences were found in the vGRF in the following foot-drills: vGRF SaA ($F_{9, 126} = 6.133$, $P < 0.01$, $\eta_p^2 = .305$), vGRF SaE ($F_{9, 126} = 4.408$, $P < 0.01$, $\eta_p^2 = .239$), and vGRF halt ($F_{4.9, 68.7} = 2.406$, $P = .046$, $\eta_p^2 = .147$). Bonferroni comparisons revealed a systematic bias in trials 10 for the aforementioned conditions. No further statistically significant within-session systematic bias was observed for the remaining conditions.

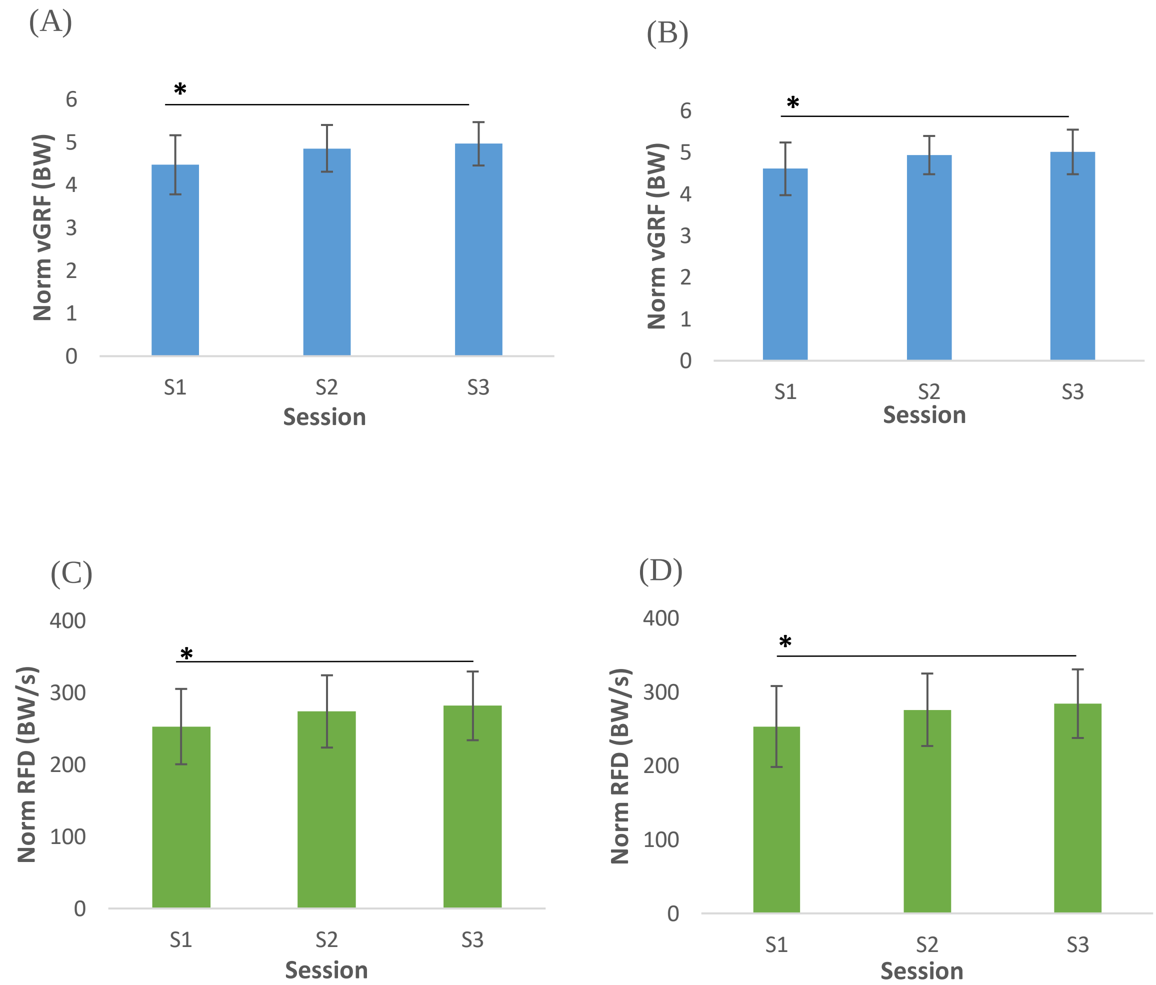


Fig 3.2: Reliability (systematic bias) of the vGRF and vRFD SaA and SaE condition. Mean values for session (1 – 3) for vGRF SaA (A), vGRF SaE (B), vRFD SaE (C), and vRFD SaA (D).*Statistically significant difference ($P<0.05$). Values are session means; bars are SD.

3.5.2 *Within-Subject Variation*

Table 3.1 illustrates the magnitude of the $CV_{te}\%$ found within repeated measurements of foot-drill data. Data were expressed in absolute (preceded by ±) or ratio form (preceded by x/÷) depending on whether the assumption of normality was violated, and log transformation was conducted (Atkinson and Nevill, 1998; Hopkins, 2000). Figure 3.3 indicates the magnitude of $CV_{te}\%$ relative to the vGRF variable, showing a mean $CV_{te}\%$ ≤10% across all foot-drills (mean±SD = halt: 6.8 ± 0.3, QM: 9.2 ± 0.72, SaA: 5.8 ± 0.31, walk: 2.9 ± 0.3, SaE: 6.3 ± 0.32) demonstrating low within-subject variability indicating good reliability. Note however, that in figure 3.3b the vRFD variable expressed a mean $CV_{te}\% \geq 10\%$ (excluding SaE) across foot drills (mean ± SD = halt: 15.9 ± 1.93, QM: 47.3 ± 6.37, SaA: 18.1 ± 4.4, walk: 56.9 ± 4.9, SaE: 9.9 ± 1.0) demonstrating high levels of within-subject variability (Hopkins, 2000).

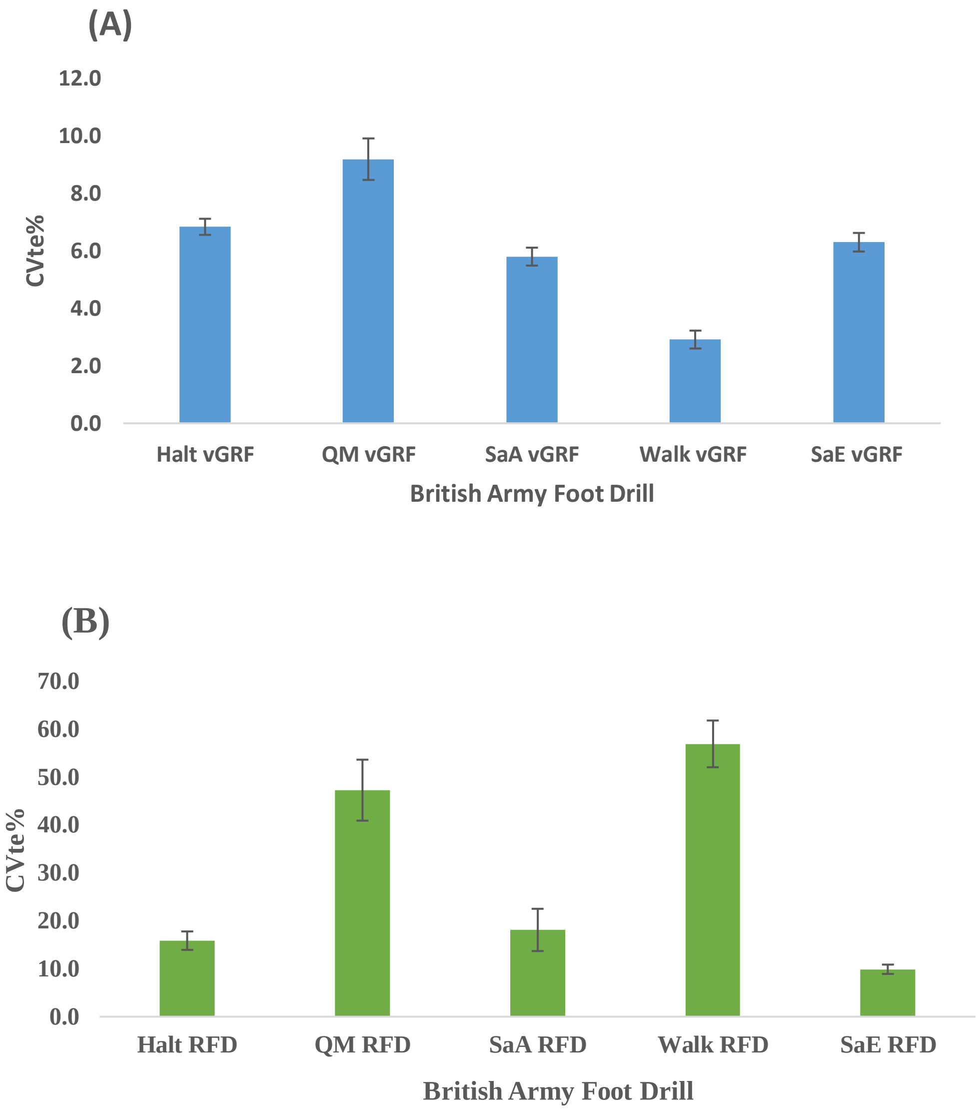


Figure 3.3: Within-Subject variation expressed as a coefficient of variation (CV) and expressed as a percentage of the typical error ($CV_{te}\%$) of the vGRF and vRFD across all foot drills (A): vGRF WS variation, (B): vRFD WS variation for all foot drills. Values are session means; bars are SD.

Vertical ground reaction force and vertical rate of force development foot-drill Within-Subject variation.

Variable (Units or Ratio)	Trials (*n*)		TE(*n*)	TE_{LCL}	TE_{UCL}		%CV	CV_{LCL}	CV_{UCL}
Halt vGRF	3	x/÷	1.08	1.06	1.11	x/÷	7.5	5.9	11.2
	4	x/÷	1.07	1.06	1.09	x/÷	7.0	5.6	9.5
	5	x/÷	1.07	1.05	1.09	x/÷	6.6	5.5	8.5
	6	x/÷	1.07	1.06	1.09	x/÷	6.9	5.8	8.6
	12	x/÷	1.07	1.06	1.08	x/÷	7.0	6.3	8.3
	18	x/÷	1.07	1.06	1.08	x/÷	6.8	6.2	7.8
	24	x/÷	1.07	1.06	1.07	x/÷	6.6	6.2	7.4
Halt RFD	3	x/÷	1.23	1.18	1.36	x/÷	23.5	18.0	35.9
	4	x/÷	1.02	1.16	1.27	x/÷	19.8	15.8	27.3
	5	x/÷	1.18	1.15	1.23	x/÷	18.0	14.7	23.5
	6	x/÷	1.17	1.14	1.21	x/÷	16.7	14.0	21.1
	12	x/÷	1.15	1.13	1.17	x/÷	14.7	13.0	17.1
	18	x/÷	1.16	1.15	1.18	x/÷	16.1	14.5	18.1
	24	x/÷	1.16	1.14	1.17	x/÷	15.5	14.2	17.2
	30	x/÷	1.14	1.13	1.16	x/÷	14.3	13.2	15.6
QM vGRF	3	x/÷	1.1	1.08	1.15	x/÷	10.0	7.8	15.0
	4	x/÷	1.11	1.08	1.14	x/÷	10.5	8.5	14.3
	5	x/÷	1.11	1.09	1.14	x/÷	10.6	8.7	13.7
	6	x/÷	1.1	1.08	1.12	x/÷	9.9	8.3	12.4
	12	x/÷	1.1	1.09	1.12	x/÷	10.1	8.9	11.7
	18	x/÷	1.09	1.08	1.1	x/÷	9.1	8.2	10.2
	24	x/÷	1.09	1.08	1.09	x/÷	8.6	7.9	9.5
	30	x/÷	1.08	1.08	1.09	x/÷	8.3	7.7	9.1
QM RFD	3	x/÷	1.55	1.41	1.9	x/÷	55.2	41.2	89.8
	4	x/÷	1.56	1.43	1.81	x/÷	55.6	43.3	80.7
	5	x/÷	1.6	1.48	1.82	x/÷	59.8	47.8	82.0
	6	x/÷	1.61	1.49	1.8	x/÷	60.7	49.4	79.9
	12	x/÷	1.49	1.43	1.58	x/÷	49.2	42.7	58.1
	18	x/÷	1.44	1.4	1.51	x/÷	44.3	39.5	50.5
	24	x/÷	1.41	1.37	1.46	x/÷	41.0	37.2	45.8
	30	x/÷	1.41	1.38	1.45	x/÷	41.1	37.7	45.4
SaA vGRF	3	x/÷	1.06	1.05	1.09	x/÷	6.3	4.9	9.4
	4	x/÷	1.06	1.05	1.08	x/÷	6.0	4.8	8.1
	5	x/÷	1.06	1.05	1.08	x/÷	6.4	5.3	8.2
	6	x/÷	1.06	1.05	1.08	x/÷	6.2	5.2	7.7
	12	x/÷	1.05	1.05	1.06	x/÷	5.5	4.8	6.3
SaA RFD	3	x/÷	1.26	1.20	1.40	x/÷	26.0	19.9	40.0
	4	x/÷	1.28	1.22	1.39	x/÷	28.2	22.4	39.4
	5	x/÷	1.24	1.20	1.32	x/÷	24.4	20.0	32.2
	6	x/÷	1.22	1.18	1.28	x/÷	22.1	18.4	28.0
	12	x/÷	1.16	1.14	1.18	x/÷	15.9	14.0	18.4
	18	x/÷	1.14	1.13	1.16	x/÷	14.3	12.9	16.1

Walk vGRF	3	x/÷	1.02	1.02	1.03	x/÷	1.9	1.5	2.9
	4	x/÷	1.02	1.02	1.03	x/÷	2.1	1.7	2.8
	5	x/÷	1.03	1.02	1.03	x/÷	2.5	2.1	3.3
	6	x/÷	1.03	1.02	1.03	x/÷	2.8	2.3	3.4
	12	x/÷	1.03	1.03	1.04	x/÷	3.1	2.4	3.3
	18	x/÷	1.03	1.03	1.03	x/÷	3.1	2.7	3.5
	24	x/÷	1.03	1.03	1.03	x/÷	3.1	2.7	3.4
	30	x/÷	1.03	1.03	1.03	x/÷	3.1	2.8	3.4
Walk RFD	3	x/÷	1.45	1.34	1.72	x/÷	45.2	34	72.2
	4	x/÷	1.5	1.39	1.71	x/÷	49.6	38.8	71.4
	5	x/÷	1.48	1.38	1.64	x/÷	47.6	38.3	64.4
	6	x/÷	1.49	1.4	1.64	x/÷	49.2	40.3	64.1
	12	x/÷	1.66	1.57	1.78	x/÷	65.7	56.6	78.3
	18	x/÷	1.59	1.53	1.68	x/÷	59.3	52.7	68.1
	24	x/÷	1.57	1.52	1.64	x/÷	57.4	51.8	64.5
	30	x/÷	1.55	1.51	1.61	x/÷	55.4	50.6	61.4
SaE vGRF	3	x/÷	1.06	1.05	1.09	x/÷	5.9	4.6	8.7
	4	x/÷	1.05	1.04	1.07	x/÷	5.4	4.4	7.3
	5	x/÷	1.06	1.05	1.07	x/÷	5.8	4.8	7.5
	6	x/÷	1.06	1.05	1.08	x/÷	6.1	5.1	7.6
	12	x/÷	1.07	1.06	1.08	x/÷	6.6	5.9	7.6
	18	x/÷	1.06	1.06	1.07	x/÷	6.4	5.8	7.1
SaE RFD	3	±	35.4	27.8	51.6	±	13.0	10.18	21.9
	4	±	31	25.2	41.5	±	10.9	8.05	17.4
	5	±	29	24.1	37	±	10.4	7.76	16.7
	6	±	28.7	24.3	35.5	±	10.5	7.39	15.9
	12	±	26.9	23.9	30.8	±	9.8	7.03	15.1
	18	±	25.7	23.4	28.7	±	9.2	6.52	14.0

Table 3.1: For the sake of brevity, a reduced number of trials were reported highlighting the initial changes in WS variation with the inclusion of additional single trials, and to highlight the extent of change in WS variation calculated from a greater number of trials. TE, typical error for *n* cycles; LCL, lower confidence limit; UCL, upper confidence limit; random error is represented in absolute form; ±, random error is represented in ratio form; x/÷. The vGRF and vRFD foot-drill data found to obtain a SB are not presented in table 3.2, explaining the variation in the total number of trials presented between foot-drills.

3.5.3 *Test-retest reliability*

Table 3.2 illustrates the level of performance stability achieved for all foot-drills across the vGRF and vRFD variable. The maximum ICC value was recorded for the walk vGRF condition (ICC = 0.92) with maximum ICC values ranging from 0.61 to 0.92. The number of trials required to achieve maximum ICC values ranged from 3 to 28 trials (mean ± SD = 12.9 ± 9.3 trials) across both predictor variables. With the exception of the vGRF SaE, vRFD SaA and halt conditions, all remaining foot-drills achieved an ICC value ≥0.75 from 3 to 10 trials (mean ± SD = 4.0 ± 2.6). The vGRF variable illustrated greater levels of performance stability (mean ± SD, ICC = 0.835 ± 0.093) when compared with the vRFD variable (mean ± SD, ICC = 0.73 ± 0.79), suggesting that the vGRF variable could be defined as a more reliable measure with which to accurately determine changes in foot-drill performance. The maximum number of trials required to achieve an ICC of 0.80 from the remaining two testing sessions and the initial eight-trials from each session ranged from 3-to 16-trials (mean ± SD = 6.8 ± 5.5). Only the QM and walk vGRF conditions achieved an ICC ≥0.85 from a total of 3 trials (mean±SD = 3.0 ± 0.0 trials).

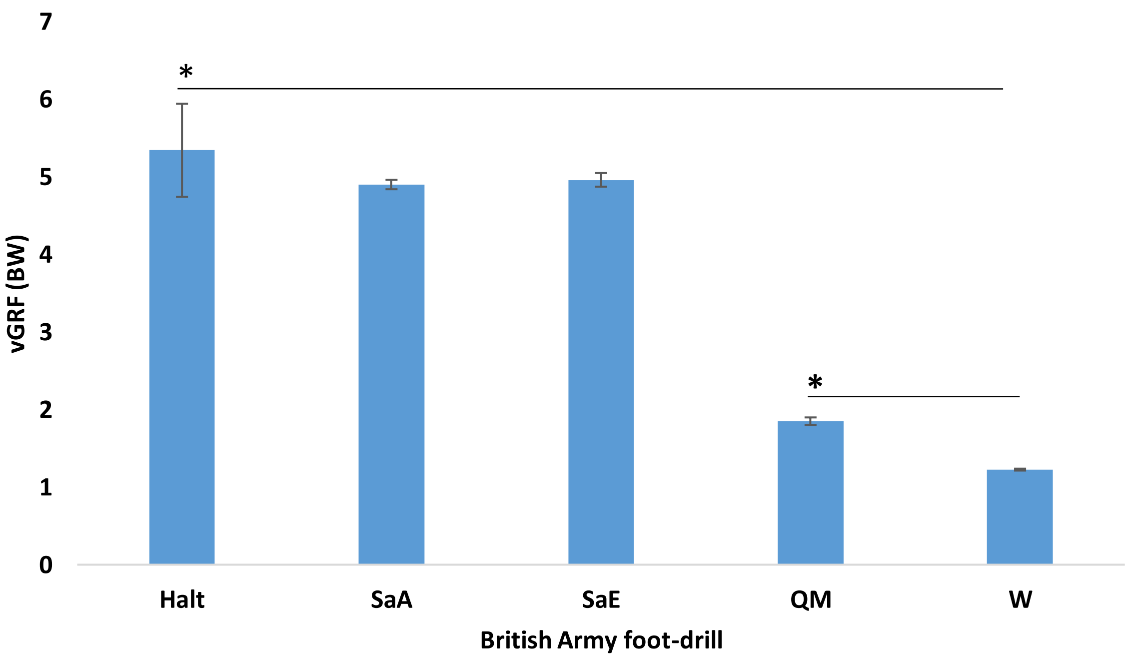
vGRF and vRFD foot-drill ICC results

Variable (Unit or Ratio)	ICC Maximum (*n* cycles)	ICC	ICC (95%LCL)	ICC (95% UCL)	ICC 0.75 (*n* cycles)	ICC 0.80 (*n* cycles)	ICC 0.85 (*n* cycles)
Halt vGRF	5	0.821	0.659	0.929	3	4	--
Halt vRFD	15	0.673	0.503	0.843	--	--	--
QM vGRF	28	0.912	0.843	0.963	3	3	3
QM vRFD	28	0.802	0.677	0.911	3	20	--
SaA vGRF	8	0.810	0.670	0.920	3	8	--
SaA vRFD	16	0.621	0.446	0.810	--	--	--
Walk vGRF	3	0.924	0.818	0.972	3	3	3
Walk vRFD	3	0.791	0.552	0.919	3	--	--
SaE vGRF	4	0.699	0.456	0.872	--	--	--
SaE vRFD	19	0.764	0.622	0.892	10	--	--
Mean (SD)	12.9(9.3)				4.0(2.6)	7.6(7.2)	3.0(0.0)

Table 3.2: Represents the maximum number of trials required to achieve poor, moderate and strong levels of test retest reliability; -- indicates that the ICC value was never achieved. The minimum number of trials required to achieve ICC levels of 0.75, 0.80 and 0.85 were also calculated. Only the walk and QM vGRF condition illustrated an ICC >0.90.

3.5.4 *Vertical Ground Reaction Force and Vertical Rate of Force Development of Foot-drill*

Post hoc power calculations using G*Power were conducted and confirmed that the total sample size of 15-male participants provided sufficient power (0.82) for this analysis. A statistically significant main effect was observed between foot-drills for the vGRF ($F_{2.2}$ =556.7, p <.001, η_p^2 = 0.96) and vRFD variable ($F_{1.9}$ =372, p <.001, η_p^2 = 0.96) both demonstrating large effect sizes (large η_p^2 effect >0.25) as per Pearson's correlation criteria (Cohen, 1973). Further post hoc analysis demonstrated significant differences between all foot-drills for the vGRF and vRFD variable (p<.001) apart from SaA vs SaE foot-drill (p = 1.00, 95%CI = -0.319 – 0.173) (Figure 3.4). Similar to previous foot-drill research (Connaboy *et al.*, 2011), the halt foot-drill demonstrated the greatest impact forces (mean: 5.4 BW) and loading rates (mean: 320.4 BW/s) when compared to all other foot-drills. In addition, the QM foot-drill demonstrated significantly greater mean peak vGRF (Δ =36.8%, p <.001, 95%CI = 0.28 – 1.04) and vRFD (Δ =89.6%, p <.001, 95%CI = 36.6 – 92.9) values when compared to the walk.



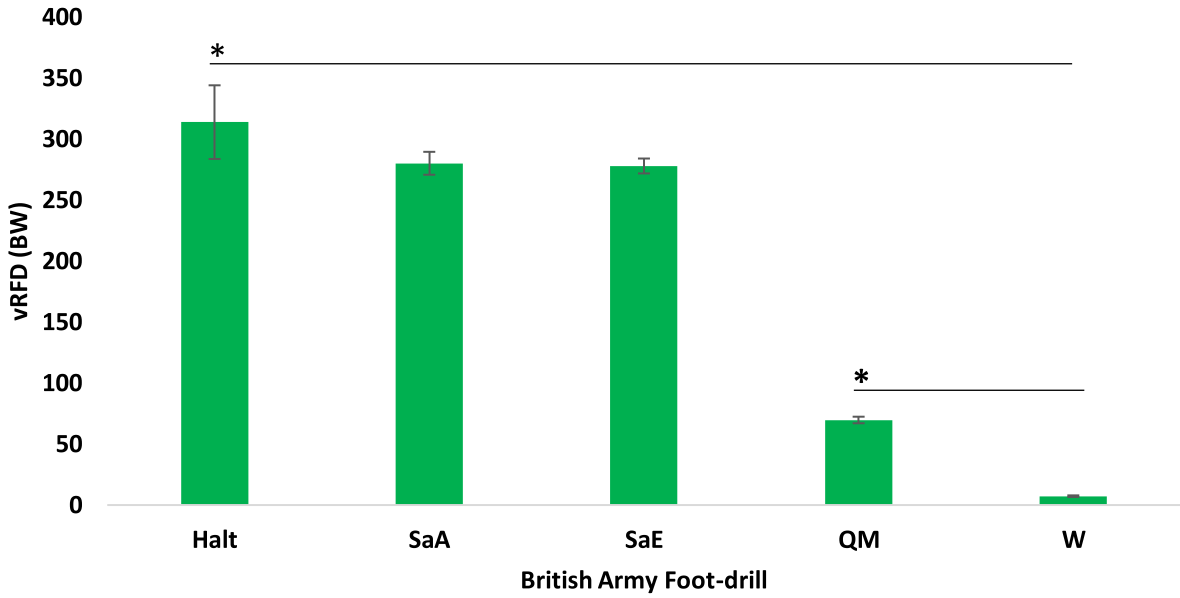


Figure 3.4: Vertical ground reaction forces of foot-drill. Normalised vGRF (BW) and vRFD (BW/s) for each of the five foot-drills. Values are means and bars are SD. * = denotes a significant

3.6 Discussion

The present study is the first to report reliability measures of the GRF variables of British Army foot-drill. The initial aim of the present study was to determine the existence and magnitude of between-session and within-session systematic bias. In addition, this study has quantified the impact loading forces and loading rates associated with British Army foot-drill in a sample of novice male drill performers. The statistically significant between-session mean differences in vGRF and vRFD for SaA and SaE indicate that a single familiarisation session is required before collecting reliable foot-drill force data; suggesting that the key performance markers of selective foot-drills (i.e., SaA and SaE) may require more time to learn when compared with other foot-drills. The requirement of a single familiarisation session can best be explained by the novelty and complexity of foot-drill for untrained males. Initial analysis of the whole data set revealed within-session (between-trial) differences of the vGRF SaA and SaE conditions. However, after the removal of the first session data no between-trial differences remained, suggesting that the systematic bias apparent in the vGRF data during the first testing session was large enough to influence the remainder of the data.

The second aim was to ascertain the magnitude of the within-subject variation in each of the variables. The levels of $\%CV_{te}$ reported for the vGRF and vRFD variables within the present study (figure 3.2a and 3.2b) demonstrate comparable magnitudes to those reported by Floria *et al.*, (2014) which examined the reliability of repeated trials (n = 3) of the GRF of two different countermovement jumps ($\%CV_{te}$ range: vGRF = 12.3% - 13.3%, range vRFD = 74.6% - 77.4%). In addition, Copic *et al.*, (2014) also revealed similar mean $\%CV_{te}$ values from repeated trials (n = 3) for GRF variables in vertical jump performance (mean $\%CV_{te}$: vGRF = 5.7%, vRFD = 29.1%). As reported in reliability literature (Connaboy *et al.*, 2010; Hunter *et al.*, 2004), the $\%CV_{te}$ was found to reduce when the number of trials utilised to calculate the average score increased, with the greatest increases in reliability ($\%CV_{te}$) shown within the initial increase in the number of trials used to calculate the mean value.

Reductions in $\%CV_{te}$ (improved reliability) were apparent within the present study for the vGRF halt, SaA, QM and vRFD SaE condition, with the greatest increases in reliability shown within the initial changes in the number of trials used to calculate the mean value. For example, an average $\%CV_{te}$ reduction of 0.97% was observed when using six trials compared with three trials, a further 0.35% average reduction by using seven trials compared with four trials, and an average reduction in $\%CV_{te}$ of 0.81% when using eight trials compared with five trials. Beyond eight trials, the use of additional trials of data to calculate the mean value across all foot-drills resulted in diminishing returns; for every additional trial utilised in the calculation of the mean values, the smaller the reduction in the $\%CV_{te}$ (Connaboy *et al.*, 2010). Similar average reductions in $\%CV_{te}$ were observed for the vRFD variable, however, these reductions did not show worthwhile improvements in levels of reliability across remaining foot-drills.

The final aim of this study was to determine the test-retest reliability of foot-drill force data to provide additional information to make decisions regarding the necessary number of trials of data required to achieve stable levels of performance, and to accurately track changes in foot-drill performance over time. However, it should be noted that ICC values at which test-retest reliability are deemed poor (ICC ≤ 0.75), moderate (ICC 0.75 – 0.85) and strong (ICC ≥ 0.85) are arbitrary values (Munro *et al.,* 1987). Nevertheless, the ICC is defined as an objective means of assessing the number of trials required to establish the stability of performance than other measures (i.e., sequential averaging), as it involves fewer arbitrary decisions when assessing performance stability (Connaboy *et al.,* 2010; James *et al.,* 2007).

The initial interpretation of the ICC analyses shows that the vGRF halt, QM, SaA and walk foot-drill achieved moderate to strong levels of test-retest reliability, with only SaE failing to achieve an ICC value ≥ 0.75. Maximum ICC values for the vRFD variable ranged from 0.62 for SaA, to 0.80 for QM, demonstrating poor to strong levels of test-retest reliability. However, strong levels of test-retest reliability were only achieved in QM and walk. The QM, SaE, and walk vRFD values achieved moderate levels of test-retest reliability, with halt (ICC range = 0.36-0.67) and SaA (ICC range = 0.24-0.62) failing to achieve an ICC value ≥ 0.75 (Hopkins, 2000). This finding suggests that multiple trials of foot-drill force data (mean ± SD: vGRF =8.5 ± 6.7 trials, vRFD =13.7 ± 12.9 trials) are required before maximum ICC values can be obtained.

It is recommended that ICC data should not be considered in isolation, rather, within-subject variability data should also be taken in to account when making decisions regarding the minimum number of trials required to accurately represent the GRF of foot-drill data, as data can be adversely influenced by the homogeneity of the test sample, which will affect any interpretation of reliability (Atkinson and Nevill, 1998; Connaboy *et al.*, 2010; Hopkins, 2000;

Hunter *et al.,* 2004; Moir *et al.,* 2008). Also, by considering the magnitude of the within-subject variation, the number of trials required to ensure a reliable assessment of each force variable can provide a measure of accuracy, whereby any future changes in vGRF and/or vRFD of foot-drill performance can be monitored (Connaboy *et al.,* 2010).

This study has reported foot-drill mean peak vGRF and vRFD data similar to those reported in previous foot-drill research (Carden *et al.,* 2015) and are comparable with peak vGRF and vRFD apparent in high level plyometric drills (Sinclair and Taylor, 2014). These data indicate that foot-drill represents a substantial mechanical load on the MSK structures of the lower-extremities, with previous authors indicating that foot-drill may be a key contributing risk factor associated with the high incidence rates of lower-extremity overuse injuries and bone stress fractures in recruit populations (Carden *et al*., 2015). Similar to previous reports (Carden *et al.*, 2015; Connaboy *et al*., 2011), the results of the present study demonstrated significant differences in mean peak vGRF and vRFD between foot-drills (p <.001, $\eta p^2 = 0.96$), with the halt foot-drill exhibiting the greatest mean peak vGRF (5.4 ± 0.6 Bw) and vRFD (320.4 ± 30.2 Bw/s) when compared to the remaining foot-drills, with SaE and SaA exhibiting vGRF and vRFD in excess of 4.9 BW and 278.1 BW/s, respectively (figure 3.4). In addition, selective participants were found to produce vGRF and vRFD values relative to the halt foot-drill in excess of 6.9 BW and 825.1 BW/s, respectively. These data suggest that some individuals performing foot-drill produce greater magnitudes of mechanical loading than others, potentially putting them at greater risk of injury. In addition, the greater loading forces reported for these participants may be associated with the high variability observed for the vRFD variable.

Recently, QM has been shown to exhibit comparable vGRF and vRFD values to running speeds of 3m/s (1.6BW) to 3.5m/s (1.3BW) (Molloy *et al.,* 2012). In this study, QM exhibited significantly greater mean peak vGRF (1.9 BW, Δ = 36.8%, p <.001) and vRFD (72.2 BW/s, Δ = 89.8%, p <.001) values when compared with a normal walking gait (vGRF = 1.2 BW, vRFD = 7.3 BW/s). The greater lower-extremity loading profiles of QM in comparison to the walk are likely associated with the forceful heel strike of QM combined with a greater hip and knee joint angular velocity prior to initial ground contact. The magnitude of temporal variables such as those mentioned previously will be investigated in the proceeding experimental studies. *In vivo* research (Milgrom *et al.*, 2012) has shown that high repetitive impact loading forces may produce tensile, shear and compressive strain-rates that may initiate bone damage at a microstructural level, resulting in single or multiple lower-extremity stress fractures. Despite some suggestions indicating that foot-drill may increase risk of stress fracture, further lab and field investigations are needed to better explain the adaptative response of bone to the loading forces of foot-drill and whether these forces expose recruits to greater risk of injury, whilst taking into consideration the influence of current standard issue British Army footwear on foot-drill loading forces.

The use of shoe inserts, orthotics, and/or greater shock absorbing footwear (Mündermann *et al.*, 2001; Logan *et al.*, 2010) are used frequently as a method of load attenuation at the foot-ground interface. For instance, Sinclair and Taylor, (2014) revealed that the impact parameters of the standard issue CB were significantly greater than those exhibited for a running-based military cross trainer (PT-03). As such, a more shock absorbent footwear worn by recruits during the initial weeks of foot-drill training may contribute to a marginal reduction in the relative magnitude and accumulative impact loading forces of foot-drill, at a time when recruits are of poor physical fitness and are suffering from muscle soreness and fatigue as a consequence of the new training stimulus. Sinclair and Taylor, (2014) further suggested that the CB may be associated with kinetic and kinematic parameters that have been linked to the etiology of injury such as reduced sagittal plan ankle motion and greater knee internal rotation during the stance phase; thus, the CB (among other military footwear) may not provide the necessary shock attenuation as required, or allow for a natural running gait pattern to be adopted. Therefore, greater consideration of the CB and other military footwear during impact-related activities (i.e., running, foot-drill) is warranted. As such, chapter 4 – study 2 determines how the vGRF and temporal parameters of foot-drill are influenced by gym and foot-drill standard issue British Army footwear.

A limitation of the current study is the all-male sample. Previous biomechanical studies have demonstrated that recreationally active females exhibit distinct loading profiles and lower-extremity kinematics when compared to their male counterparts (Carden *et al.*, 2015; Sinclair and Taylor, 2014). Therefore, it is unlikely that these results can be generalised to a recreationally active female population. In addition, study participants performed foot-drill in a training shoe, however, foot-drill is commonly performed in one of three military footwear, the CB during training, the AB during ceremonial drill, or more recently, the new defender combat boot (DCB). Due to a lack of available CB and DCB each participant wore military issue training shoes (Hi-Tech Silver Shadow™) to reduce the risk of different shock absorbent properties on GRF data. However, this means that the reported vGRF variables of foot-drill may not truly reflect those experienced when wearing the CB or DCB. Therefore, based on footwear research (Sinclair and Taylor, 2014; Nunns *et al.*, 2011), it is hypothesised that the CB, when compared to a training shoe, will produce greater vertical peak loading forces and loading rates during foot-drill. Chapter 4 – study 2 provides empirical evidence that elucidates the hypothesis.

3.7 Conclusion

The findings of the present study support the inclusion of a single familiarisation session specific to the SaA and SaE foot-drills. It was determined that the vRFD variables exhibited poor levels of reliability across foot-drills. Similar levels of reliability of the vRFD variable have been reported in previous literature (Copic *et al.*, 2014; Floria *et al.*, 2014). Nevertheless, it was determined that an average of eight-trials is required to achieve moderate to strong levels of reliability of foot-drill GRF data. The reliability of the vGRF and vRFD variable differed notably. However, in the majority of foot-drills there was a consistent trend for reliability to marginally improve when the average score of multiple trials was used as the measurement of interest.

A pragmatic approach is recommended when deciding on the number of trials used to represent foot-drill force data considering the requirement of high test-retest reliability and acceptable levels of within-subject variation concurrently with the economic, practical and logistical concerns of collecting repeated trials/sessions of foot-drill data (Connaboy *et al.*, 2010; Hunter *et al.*, 2004). As stated previously, the greatest increases in stability and reliability are shown within the initial changes in the number of trials used to calculate the mean ICC and $\%CV_{te}$ value; with diminishing returns in reductions in $\%CV_{te}$ data observed beyond eight-trials, with the achievement of a moderate level of test-retest reliability for each foot-drill of the vGRF variable, excluding SaE. Each one of the foot-drills (excluding SaE) relative to the vGRF variable demonstrated acceptable levels of reliability. However, in accordance with previous reliability literature (Atkinson and Nevill, 1998; Connaboy *et al.*, 2010; Hunter *et al.*, 2004) the magnitude of a variable's stability and reproducibility depends on its intended use, and subsequently, the researcher must determine whether it is sufficiently reliable to measure the smallest worthwhile change in an individual's performance.

Leading on from experimental chapter 3 – study 1, it was hypothesised that British Army in-service footwear may have a significant impact on the magnitude of impact loading forces of foot-drill, and that a particular type of footwear (i.e., training shoe and/or boot) may provide the recruit with a means of better protecting against the potential injurious loading profiles of foot-drill during the initial weeks of basic training - a time when recruits are most susceptible to injury due to a number of intrinsic (i.e., poor initial physical fitness levels) and extrinsic (i.e., rapid rise in training intensity during initial weeks of basic training) risk factors. Therefore, to better understand the influence in-service footwear has on the loading profiles of foot-drill and their potential role in the mitigation of impact shock being transmitted up the kinetic chain, experimental chapter 4 – study 2 investigated the capability of in-service footwear to reduce the magnitude of GRF variables of popular British Army foot-drill in a group of recruit age-matched civilian men.

4.0 Experimental Chapter 4: Study 2

4.1 The Effects of Standard Issue British Army Footwear on the Vertical Ground Reaction Forces of British Army Foot-Drill

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Experimental Chapter 4 – study 2: Published (Appendix 3b)

Rawcliffe AJ, Graham SM, Simpson RJ, Moir GL, Martindale RJJ, Psycharakis SG, and Connaboy C. The Effects of British Army Footwear on Ground Reaction Force and Temporal Parameters of British Army Foot-Drill. *J Strength Cond Res*, 2017 Aug 9. **Doi: 10.1519/JSC.0000000000002139**.

4.2 Introduction

The aetiology of occupational training-related injuries sustained during basic training are multi-factorial and diverse. Therefore, efforts to minimise the injury incidence during recruit physical training is of primary focus for military organisations worldwide (Rosendale *et al.,* 2003). British Army foot-drill is performed in standard issue military footwear, namely, the CB (or similar), and ammunition boot (AB). The CB is issued to entry-level recruits on induction to basic training, and worn with uniforms on a daily basis, and by military units on parade in full dress uniform. The AB (or similar) is commonly worn by British military personnel in dress uniform or during ceremonial and/or drill duties (MOD, 2012) (figure 4.1). Understanding the functionality and utility of different military footwear and their implications with respect to injury potential (and its mitigation) in recruits during basic training is essential for maintaining effective operational and tactical performance and could provide important information regarding injury prevention and performance optimisation strategies for commanding officers.

Measurement of GRF and temporal parameters such as vGRF, and time to peak vertical force (TTP) have been utilised as non-invasive measures of lower-extremity bone loading to quantify the potential development of MSK overuse injuries, most notably, bone microdamage and subsequent stress fracture of the foot and/or shank (Carden *et al.,* 2015; Sinclair and Taylor, 2014). Furthermore, these specific vGRF and temporal parameters are frequently utilised to indirectly assess the shock absorbing functionality of specific footwear, during a variety of lower-extremity tasks (Hamill and Bensel, 1996; Harman *et al.,* 1999; Sinclair and Taylor, 2014). For example, footwear research has demonstrated that the CB, when compared with other military and commercially available footwear, produces significantly greater impact loading forces when running and marching at velocities of 4m-s^{1} and 1.5m-s^{1}, respectively (Hamill and Bensel, 1996; Sinclair and Taylor, 2014). In addition, the CB has also been shown to significantly increase the risk of metatarsal stress fracture when running at 3.6m-s^{1} (Nunns, *et al.,* 2012).

The magnitude of specific vGRF parameters representative of foot-drill, irrespective of the type of footwear worn, may be a contributing risk factor in the development of lower- extremity MSK overuse injuries within recruit populations (Carden *et al.,* 2015; Rawcliffe *et al.,* 2017). To date, only three studies have investigated the impact loading forces of foot-drill whilst wearing training shoes (Connaboy *et al.,* 2011; Experimental chapter 3 – study 1) and defender combat boots (Carden *et al.,* 2015); reporting peak vGRF (range = 1.3 – 5.1 BW) and peak vRFD (range = 67.6 – 536 BW/s) values similar to, and in some cases greater than those observed for high level plyometric exercises (Bauer *et al.,* 2001; Wallace *et al.,* 2010). These studies quantified vGRF parameters of foot-drill yet did not consider the potential influential factors of standard issue footwear on impact loading forces of foot-drill.

Factors that mitigate the magnitude and rate of force transmitted to the MSK structures of the lower-extremities can be achieved from the use of footwear with shock absorbing capabilities (Logan *et al.,* 2010), thereby potentially reducing the risk of developing such MSK injuries as lower-extremity stress fractures. Recently, military footwear has undergone considerable scrutiny regarding its functionality and capacity to provide military personnel with the necessary shock absorbing properties required to withstand the demands of occupational training-related activities/tasks. For example, Nunns *et al.,* (2012) and Sinclair and Taylor, (2014) demonstrated that the CB increased the magnitude of several biomechanical risk factors associated with third metatarsal stress fractures during marching and was inferior in minimising the instantaneous and average loading rates of running when compared with training shoes. Other footwear research (Harman *et al.,* 1999; Williams *et al.,* 1997) demonstrated that the CB produced significantly greater peak decelerations, shorter times to deceleration, higher peak-plantar pressures, and greater vGRF forces at the heel and forefoot when compared with hiking boots and training shoes. From these studies, it can be suggested that the CB does not have the necessary shock absorbing capacity required to effectively attenuate the cyclic high impact loading forces during running, marching or drop landings. Therefore, the CB and its use during cyclic high impact loading activities may contribute to, in part, the high rates of lower-extremity MSK overuse injuries sustained by recruits during basic training (Nunns *et al.,* 2012; Hamill and Bensel, 1996; Williams *et al.,* 1997). Nevertheless, it remains unclear due to scant research as to how the vGRF and temporal parameters of foot-drill are influenced by the CB and other types of British Army footwear.

Knowledge of the biomechanical loading forces of these regimented movements is an essential component of understanding the dynamics of foot-drill as a potential training-related lower-extremity MSK overuse injury risk factor. Furthermore, these data can provide a greater understanding of whether the use of a shock absorbing footwear is effective in the attenuation of the impact loading forces of foot-drill. Therefore, the aim of the present study was to compare the magnitude of the vGRF and temporal parameters of each foot-drill, namely, peak vGRF, peak vRFD, and TTP across three different types of standard issue British Army footwear, namely the CB, AB and Hi-Tech Silver Shadow training shoe (TR). This study tests the hypothesis that foot-drill, when compared with the loading patterns of a normal walk would produce greater peak vGRF, peak vRFD, and shorter TTP values; and that the TR would significantly attenuate peak vGRF, peak vRFD, and produce longer TTP values when compared with the CB and AB for all foot-drills.

4.3 Methods

4.3.1 *Participants*

Due to a lack of available resources and time it was not possible to collect pilot data prior to this study. Sample size was estimated using G*Power software (v3.1.9.2, Germany) for two-way (3[footwear] x 5 [foot-drill]) repeated measures ANOVAs (within-interaction) to statistically determine differences in the magnitude of vGRF, vRFD, and TTP of five foot-drills across footwear. Only a standard G*Power function was used to determine sample size. With an estimated 20% probability (power=.80) of a type II error, an alpha level set at .05, and an estimated effect size of 0.3 (medium-to-large), it was estimated that a sample size of 15 male participants would be sufficient to detect a significant difference from zero. Therefore, fifteen recreationally active healthy males (mean ± SD; age 22.4 ± 2.6years; height 1.78 ± 2.8m; weight 78 ± 3.3kg) with no pathological lower-extremity, hip or spinal conditions volunteered to participate in the present study.

All participants at the time of testing were taking part in moderate physical activity (gym training) and/or sport (soccer, rugby, badminton). Forty-eight hours prior to testing participants refrained from high intensity activity as to eliminate potential fatigue effects on performance data. Ethical approval for the present study was gained from Edinburgh Napier University's ethics committee and written informed consent was obtained from each participant prior to data collection. Study participants were defined as "novice drill performers" as they had no prior experience performing British Army foot-drill prior to data collection and had similar anthropometric characteristics to that of male entry-level recruit populations (Blacker *et al*., 2009) (Δ *n*, %: age = 2 years, 8.1%; height = 2.2m, 1.3%; body mass = 8kg, 9.3%).

4.3.2 *Experimental Design*

A within-participant repeated-measures study design was employed to assess the vGRF dependent variables of five British Army foot-drills involving; SaA, SaE, QM, halt, and a normal walk. Based on the reliability analysis conducted as part of experimental chapter 3 - study 1, eight-trials of a normal walk were collected to act as a comparison with the vGRF and temporal data of QM based on similar lower and upper extremity biomechanical movement patterns (i.e., arm swing and gait cycle). Although it is reasonable to suggest that both marching and walking are similar in terms of the gait cycle, additional research is required to determine the extent of differences between these two activities.

4.3.3 *Experimental Procedures*

The vGRF and temporal parameters of each foot-drill were assessed across three different types of standard issue British Army footwear. The allocation of footwear was counterbalanced for each day of testing using a randomisation (RAND) sort function in Microsoft Excel (2013). Kistler force plate (Kistler Instruments AG, 9281CA, Switzerland) flush with the lab floor (Force plate dimensions: 600mm x 400mm x 100mm) situated in a 10-m walkway was used to measure and record peak vGRF, peak vRFD, and TTP. Study participants attended the lab on three non-consecutive days with 24-hours separating each test day. Each testing session was conducted at the same time of day and performed under the instruction and guidance of the same researcher.

Each participant performed a standardised 10-min warm up consisting of dynamic lower-extremity bodyweight exercises, namely, variations of the lunge and bilateral squat (Baechle and Earle, 2008). Preceding the collection of foot-drill vGRF and temporal data, a single familiarisation session was conducted on the first day of testing, whereby each participant performed ten trials of each foot-drill based on reliability analysis (study 1). Post familiarisation and a 15-min recovery period, a total of eight-trials per foot-drill were collected, as it has been demonstrated that a minimum of eight-trials is required to produce accurate and stable levels of foot-drill vGRF data (CV_{te}% <10%, ICC > 0.75) (Experimental chapter 3 – study 1). The force plate was interfaced with BioWare 3.2.5 software and set at a sampling frequency (fs) of 1000Hz, with each foot-drill recorded for a maximum of 3-sec. The foot-drill vGRF and temporal data were collected using an eight channel 16-bit analog to digital converter (Qualisys, 8128, Sweden). A 90-sec recovery period between each trial and a 15-min recovery between foot-drills was employed. All footwear used for analysis in this study was unworn prior to data collection, eliminating the influence of retrospective wear on foot-drill data. Trials were discarded and repeated if targeting (Challis, 2001) and/or adjustments in key performance markers of foot-drill were observed.

Figure 4.0: British Army Standard Issue Footwear. Depicts the three different types of standard issue British Army Footwear used in the present study. From left to right - Combat boot (CB), Ammo Boot (AB), and Hi-Tech Silver Shadow^{TM} training shoe (TR).

The foot that struck the force plate during each of the foot-drills was referred to as the active limb with the opposite limb referred to as the support limb (figure 4.1). Study participants were instructed to walk at their preferred walking speed. Speed (m/s) was measured from using timing gates (Fusion sport, SmartSpeed, Australia) situated at 0-m, 5-m and 10-m along the 10-m walkway, and monitored across each test session, with a maximum deviation of +/- 5% allowed from each participant's predetermined walking velocity (Sinclair and Taylor, 2014).

The mean walking speed for all participants was 1.6 ± 0.6m/s. Although a metronome was used to standardise QM pacing across participants, the mean speed for QM was 2.02 ± 0.01m/s.

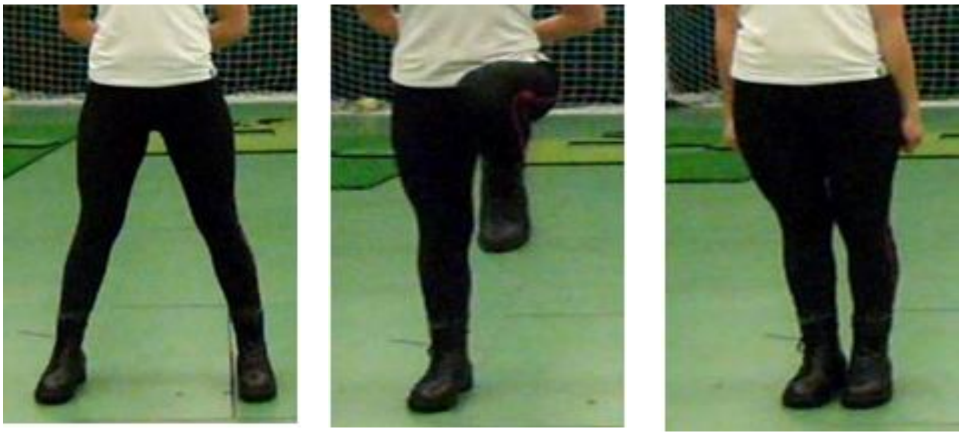

Figure 4.1: Representation of a typical British Army Stand-at-Attention foot-drill wearing the CB. From left to right, the SaA is performed from the SaE position. On command, the participant flexes at the hip to 90° followed by an exaggerated stamping of the foot onto the surface of the force plate, landing with the knee in an extended position.

The foot-drill vGRF and temporal data were exported from BioWare 3.2.5 system. Based on power spectrum analysis, ensuring that 90% of the signal content was retained, vGRF data were filtered with a low pass 4th order zero-lag (single bi-directional) Butterworth filter with a cut off frequency (fc) ranging between 25hz (walk) and 70Hz (SaA, SaE, Halt, QM). As a means of comparing between participants the vGRF and vRFD foot-drill data were normalised to BW (Eq. 1, 3 and 4), with time to peak vGRF expressed in milliseconds (Eq. 2). The initial onset of vGRF was defined as when the vGRF component exceeded a threshold of 20N (Puddle and Maulder, 2013).

4.4 Statistical Analysis

Prior to statistically analysing the vGRF dependent variables of foot-drill and walk data between footwear; peak vGRF, peak vRFD, and TTP were analysed for the assumption of normality (Field, 2012). The vGRF (W: p <.001), vRFD (W: p <.001) and time to peak force (TTP) (W: p <.010) variable illustrated a significant violation in the assumption of normality for each foot-drill. Therefore, these data were log transformed in SPSS using natural logarithm (x10) of the observed value as a means of reducing the magnitude of skewness within the data (Field, 2012). A series of two-way (3[footwear] x 5[foot-drill]) repeated-measures ANOVAs with Bonferroni adjusted multiple comparisons were conducted for each of the vGRF dependent variables (vGRF, vertical RFD, and TTP) for each of the foot-drills and walk across each footwear. A paired samples t-test was conducted to quantify potential significant differences in mean peak vGRF and vertical RFD between the QM and walk foot-drill across footwear.

4.5 Results

Post hoc power calculations using G*Power were conducted and confirmed that the total sample size of 15 male participants provided sufficient power (0.81) for these analyses.

4.5.1 *Ground Reaction Force-Time Characteristics of QM and Walk*

Significant differences in force-time characteristics between the QM and walk foot-drill were determined. As illustrated in figure 4.2, the QM foot-drill demonstrates a distinct impact peak in comparison to the walk, with QM showing a steeper initial slope from initial contact to peak vGRF; characterising the magnitude of the vRFD of the initial portion of the vGRF component. The significantly greater vRFD observed for QM is likely associated with the forceful heel-strike, with the knee joint in an extended position at initial contact.

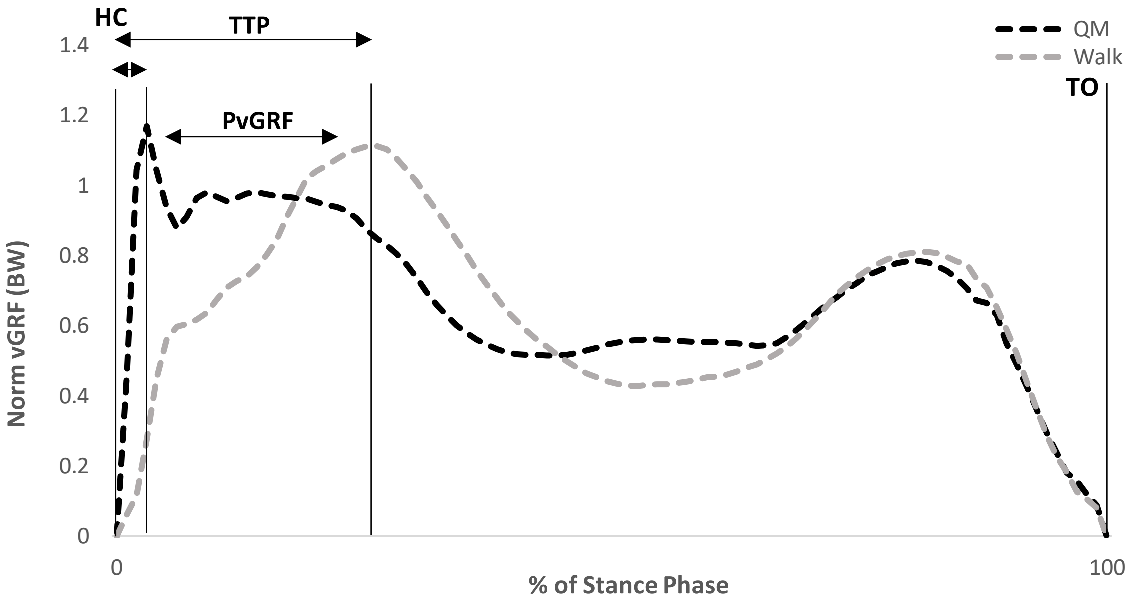

Figure 4.2: An exemplar of a typical QM and walk (right foot) gait cycle of a single participant whilst wearing the CB. These data were time normalised in Visual 3D to 100 data points representing 0% to 100% of the stance phase from heel contact to toe off. HC = Heel contact for both QM and Walk, TO = toe off for both QM and Walk, TTP = time to peak vertical force, PvGRF = peak vertical ground reaction force.

4.5.2 *Foot-drill vs Footwear: Peak Vertical Ground Reaction Force*

Statistically significant main effects were found for the peak vGRF variable between footwear for the SaA (p <.001, $\eta_p^2 = 0.8$), SaE (p <.001, $\eta_p^2 = 0.8$), and halt (p <.001, $\eta_p^2 = 0.7$) foot-drill, with no differences observed for the QM foot-drill (p = 0.106, $\eta_p^2 = 0.2$) or the walk (p = .973, $\eta_p^2 = .003$). The TR demonstrated significantly smaller magnitudes of vGRF when compared to the CB and AB for the SaA (CB: p <.001, Δ = 19.2%, d = 2.0, AB: p <.001, Δ = 16%, d = 1.6), QM (CB: p <.001, Δ = 11.7%, d = 0.9, AB: p <.001, Δ = 8.6%, d = 0.6), SaE (CB: p <.001, Δ = 19.3%, d = 2.3, AB: p <.001, Δ = 21%, d = 2.4), and halt foot-drill (CB: p <.001, Δ = 16.3%, d = 1.7, AB: p <.001, Δ = 17.3%, d = 1.6) (Figure 4.3).

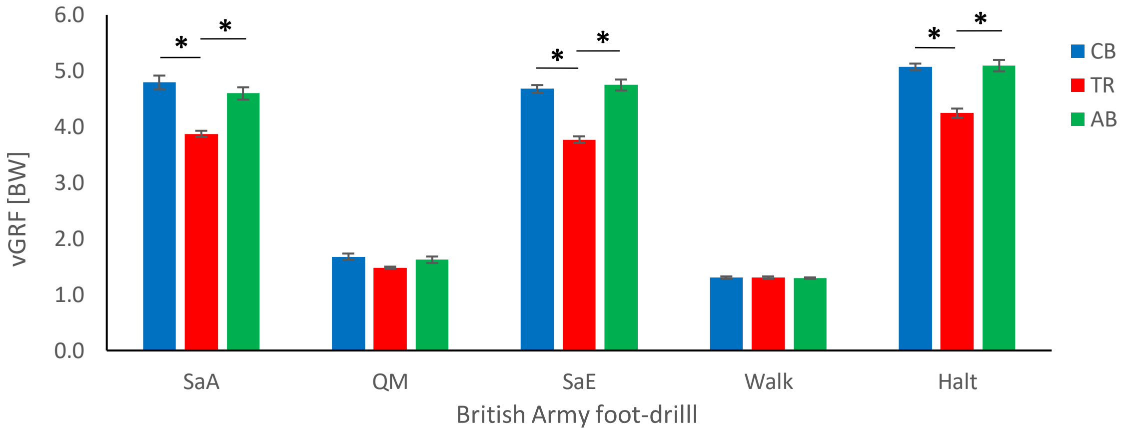

Figure 4.3 The vGRF as a function of footwear across British Army foot-drill: The mean peak vGRF of each foot-drill across each footwear, showing significant differences (*p*<0.05) between footwear across foot-drill with vGRF data normalised to bodyweight (BW). ***** = illustrates a significant difference. Values are means; bars are SD.

4.5.3 *Foot-drill vs Footwear: Peak Rate of Force Development*

Statistically significant main effects were found for the peak vRFD variable between footwear for the SaA (p <.001, $\eta_p^2 = 0.9$), SaE (p <.001, $\eta_p^2 = 1.0$), QM (p <.001, $\eta_p^2 = 0.8$), and halt foot-drill (p <.001, $\eta_p^2 = 1.0$), with no significant differences observed for the walk (p = .587 $\eta_p^2 = 0.02$). The TR demonstrated significantly smaller magnitudes of vRFD when compared to the CB and AB for the SaA (CB: p <.001, Δ = 22.1%, d = 1.3, AB: p <.001, Δ = 23.7%, d = 1.5), QM (CB: p <.001, Δ = 45.2%, d = 1.2, AB: p <.001, Δ = 55.2%, d = 1.4), SaE (CB: p <.001, Δ = 21.2%, d = 1.4, AB: p <.001, Δ = 33.1%, d = 2.1), and halt foot-drill (CB: p <.001, Δ = 17%, d = 0.9, AB: p <.001, Δ = 27.2%, d = 1.5), with the AB exhibiting significantly greater vRFD when compared to the CB (p <.01, Δ = 12.4%, d = 0.7) only for the halt foot-drill (Figure 4.4).

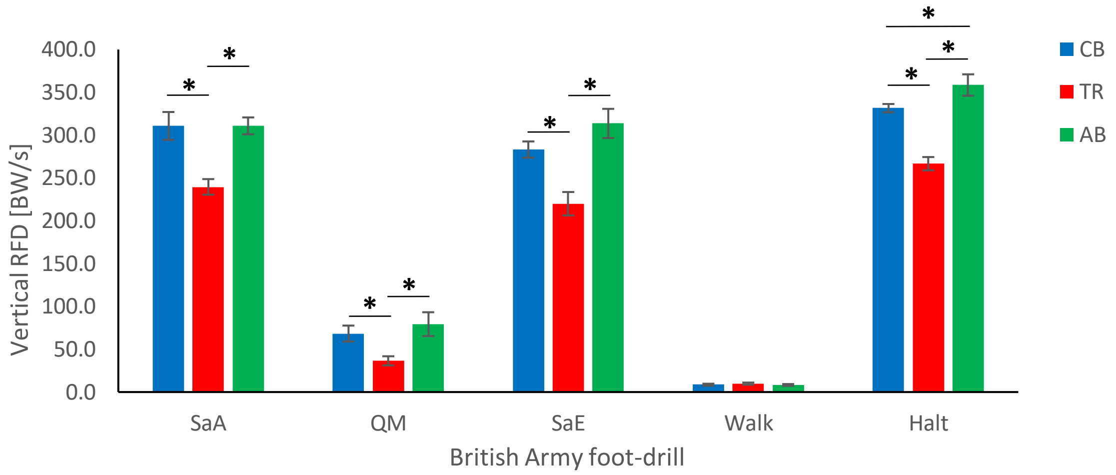

Figure 4.4 The mean peak vertical RFD as a function of footwear across British Army foot-drill: The mean peak vertical RFD of each foot-drill across the three types of footwear, showing significant differences (p<0.05) between footwear across foot-drill with vertical RFD data normalised to bodyweight/second (BW/s). * = illustrates a significant difference. Values are means; bars are SD.

4.5.4 *Ground Reaction Force Differences: QM vs Walk*

Based on the paired samples t-test conducted to determine differences in the magnitude of peak vGRF and vRFD between the QM foot-drill and walk across each footwear, statistically significant differences were observed, whereby the QM foot-drill produced significantly greater peak vGRF and vRFD for the TR (vGRF: t_{10} 4.8, p <.01, Δ =12%, d = 1.4; vRFD: t_{10} 3.7, p =.004, Δ =73%, d = 2.1), CB (vGRF: t_{10} 4.9, p <.01, Δ =22.3%, d = 2.4; vRFD: t_{10} 7.5, p <.001, Δ =87.1%, d = 4.3), and AB (vGRF: t_{10} 3.3, p = .007, Δ = 19.4%, d = 1.5; vRFD: t_{10} 6.2, p <.001, Δ =89.6%, d = 3.4) when compared to the walk (Figure 4.5).

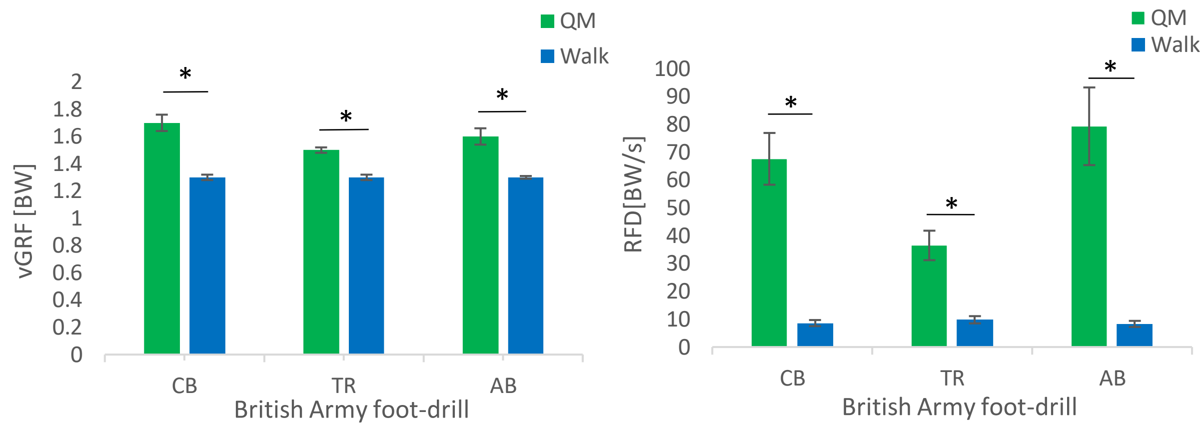

Figure 4.5 The vGRF and vertical RFD as a function of footwear across the QM and Walk foot-drill: Significant differences (p<0.05) between the QM and Walk foot-drill across footwear, with vGRF normalised to (BW), and vertical RFD data normalised to BW/s. ***** = illustrates a significant difference. Values are means; bars are SD.

Statistically significant main effects were observed for TTP variable across each footwear for the SaA (p = .003, $\eta_p{}^2 = 0.5$), SaE (p <.001, $\eta_p{}^2 = 0.6$), QM (p <.001, $\eta_p{}^2 = 0.7$), and halt foot-drill (p <.001, $\eta_p{}^2 = 0.8$), with no significant differences observed for the walk (p = .116, $\eta_p{}^2 = 0.2$). Further pairwise comparisons indicted significant differences between footwear for all foot-drills apart from the walk (table 4.0).

The TTP as a function of footwear across each British Army Foot-drill

Foot-drill	**British Army Footwear**			**Δ (%), *d***		
	CB[a]	**TR**[b]	**AB**[c]	**ac, *d***	**bc, *d***	**ab, *d***
SaA	0.016 ± .002	0.017 ± .003	0.015 ± .001	6.3, 0.7	11.8, 1.0	5.9^{Ŧ}, 0.4
SaE	0.017 ± .001	0.018 ± .002	0.015 ± .002	11.8^{Ŧ}, 1.3	16.7***, 1.5	5.6, 0.7
Halt	0.017 ±.012	0.016 ± .002	0.014 ± .002	17.6^{Ŧ}, 0.4	12.5***, 1.0	5.9, 0.1
QM	0.036 ± .032	0.071 ± .037	0.026 ± .077	27.8, 0.2	63.4**, 2.1	49.3^{Ŧ}, 1.0
Walk	0.229 ± .167	0.196 ± .169	0.275 ± .190	16.7, 0.3	28.7, 0.5	14.4, 0.2
Mean±SD				16.1 ± 7.9	26.6 ± 21.6	16.2 ± 18.8

Table 4.0: The mean (SD) time to peak vGRF (TTP) (sec) of each foot-drill across footwear, showing percentage differences (Δ%) and effect size (d) between footwear and foot-drill, with TTP expressed in seconds (sec). ^{Ŧ} = p <.05, ****** = p <.01, *** = p <.001 indicates level of significance between footwear. CB=Combat boot, TR=Training shoe, AB=Ammunition boot.

4.6 Discussion

The results of this study provide important information regarding the possible risk factors for lower-extremity MSK injuries/disorders associated with specific vGRF and temporal parameters of foot-drill, specifically for male recruits. These results confirm the hypothesis, indicating that when performing British Army foot-drill in footwear with greater shock absorbing capabilities, namely the TR, significant reductions in peak vGRF and peak vRFD are achieved when compared to CB and AB.

Given the structural and mechanical properties of the AB outsole, it was anticipated that the AB would provide less shock absorbency resulting in greater peak vGRF and vRFD when compared with the CB. However, similar magnitudes of peak vGRF and vRFD to that of the CB was observed. The male participants of the present study were very aware of the lack of cushioning properties of the AB, thus it is likely that participants may have marginally altered their landing biomechanics to compensate for the lack of cushioning at the foot-sole interface, resulting in similar GRF magnitudes to those of the CB. Nevertheless, these results mirror those of others (*Logan et al.*, 2010) whereby no significant differences in the magnitude of impact forces between hard and moderately hard midsole footwear were observed. Apart from QM, the AB demonstrated significantly shorter TTP when compared to CB and TR. However, all foot-drills (excluding walk) regardless of footwear type, demonstrated TTP values ≤50ms, indicating that any active force (i.e., under neuromuscular control) is unlikely to have been generated during this period (Fowler and Lees, 1998).

The CB and AB exhibited mean peak vGRF and vRFD in excess of 5.1 BW and 358.6 BW/s for SaA, SaE, and halt. Two participants wearing the CB and AB demonstrated peak vGRF and peak vRFD in excess of 6.6 BW and 514 BW/s for SaA, SaE, and halt. Accumulatively, the magnitude of loading experienced by these individuals may put them at greater risk of lower-extremity stress fracture in comparison to those who exhibited reduced loading profiles (Carden *et al*., 2015). In contrast, a body of evidence suggests that the human skeleton responds to high external loading forces with enhanced bone mineral density at specific anatomical locations (Fehlin *et al*., 1995; Hind and Burrows, 2007). For instance, Allison *et al*., (2013) reported enhanced bone mineral density, bone mineral content, and cross-sectional area in men of the femoral neck of the experimental leg (+0.7, +0.9 and +1.2%, respectively) in comparison to the control leg (-0.9, -0.4, and -1.2%, respectively) post 12 months of high impact unilateral exercise (hopping mean vGRF: 2.87 ± 0.21 BW). Additionally, loading cycles of 3.5 BW to 8 BW from single countermovement jumps and repetitive drop jumps (61cm), similar to those reported for foot-drill, have been shown to produce the greatest increases in bone mineral density in the femoral neck in children and adolescents (Hind and Burrows, 2007). Therefore, irrespective of the type of footwear worn, the magnitude and accumulation of the impact loading forces of foot-drill reported in this study may have contributed to increased bone density and periosteal expansion of the tibia in a study involving male British Army recruits assessed post 10 weeks of basic training (Izard *et al*., 2016). However, it remains unclear as to what constitutes as the optimal exercise/loading programme for enhancing bone health. Additional quantitative, dose-response studies are warranted to determine the most and least effective exercise/loading programmes for bone mineral accrual in British Army recruit populations to reduce stress fracture.

The magnitude of impact loading forces of foot-drill are similar to those reported by Carden *et al.*, (2015). Despite footwear was not a variable of interest, recruits exhibited mean peak vGRF and vRFD in excess of 4.6 BW and 536 BW/s whilst wearing the DCB, respectively. The DCB has been standard issue within the British Army since 2012; specifically designed to minimise the risk of lower-extremity MSK injury in the dismounted soldier from the integration of an inbuilt shock absorbing mid-layer (MOD, 2012). However, based on the vGRF and temporal parameters of foot-drill, along with the direct comparison from this study and an indirect comparison of the data from Carden *et al.*, (2015) would suggest that the DCB may not provide greater shock absorbing capabilities when compared with the CB, thus questioning the DCB's functionality to sufficiently reduce the relative magnitude and/or accumulative impact loading forces of foot-drill and other cyclic impact loading activities.

In comparison to CB and AB, the TR demonstrated significantly smaller magnitudes of peak vGRF and vRFD across the majority of foot-drills. These results are comparable to others (Sinclair and Taylor, 2014), whereby training shoes (i.e., running and cross trainer) demonstrated superior shock absorbing capabilities when compared with military boots. However, the TR demonstrated peak vGRF and peak vRFD in excess of 4BW and 260.7 BW/s, respectively, with two participants producing values in excess of 5.8 BW and 420 BW/s for halt. Although the TR displayed significant reductions in impact force, the mean peak vGRF of SaA, SaE, and halt whilst wearing the TR are similar to those reported for 30cm, 60cm, and 90cm drop landings in adolescent Division 1 collegiate gymnasts (Seegmiller and McCaw, 2003). In addition, the peak vRFD observed for the TR are similar to those observed during running speeds of 6.7m/s whilst wearing a hard-soled spike running shoe (Logan *et al.*, 2010), (mean±SD: 249.1 ± 18.6 vs 232 ± 177 Bw/s, Δn, % = 17.1, 6.9%), suggesting that even with superior shock absorbing footwear foot-drill exhibits substantial mechanical loading.

The unique landing techniques of foot-drill combined with the lack of shock absorbing capabilities of standard issue footwear, namely the CB and AB, typically present high vRFD. The magnitude of peak vRFD of SaA, SaE, and halt (range: 286.3 – 514 BW/s) are considerably higher than those reported for countermovement jumps and box step offs (Afifi and Hinrichs, 2012), and moderately higher than those reported for 61cm drop landings (Bauer *et al.*, 2001).

The large disparity in the magnitude of vRFD between foot-drill and other high impact activities is that individuals will attempt to actively mitigate the impact loading forces by increasing the duration of loading from greater hip and knee flexion and ankle plantarflexion, whereas during foot-drill they will not, as recruits are instructed to impact the ground with the heel and land with an extended-knee (Carden *et al.,* 2015). All biological MSK structures are viscoelastic in nature, whose material properties are rate dependent (Fowler and Lees, 1998). Therefore, when considering the relative safety of high impact loading activities, it is important to determine the vRFD as it is generally accepted that greater magnitudes of vRFD are more injurious; as MSK structures are generally stiffer under high velocity movements (Fowler and Lees, 1998). Although the experimental evidence to support these claims is scant, it is likely that the high mean vRFD of foot-drill ($\bar{x}$ range: 8.3 – 358BW/s) could place recruits at greater risk of lower-extremity MSK injury (Donoghue *et al.,* 2011).

Results of this study are similar to those reported previously (Carden *et al.,* 2015; Decker *et al.,* 2003) demonstrating similarities in the magnitudes of the impact loading forces of QM within trained and untrained men and women. The QM foot-drill, regardless of the type of footwear worn, exhibited significantly greater magnitudes of peak vGRF ($\bar{x}\Delta$: 18.4%), peak vRFD ($\bar{x}\Delta$: 85.4%), and shorter TTP ($\bar{x}\Delta$: 80.7%) when compared to walk. These significant differences observed between QM and walk are likely associated with the greater mean speeds observed during QM (0.39m/s, $\bar{x}\Delta$:19.2%), coupled with the exaggerated heel-strike and greater extended-knee at impact, resulting in a distinct impact peak when compared to the walk and producing a steeper initial slope from initial contact to peak vGRF (figure 4.2). The specific gait characteristics of QM (i.e., exaggerated heel strike and extended-knee) are likely responsible for the magnitude of peak tibial impact accelerations (38 ± 16m/s^{-2}) reported by Carden *et al*., (2015), found to be similar to data reported for male participants running at 10.8

km/h. Given the principle feature of foot-drill is aggressive "stamping", these greater forces and shorter TTP of QM in comparison to walk are likely a consequence of the effective mass of the stamping (active) limb travelling at a higher velocity prior to ground contact (Carden *et al.*, 2015). Despite this being the most likely aetiology, further lower-extremity kinematic and kinetic analysis of foot-drill is required to confirm the association between an increased joint angular velocity between QM and walk prior to initial contact. This may be a key factor related to the occurrence of marching related lower-extremity MSK injuries.

During cyclic high impact loading activities, the MSK system is exposed to forces that contain passive components; forces that peak within the initial 10ms, and active components; forces that peak over a longer period and represent the role of the muscles in force attenuation (Makinejad *et al.*, 2013). The mean TTP relative to halt, SaA, and SaE ranged between 18–14ms, which is considerably lower than the threshold range (50-70ms) for muscle to actively respond to the landing/contact stimulus (Donoghue *et al.*, 2011). In accordance with research (Donoghue *et al.*, 2011), it is reasonable to suggest that the peak vGRF of SaA, SaE and halt are passive forces, and when achieved, may not be under neuromuscular control, potentially causing the corresponding high deflection in the vertical direction to exceed the threshold stress (maximum tolerable stress) resulting in contact between the tibia and femur (Makinejad *et al*., 2013; Podraza and White, 2010; Pollard *et al.*, 2010).

Unlike traditional athletic landing techniques, whereby athletes are encouraged to land with greater degrees of knee and ankle flexion as a means of attenuating and dispersing the impact loading forces at foot-ground contact, foot-drill necessitates an extended-knee landing, whereby both men and women recruits are taught to forcefully impact the ground with minimal hip and knee flexion. Previous biomechanical studies have indicated that non-contact forces, coupled with sudden deceleration with the knee joint positioned in near full extension, are factors associated with an increased risk of bone-on-bone contact, and subsequent depression of the tibial and femoral cartilage and meniscus (Makinejad *et al*., 2013). Therefore, a 3-dimensional lower-extremity analysis of British Army foot-drill is essential to provide a greater understanding of potential sex-specific lower-extremity MSK injury mechanisms and/or risk factors associated with the exaggerated heel-strike of QM, and the forceful extended-knee landing of SaA, SaE, and halt, quantifying such biomechanical variables as; joint angular positions, velocities, accelerations, and external joint forces exhibited by untrained men and women.

It should be noted that during this study's (study 2) data collection, the MoD issued a new range of combat boots and training shoes, whereby the CB and TR were removed from service and replaced with a new brown boot series, along with a modified Hi-tech indoor and outdoor gym trainer. However, the AB remains in-service and utilised mainly on parade and when conducting ceremonial drill duties. In addition, it is unlikely that these results can be generalised to an age-matched female population due to differences in physiology and anatomy, along with the influence these differences are likely to have on GRF and temporal variables of foot-drill and other high impact loading activities and tasks.

4.7 Conclusion

The regimental movement patterns of foot-drill performed in the TR resulted in a total reduction in the magnitude of peak vGRF and peak vRFD of 17.9% and 16.8% when compared to the CB, and 25.5% and 32.3% when compared to the AB, respectively. Therefore, a strategically more robust shock absorbing outsole design worn during foot-drill training may contribute to a marginal reduction in the relative magnitude and accumulative impact loading forces of foot-drill, potentially reducing stress distributions and bone-on-bone contact of the tibia and femur (knee joint) during the extended-knee landing of SaA, SaE, and halt; subsequently contributing to a potential reduction in the high incidence rates of lower-extremity MSK injuries/disorders of British Army recruit populations. These data provide 2* military personnel with important information concerning the shock absorption interactions of specific standard issue footwear during foot-drill and the potential for impact-related lower-extremity MSK overuse injury.

Leading on from experimental chapter 4 – study 2, it became apparent that the specific aetiological factors hypothesised to be responsible for the high impact loading forces of foot-drill (i.e., key kinematic and kinetic variables of the extended-knee landings of SaA, SaE and halt, and the exaggerated heel strike of QM) require additional empirical study, namely, 3-dimensional lower-extremity motion analysis investigating such variables as joint angular velocity, accelerations, joint angles and moments, and GRF profiles. Therefore, to better understand the potential sex-specific biomechanical risk factors of foot-drill and how best to manage and/or manipulate the modality that is foot-drill in reducing risk of injury, experimental chapter 4 – study 3 conducted a lower-extremity 3-dimensional analysis of popular British Army foot-drills in both age-matched civilian men and women.

5.0 Experimental Chapter 5 – Study 3

5.1 A Kinetic and Kinematic Analysis of British Army Foot-Drill in Novice Male and Female Drill Performers

5.2 Introduction

According to UK Armed Forces 2016/17 medical discharge report (MoD, 2017) lower-extremity MSK injuries/disorders accounted for 59% (n = 1,079) of all cause-coded medical discharges. The most common injuries included knee injuries/disorders (20%, n = 221), knee pain (5%, n = 83) and ankle and foot injuries/disorders (6%, n = 107). In previous reporting periods (2011/15), no significant differences in medical discharge rates had been observed between men and women. However, the Defence Statistics 2016/17 report demonstrated significantly greater medical discharge rates in women when compared to men (26.0 vs 21.9 per 1,000 women at risk). These data support research indicating that women operate at a higher physiological strain when performing the exact same tasks and activities as men, thus increasing their risk of overtraining, injury and subsequent medical discharge (Geary *et al*., 2002). In addition, recruit personnel experience considerably greater medical discharge rates in comparison to their trained counterparts (Δ= 75.5%), reflecting the intense physical rigour of BMT, lack of previous exposure to submaximal cyclic loading, training statues, mixed-sex training, and the physical rigours of specific occupational military activities and tasks (i.e., load carriage, repetitive box lifting, running, and foot-drill) (Carden *et al*., 2015; Geary *et al*., 2002).

British Army foot-drill is a fundamental military occupational activity, routinely practiced by recruits during the initial weeks of basic training and throughout their career. The volume and frequency of foot-drill has been reported to range from 40min to two-hour sessions per day during the initial four weeks of basic training (Williams, 2005), whereby the volume of foot-drill is known to be markedly higher for recruits in comparison to their trained counterparts; performing many hours of foot-drill training during formerly timetabled sessions and whilst transiting through camp. In addition, anecdotal evidence suggests that foot-drill is utilised as a method of informal punishment at initial training centres, further increasing the accumulative mechanical loading on the MSK system and demonstrating a limited understanding and knowledge by training staff and commanders of the potential injury implications of foot-drill. The regimental biomechanical movement patterns of foot-drill are uniquely different to those observed for more traditional landings and are the reason why foot-drill is considered a risk factor for lower-extremity MSK injury. For example, foot-drills such as SaA, SaE and halt involve raising the active limb to 90° hip flexion, with the plantar surface of the foot parallel with the ground, forcefully stamping down onto the surface of the ground with an extended-knee (stiff-leg landing), whilst actively reducing the range of sagittal plane hip and knee motion at impact. At this point, the tibia and knee joint are exposed to high impact shock predominantly in the vertical direction due to the lack of flexion and subsequent shock absorbency from local musculature (Makinejad *et al*., 2013). In addition, the extended-knee landing of foot-drill may increase the risk of potentially injurious lower-extremity joint kinetics/kinematics, as research has shown greater degrees of frontal plane motion of the knee joint (i.e., knee valgus) during stiff-leg (≤ 90°) landings, defined as a key contributing factor linked to anterior cruciate ligament (ACL) injury mechanism.

Currently, only two studies have analysed GRF and temporal variables of foot-drill in untrained men and trained men and women (Carden *et al*., 2015; Connaboy *et al*., 2011), with no research investigating differences in lower-extremity joint kinematics and kinetics linked to the high loading profiles of British Army foot-drill. However, current evidence shows that the peak vGRF (PvGRF) (range = 1.3 - 4.6 BW), peak vRFD (vRFD) (range = 70 - 536 BW/s), time-to PvGRF (TTPvGRF) (range = 0.014 - 0.275 ms), and peak tibial impact accelerations (range = 23 - 207.2 m/s^2) of foot-drill are similar, and in some cases greater than those reported for high level plyometrics (Decker *et al*., 2003) - a training modality more commonly performed by highly conditioned athletic populations due to the high risk of soft tissue injury and bone stress fractures associated with the sudden deceleration of the body's centre of mass at landing (Makinejad *et al.*, 2013). In addition, it is well-recognised that men and women both adopt different lower-extremity landing strategies for the same task due to differences in their physiology, anatomy, and biomechanics (Greeves, 2015). For instance, significantly reduced sagittal plane and greater frontal plane lower-extremity joint motion is commonly observed for women when compared to men for the same jump-landing task (Kernozek *et al.*, 2005), implying that women employ a strategy of reliance on the passive restraints in the frontal plane to control deceleration of the body's centre of mass during jump/landing activities (Pollard *et al.*, 2010).

Regardless of sex, the effect of landing 'stiffness' (i.e., landing with ≤90° knee flexion) reduces the capability of lower-extremity muscle to adequately absorb and/or attenuate impact forces, exposing both men and women to considerably greater MSK mechanical loading in comparison to more flexed knee landings. However, it is thought that women are likely at greater risk of injury as a consequence of stiff-leg landings, as studies have shown a link between reduced sagittal plane knee motion and greater frontal (valgus) plane knee motion, commonly referred to as 'ligament dominance' – a key aetiological factor related to greater knee valgus motion and characterised by the use of anatomical and static stabilisers (ligaments) to attenuate the GRF experienced during jump-landing activities (Hewett *et al.*, 2010), resulting in potentially greater risk of ACL disturbances (Kernozek *et al.*, 2005).

It has been suggested that the forceful extended-knee landing of SaA, SaE, and halt, coupled with the exaggerated heel-strike of QM are responsible for the high tibial impact accelerations ($\geq 200 m/s^2$)[4], vGRF (≥7 BW), loading rates (≥900 BW/s), and TTP values (<0.020s) observed for foot-drill (Carden *et al.*, 2015). In addition, little is known regarding the influence foot-drill has on lower-extremity kinematics and kinetics despite the regimental and standardised movement patterns of foot-drill. Therefore, the purpose of this experimental study was to quantify differences between 3D lower-extremity joint kinematics and kinetics, coupled with ground reaction force (GRF) profiles and temporal variables of common British Army foot-drills within and between groups of recruit age-matched men and women. It was hypothesised that men would produce far greater impact loading profiles in comparison to women, and that women would produce reduced sagittal plane and greater frontal plane knee motion at PvGRF in comparison to men, regardless of the standardised foot-drill manoeuvres.

5.3 Methods

5.3.1 *Participants*

Sample size was estimated using G*Power software (v3.1.9.2, Germany) for a two-way (2[sex] x 5 [foot-drill]) repeated measures ANOVAs (within-interaction) to statistically determine differences in the magnitude of GRF and temporal variables of each foot-drill. Additionally, a three-way (5[foot-drill] x 3[joint] x 2[sex]) repeated measures ANOVA to statistically determine differences in joint kinematics and kinetics across foot-drill and between sex. Only standard G*Power functions were used to determine sample sizes. With an estimated 20% probability (power=.80) of a type II error, an alpha level set at .05, and an estimated effect size of 0.3 (medium-to-large), it was estimated that a total sample size of 16 (8 males, 8 females) was shown to be sufficient to detect significant differences from zero for both types of analyses. Therefore, sixteen novice drill performers volunteered (men n = 8, 26.1 ± 0.8yrs, 179.6 ± 2.5cm, 79.3 ± 6.3kg; and women n = 8, 24.2 ± 2.3yrs, 1.67 ± 4.8cm, 64.8 ± 4.7kg) with no pathological lower-limb, hip or spinal conditions volunteered to participate in this study.

All participants at the time of testing were taking part in moderate physical activity (gym training) and/or sport (soccer, rugby, badminton). Forty-eight hours prior to testing participants refrained from high intensity activity as to eliminate potential fatigue effects on performance data. Ethical approval for this study was gained from Edinburgh Napier University's ethics committee and written informed consent was obtained from each participant prior to data collection. Study participants were defined as "novice foot-drill performers" as they had no prior experience of British Army foot-drill prior to data collection and had similar anthropometric characteristics to that of male and female entry-level recruit populations (Blacker *et al*., 2009) (Men: Δ *n*, %: age = 2 years, 8.1%; height = 2.2m, 1.3%; body mass = 8kg, 9.3%; Women: Δ *n*, %: age = 4.6 years, 19%; height = <0.1m, 0.6%; body mass = 2.4kg, 3.7%).

5.3.2 *Experimental Design and Procedures*

Participants wore a standardised military combat boot and completed a 10min warm up prior to data collection, consisting of dynamic lower-extremity bodyweight exercises, namely, variations of the lunge and bilateral squat (Baechle and Earl, 2008). A single familiarisation session involving ten repetitions of each foot-drill was performed 48h preceding testing. The order of foot-drills was randomised using the RAND function in Microsoft Excel. Each foot-drill is characterised by their own unique movement patterns (BADIM, 2009); QM involves marching at two paces per second whilst impacting the ground with an exaggerated heel strike (controlled by a metronome), whereby SaA, SaE (left-leg) and halt (right-leg) consists of raising the active limb to 90° hip flexion and forcefully stamping the heel onto the ground with an extended-knee (straight-leg) landing. The mean of eight-trials per foot-drill were captured to represent each kinematic, kinetic, and temporal variable for both male and female participants ($CV_{te\%}$ <10%, ICC > 0.75) (Experimental chapter 3 – study 1). A 3D lower-extremity analysis was conducted using time-synchronised motion and force plate analysis. Kinematic data were collected using 12-camera 3-dimensional motion capture (500Hz) (Qualisys Oqus 300, Sweden). Kinetic data were collected using a single piezoelectric Kistler force plate (1000Hz) (Kistler Instruments AG, 9281CA, Switzerland). Marker coordinate data were analysed using Visual 3D v6 professional software (C-Motion, Inc, Germantown, Maryland).

Lower-extremity kinematic data were generated for each foot-drill trial from the 3D coordinates by bilaterally securing 20 retro-reflective markers to anatomical landmarks; anterior superior iliac spine, posterior superior iliac spine, greater trochanter, thigh clusters, medial-lateral epicondyles, medial-lateral malleoli, shank clusters, calcaneus, and 1st and 5th metatarsal heads (Salci *et al.,* 2004), with foot markers secured on the boot (Pollard *et al.,* 2010), defining a three-segment rigid six-degrees-of-freedom link model (Figure 5.0). A static calibration trial was collected from each participant. Participants assumed the anatomical "neutral" position allowing the computation of the transformation matrix between the global and local coordinate systems.

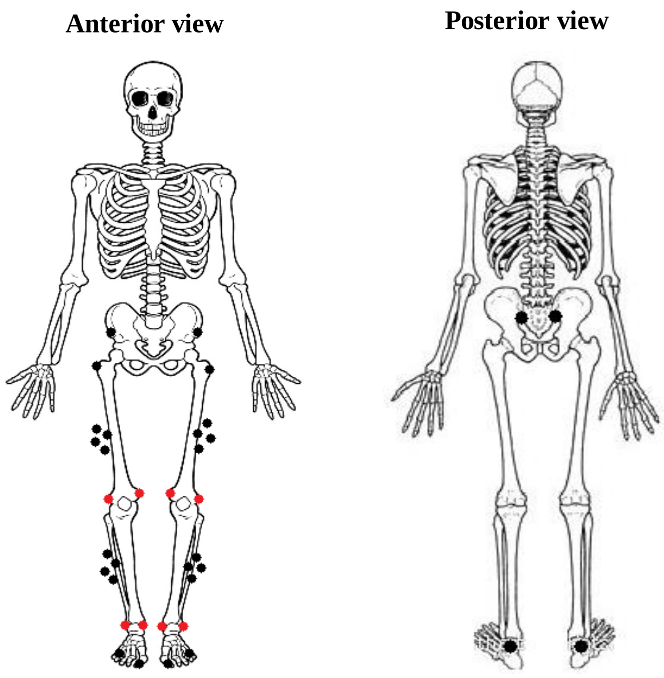

Figure 5.0: Anterior and posterior anatomical 3D motion capture landmarks based around the Helen Hayes model. Red markers represent the calibration markers and were removed prior to data collection.

Based on a frequency content analysis of the digitized coordinate data, using the Fast Fourier Transform (FFT) function in Matlab, marker trajectories were filtered at 10Hz, with halt, SaA, QM, and SaE force plate data filtered at 70Hz, and walk force plate data filtered at 25Hz using a low pass 4th order (single bi-directional) Butterworth filter (Winters, 2009). Joint angular positions and velocities were calculated from the filtered coordinate data. Left and right hip joint centres were calculated automatically from the CODA pelvis (Bell *et al.,* 1990), while knee and ankle joint centres were calculated as 50% of the distance between the medial and lateral knee and ankle markers. Using the static calibration trial as a reference; 0° at the hip, knee, and ankle corresponds to an anatomical standing posture with the thigh and shank in a straight-line, and the foot segment at a right angle relative to the shank (Decker *et al.,* 2003). The Cardan sequence was used to define the ordered sequence of rotations within this study (x=flexion/extension; y=abduction/adduction; z=inversion/eversion) (Kernozek *et al.*, 2005).

By convention, right and left hip flexion and abduction angles, right and left knee extension and abduction angles and, right and left ankle dorsiflexion and inversion angles were described as positive values. In accordance with recommendations from Visual 3D, the right-hand rule was utilised to define the sign conventions for the hip, knee and ankle for both left and right legs as data were extracted from the left (SaA and SaE) and right (halt, QM and walk) leg. Table 5.0 illustrates the specific joint angle sign convention in accordance with the right-hand rule for the left and right hip, knee, and ankle joint. The specific sign convention for the ankle was based on the typical kinetic foot, whereby the z-axis is directed from the metatarsals to the ankle centre. The + and – represent positive and negative rotations about a given axis, respectively.

Joint angle sign conventions for the left and right hip, knee and ankle joints.

		Joint angle sign convention						
Leg	**Joint**	**Flex**	**Ext**	**P/D**	**Abd**	**Add**	**Inver**	**Ever**
Right	Hip	+	-		+	-		
	Knee	-	+		+	-		
	Ankle			+			+	-
Left	Hip	+	-		-	+		
	Knee	-	+		-	+		
	Ankle			+			-	+

Table 5.0: Flex=flexion, ext=extension, P/D=plantarflexion/dorsiflexion, abd=abduction, add=adduction, inver=inversion, and ever=eversion.

From the kinematic and force plate data, the net internal moments for the hip, knee, and ankle joints were calculated from Visual 3D. Peak medio-lateral, anterior-posterior, and vGRF data were calculated. The TTP was determined as the time taken to reach PvGRF from the onset (≥10 N) of the vGRF component. The vRFD was determined as the peak value of the change in vertical force over time. Peak vertical knee joint acceleration (average) was derived from the displacement of the knee joint centre between maximum knee flexion and prior to initial contact (IC) with the supporting surface, defined as the greatest vertical acceleration (m/s^2) prior to initial contact. Mean peak hip and knee joint angular velocity (JAV) was calculated between maximum knee flexion and IC (Decker *et al.*, 2003). All force and vRFD values, and joint moment parameters were normalised relative to BW, BW/s, and Newton-meters per kg of body mass (Nm/kg), respectively (Kernozek *et al.*, 2005; Moisio *et al*., 2003).

5.4 Data Analysis

To statistically compare with the biomechanical variables of QM, eight-trials of a normal walk were analysed. Participants were instructed to walk at their preferred walking speed as measured using timing gates (Fusion sport, SmartSpeed, Australia) with trials excluded if inter-trial variability exceeded +/-5% (Sinclair & Taylor, 2014). For each trial, PvGRF values relative to each lower-extremity kinematic and kinetic parameter were determined. Statistical means and standard deviations for each variable were calculated. Each dependent variable was analysed in the assumption of normality. The TTPvGRF, and sagittal plane angle and moment variables illustrated a significant violation in the assumption of normality for each foot-drill (W: $p<.001$). Therefore, these data were log transformed in SPSS using natural logarithm x10 of the observed value to reduce the magnitude of skewness within the data (Field, 2012).

Data were analysed from the active limb only and averaged across eight-trials for each condition. A series of two-way repeated measures ANOVAs (sex [2 levels]; foot-drill [5 levels]) were used to determine differences in the GRF components and temporal variables, with Bonferroni post hoc analysis performed on significant main effects. Additionally, a three-way repeated measures ANOVA (foot drill [5 levels]; joint [3 levels]; sex [2 levels]) was used to determine differences in joint data, with Bonferroni post hoc analysis performed on significant main effects. All analyses were conducted in SPSS (IBM SPSS^{TM} 20), with an *a priori* exploratory α level of .05.

5.5 Results

Post hoc power calculations using G*Power were conducted and confirmed that the total sample size of 16 (8 male, 8 female) participants provided sufficient power (≥0.84) for both analyses.

5.5.1 *Peak ground reaction forces and vertical rate of force development at PvGRF*

The greatest magnitudes of impact force across all three GRF components were observed for the halt, SaA, and SaE foot-drill (table 5.3). *Between foot-drill:* Statistically significant main effects were observed for each GRF parameter between foot-drills ($p<.001$, range $\eta p^2 = 0.6$-

0.8) with the halt foot-drill demonstrating the greatest magnitudes of GRF for the anterior (0.56 Bw, p <.001), vertical (4.0 Bw, p <.001) and medial components (0.86 Bw, p <.01), with the SaA foot-drill exhibiting the greatest GRF for lateral (1.4 Bw, p <.01), and posterior components (0.4 Bw, p <.01). No significant differences between QM vs walk were observed for any GRF components. *Between sex:* Men produced significantly greater magnitudes of peak vGRF for halt (Δ: 41.5%, d = 2.7, p<.01), SaA (Δ = 31.6%, d = 2.4, p<.01), and SaE (Δ: 33.5%, d = 2.0, p<.01), and significantly greater peak anterior GRF for SaA (Δ: 47.7%, d = 2.4, p<.01), and SaE (Δ: 33.3%, d = 1.1, p =.035) when compared to women. In addition, men demonstrated significantly greater peak medial GRF for halt (Δ: 43.1%, d = 1.5, p= 0.023) and SaE (Δ: 46.5%, d = 1.6, p=.019) when compared to women.

Between foot-drill: Statistically significant main effects indicated significant differences between foot-drill for the vRFD variable (p <.001, $\eta p^2 = 0.7$), with the halt foot-drill exhibiting the greatest magnitudes of vRFD when compared to all other foot-drills (501.7 Bw/s, p <.01). Despite no significant differences between QM and walk for the vGRF, significant differences were observed between QM and walk for the vRFD variable (Δ =72.8%, p =.016, d =1.5). *Between sex:* Men exhibited significantly greater vRFD for halt (Δ = 66.2%, d = 2.7, p<.01), SaA (Δ = 58%, d = 2.5, p<.01), SaE (Δ = 58.4%, d = 1.9, p = 0.016), and walk (Δ = 52%, d = 1.8, p<.01). Despite no significant differences between sex for the QM vRFD variable (p =0.352), men exhibited 39.9% greater vRFD for QM when compared to women exhibiting a large effect (d = 0.6).

5.5.2 *Time to peak vertical ground reaction force and Hip and Knee Joint Angular Velocity*

Lower TTPvGRF values represent a more rapid rise/increase in vertical force. *Between foot-drill:* A statistically significant main effect was observed for the TTPvGRF variables between foot-drills (p <.001, ηp^2 = 0.6), whereby the halt foot-drill for both men and women exhibited the smallest TTPvGRF values when compared to QM (Δ = 95 ms, p = .004, d = 2.1), walk (Δ = 17 ms, p <.001, d = 2.7), and SaE (Δ = 19 ms, p = <.001, d = 1.0), with no significant differences observed for SaA (p =0.078, d = 0.6) when compared to the halt foot-drill. As expected, the walk exhibited the greatest TTPvGRF values when compared to all other foot-drills (mean range: 0.197 vs 0.039 s, Δ = 80.4%). *Between sex:* Men demonstrated significantly smaller TTPvGRF values for the halt (Δ = 44.2%, d = 1.4, p=.034) and SaA foot-drill (Δ = 42.2%, d = 1.4, p=.028) when compared to their female counterparts. Although no further significant sex differences were observed for the TTPvGRF variable, men consistently demonstrated smaller TTPvGRF for the remaining foot-drills (QM: Δ = 54.2%, d = 1.1, SaE: Δ = 33.4%, d = 1.0, and Walk: Δ = 18.7%, d = 0.3) when compared to women.

Between foot-drill: A statistically significant main effect was observed between foot-drills for hip JAV (p <.001, ηp^2 = 0.96) and knee JAV (p <.001, ηp^2 = 0.96). As expected, the halt, SaA, and SaE foot-drill demonstrated significantly greater hip JAV when compared to QM (mean Δ = 426.1°/s, p <.001) and walk (mean Δ = 471.7°/s, p <.001), with the knee JAV expressing a similar pattern when compared to QM (mean Δ = 659.9°/s, p <.01) and walk (mean Δ = 666.8°/s, p <.001). *Between sex:* No statistically significant differences were observed between gender for any foot-drills for the hip and knee JAV variable. However, men consistently demonstrated greater hip and knee JAV for all foot-drills when compared to women (table 5.1).

Hip and knee JAV percentage difference and effect sizes for men and women

	Foot-drill	SD (pooled)	% Δ	Es (*d*)
Hip JAV (°/sec)	Halt	79.3	7.3	0.6
	QM	42.4	17.7	0.8
	Walk	34.8	20.3	0.8
	SaA	41.8	6.7	1.0
	SaE	52.1	4.7	0.5
Knee JAV (°/sec)	Halt	85.5	4.8	0.6
	QM	68.25	2.5	0.1
	Walk	97.13	8.0	0.3
	SaA	76.9	8.6	1.1
	SaE	72.84	8.7	1.2

Table 5.1: SD (pooled) represents the pooled (averaged) SD for both men and women for each foot-drill as to calculate the relative effect size (Es) for each foot-drill as per Cohen's d (*d*) criteria (small: 0.2, med: 0.5, large: 0.8). %Δ = percentage difference between men and women, with men as the denominator.

5.5.3 *Peak vertical knee joint acceleration*

Between foot-drill: A statistically significant main effect was observed for peak vertical knee joint acceleration prior to contact between foot-drill (p <.001, $\eta p^2 = 0.98$) and between sex (p <.01, $\eta p^2 = 0.92$). Unsurprisingly, the halt, SaA, and SaE foot-drill demonstrated significantly greater peak vertical knee joint accelerations when compared to the QM foot-drill and walk (p <.05). As a consequence of the exaggerated heel strike of QM, significantly greater peak vertical knee joint accelerations were observed for QM when compared to the walk (Δ =13 m/s^2, d = 0.2, p <.01). *Between sex*: When compared to women, men exhibited significantly greater peak vertical knee joint accelerations for the halt (Δ =25.7 m/s^2, d = 2.0, p =0.018), SaA (Δ =16.6 m/s^2, d = 2.4, p =0.029) and SaE (Δ =26 m/s^2, d = 1.4, p =0.038) foot-drill, with no significant differences observed between sex for the QM foot-drill (Δ =6.3 m/s^2, d =0.7, p =0.141) or walk (Δ =2.2 m/s^2, d = 0.5, p =0.303), however medium to large effect sizes were observed.

Ground reaction force and temporal variables for men and women.

GRF and Temporal	SaA^L	SaE^L	Men (n = 8) Halt^R	QM^R	Walk^R	SaA^L	SaE^L	Women (n = 8) Halt^R	QM^R	Walk^R
Peak Joint Ang Vel (°/sec)										
Hip	-623.48±41.68	-580.73±57.09	-638.41±76.64	-185.26±24.47	-137.19±26.27	-581.72±41.96	-553.62±47.19	-591.86±81.88	-152.52±60.40	-109.37±43.45
Knee	1029.04±28.12	1004.48±21.44	1082.28±58.80	401.62±72.90	405.97±79.74	940.72±125.71	916.98±124.23	1030.86±111.50	391.70±63.59	373.60±114.52
Peak Vert Knee Acc (m/s^{-2})	109.6±9.1*	111.2±19.2*	140.1±6.5*	27.3±9.9	14.4±5.5	91.4±15.5	85.2±18.6	105.9±30.1	20.9±8.1	12.1±2.9
Peak GRF (BW)										
Medial (+)	0.50±0.19	0.43±0.14*	1.09±0.17*	0.38±0.04	0.35±0.04	0.29±0.24	0.23±0.11	0.62±0.46	0.35±0.25	0.27±0.20
Lateral (-)	-1.66±0.56	-1.41±0.54	-0.92±0.64	-0.34±0.07	-0.27±0.04	-1.15±0.46	-1.15±0.35	-0.89±0.58	-0.29±0.08	-0.31±0.07
Anterior (+)	0.44±0.11*	0.54±0.19	0.62±0.13	0.12±0.02	0.11±0.02	0.23±0.06	0.36±0.15	0.49±0.23	0.12±0.03	0.10±0.03
Posterior (-)	-0.42±0.21*	-0.28±0.22	-0.39±0.15*	-0.08±0.05	-0.09±0.05	-0.38±0.26	-0.32±0.10*	-0.43±0.25*	-0.11±0.07	-0.12±0.05
Vertical	4.26±0.47*	4.18±0.76*	6.19±0.77*	1.38±0.10	1.29±0.08	2.91±0.72	2.78±0.64	3.62±1.14	1.31±0.26	1.22±0.24
Peak vRFD (BW/s)	395.72±74.95*	312.81±121.98*	749.80±235.36*	43.13±22.64	12.70±5.25*	166.19±108.99	130.02±67.24	253.63±127.87	25.88±31.84	6.05±2.27
TTPvGRF (ms)	0.012±0.004	0.015±0.006	0.009±0.001	0.067±0.035	0.176±0.138	0.020±0.009*	0.023±0.010	0.016±0.008*	0.147±0.105	0.217±0.127

Table 5.2: Mean ± SD data for peak extension joint angular velocity for the hip and knee, peak vertical knee joint acceleration, peak X, Y and Z GRF, peak vRFD, and TTPvGRF. * indicates a significantly greater value for that specific sex when compared to the opposite sex. For example, men demonstrated statistically significantly greater mean peak vertical knee acceleration for SaA*, SaE*, and halt * when compared to women. The superscript L and R (left and right) at each foot-drill name corresponds to the specific limb/joint data was taken from.

5.5.4 *Sagittal Plane Joint Angles at PvGRF*

Between foot-drill: Statistically significant main effects were observed for hip (p <.01, ηp^2 = 0.6) and knee (p <.001, ηp^2 = 0.5) sagittal plane joint angles at PvGRF between foot-drills, with no differences observed for the ankle P/D angles (p =.754, ηp^2 = 0.01). The QM foot-drill demonstrated significantly greater hip flexion angles at PvGRF when compared to the SaA ($\Delta°$ =12.1, d =1.1) and SaE foot-drill ($\Delta°$ = 13.8, d =1.2), with the halt foot-drill demonstrating significantly greater knee flexion angles at PvGRF when compared to SaA ($\Delta°$ = 2.5, d =0.1), SaE ($\Delta°$ =6.6, d =0.2) and QM ($\Delta°$ = 9.7, d =0.4). *Between sex:* Statistically significant main effects were observed between sex for hip (p <.001, ηp^2 = 0.6), knee (p <.001, ηp^2 = 0.6), and ankle angles (p <.001, ηp^2 = 0.8) across foot-drill. Women demonstrated significantly smaller mean hip flexion angles for the SaA ($\Delta°$ =8.92, d = 1.4, p =.033) foot-drill relative to PvGRF when compared to men (table 5.5). In addition, women exhibited significantly smaller knee flexion angles for the halt ($\Delta°$=6.6, d = 1.6, p= .042), QM ($\Delta°$ =6.7, d = 1.8, p = .044) and SaA foot-drill ($\Delta°$= 6.6, d = 1.1, p = .014) in comparison to men. These data further indicated that men, when compared to women, exhibited significantly greater ankle plantarflexion angles for SaA ($\Delta°$ =4.2, d = 2.7, p<.001) and SaE ($\Delta°$ =4.4, d = 1.5, p =.006).

5.5.5 *Frontal Plane Joint Angles at PvGRF*

Between foot-drill: Statistically significant main effects were observed for frontal plane hip (p <.001, ηp^2 = 0.9), and knee (p <.001, ηp^2 = 0.6) joint angles, and ankle (p <.001, ηp^2 = 1.0) IN/EV angles at PvGRF. The QM (mean $\Delta°$ =3.3, p <.001), walk (mean $\Delta°$ =4.3, p <.001), and SaE (mean $\Delta°$ =2.8, p <.001) foot-drill exhibited significantly greater hip abduction angles at PvGRF when compared to all other foot-drills, with significantly greater knee abduction angles observed for the halt (mean $\Delta°$ = 2.2, p <.01) and SaE foot-drill (mean $\Delta°$ =1.4, p <.001). In addition, the SaA (mean Δ° = 2.7, p <.01) and SaE (mean Δ° =5.5, p <.01) foot-drill exhibited significantly greater ankle inversion angles at PvGRF in comparison to all other foot-drills. *Between sex:* Significant main effects were observed between sex for frontal plane hip (p <.001, $\eta p^2 = 0.9$), and knee (p <.001, $\eta p^2 = 0.7$) joint angles, and ankle (p <.001, $\eta p^2 = 0.9$) IN/EV angles at PvGRF. In comparison to men, women demonstrated significantly greater hip abduction angles for the SaE foot-drill (Δ° = 4.7, d = 1.7, p = .031), with significantly greater knee adduction angles for the SaA (Δ° = 4.1, d = 1.4, p = .002) and SaE (Δ° = 2.7, d = 1.7, p = .003) foot-drill. In addition, women demonstrated significantly greater ankle inversion angles for the SaE foot-drill (Δ° = 5.34, d = 2.5, p = .007) when compared to men at PvGRF.

5.5.6 *Sagittal Plane Joint Moments at PvGRF*

Between foot-drill: No significant main effects were apparent between foot-drills (p <.05, ηp^2 = 0.3) for hip sagittal plane joint moments. However, significant main effects were observed for knee sagittal plane moments (p <.001, $\eta p^2 = 0.5$), whereby the halt foot-drill exhibited significantly greater knee flexor moments when compared to the QM (Δ° = 2.1 Nm/kg, p = .022), SaA (Δ = 1.7 Nm/kg, p = .018), and SaE foot-drill (Δ = 1.2 Nm/kg, p = .013). In addition, the halt foot-drill exhibited significantly greater dorsiflexion moments at PvGRF when compared to all other foot-drills (mean Δ = 1.6 Nm/kg, p <.001). *Between sex*: No significant main effects were observed for sagittal plane hip (p = .880, ηp^2 = .04), knee (p = 494, ηp^2 = .07), and ankle (p = .580, ηp^2 = .05) between sex across foot-drill at PvGRF.

5.5.7 *Frontal Plane Joint Moments at PvGRF*

Between foot-drill: No significant main effects were observed for frontal plane hip joint moments (p >.05, ηp^2 = .03). However, significant main effects were apparent for frontal plane knee joint moments (p <.001, ηp^2 = 0.6), whereby the halt foot-drill produced the greatest knee abduction moments (mean Δ = 1.6 Nm/kg, p <.01) when compared to all other foot-drills, with the SaA (mean: -0.69 Nm/kg) and SaE (mean: -0.93 Nm/kg) foot-drill exhibiting the greatest adduction moments (mean Δ = -0.81 Nm/kg, p <.01) at PvGRF. In addition, significant main effects were observed for frontal plane ankle joint moments (p <.001, ηp^2 = 0.5), whereby the halt foot-drill exhibited significantly greater inversion ankle joint moments when compared to all other foot-drills (mean Δ = -1.01 Nm/kg, p <.01). *Between sex:* Significant main effects were observed for hip (p <.001, ηp^2 = 0.6) and ankle (p<.001, ηp^2 = 0.8) frontal plane joint moments between sex, with no significant differences observed for the knee joint (p = .560, ηp^2 = .051) at PvGRF. Women demonstrated significantly greater hip adduction (Δ = -1.53 Nm/kg, d = 2.0, p = .013) and ankle inversion (Δ = 0.31 Nm/kg, d = 1.3, p = .025) moments for the SaE foot-drill when compared to men.

Kinematic and kinetic biomechanical foot-drill variables for men and women

Kinematics and Kinetics	Men (*n* = 8)					Women (*n* = 8)				
	SaA^L	SaE^L	$Halt^R$	QM^R	$Walk^R$	SaA^L	SaE^L	$Halt^R$	QM^R	$Walk^R$
Flex/Ext Ang at PvGRF										
Hip	-25.41±9.05	-23.52±12.92	-27.22±9.43	-39.35±11.42	-32.66±18.99	-16.49±3.98*	-15.04 ± 3.64	-22.27±7.23	-26.73±12.06	-29.12±9.67
Knee	-31.91±2.46	-27.98±7.09	-34.37±2.81	-24.77±4.55	-25.29±6.87	-25.27±4.83*	-20.93 ± 6.55	-27.80±5.54*	-18.07±7.33*	-23.97±5.84
Ankle (P/D)	94.54±1.17	91.83±2.70	89.16±2.54	80.17±10.07	78.90±5.77	90.33±1.97*	87.44 ± 3.04*	87.79±2.16	81.46±6.23	80.59±8.37
Abd/Add Ang at PvGRF										
Hip	1.72±3.02	5.11±3.90	-0.35±4.48	-6.79±3.13	-9.01±4.07	1.95±2.15	9.83 ± 1.75*	0.80±3.33	-8.87±3.02	-8.25±4.07
Knee	-0.44±2.16	-1.19±1.49	-3.12±2.94	-0.75±1.32	-0.18±2.72	-5.34±2.77*	-6.78 ± 2.90*	-6.18±3.35	-2.14±3.02	-2.90±3.24
Ankle (Inver/Ever)	11.43±2.93	12.57±2.39	-6.70±2.63	-8.39±3.68	-7.67±±2.90	14.23±3.11	17.91±2.62*	-9.58±2.80	-8.83±2.46	-8.00±1.19
Flex/Ext Mom at PvGRF										
Hip	-2.40±4.13	-2.79±4.97	2.23±4.71	-0.40±0.68	-0.37±1.00	-1.35±2.77	-2.17 ± 2.78	5.00±3.59	-0.27±0.92	1.00±1.01*
Knee	-1.70±2.69	-2.32±3.34	2.89±2.65	0.10±1.09	0.75±1.21	-0.83±1.81	-1.35 ± 1.67	2.74±1.83	-0.14±1.19	0.82±0.72
Ankle (P/D)	-1.03±0.75	-1.39±1.03	0.68±1.06	-0.10±0.92	-0.47±1.09	-0.40±1.07	-0.57 ± 0.82	1.12±0.79	-0.88±0.94	-0.64±1.14
Abd/Add Mom at PvGRF										
Hip	-0.20±0.63	-0.16±0.52	1.08±2.40	0.30±0.62	0.34±0.62	-1.43±1.73	-1.69 ± 1.00*	0.66±1.03	0.75±0.94	0.67±1.14
Knee	-0.60±0.33	-0.87±0.22	1.78±1.98	0.15±0.51	-0.18±0.48	-0.91±1.15	-1.13 ± 0.35	1.27±0.81	0.27±0.83	0.06±1.09
Ankle (Inver/Ever)	0.08±0.10	0.12±0.26	1.03±1.43	-0.05±0.21	-0.09±0.25	-0.12±0.27	-0.19±0.23*	0.86±0.66	-0.01±0.27	-0.08±0.21

Table 5.3: Mean ± SD data for hip, knee and ankle joint angles and moments at PvGRF for men and women across foot-drills. * indicates a significantly greater value for that specific sex when compared to the opposite sex. For example, women demonstrated statistically significant smaller sagittal plane knee angles for SaA*, halt*, and QM. The superscript L and R (left and right) at each foot-drill name corresponds to the specific limb/joint data was calculated from.

5.6 Discussion

This experimental study is the first to quantify the lower-extremity kinetics and kinematics of British Army foot-drill and compare between age-matched civilian men and women. Based on the distinct physiology and anatomy of women in comparison to men, it was hypothesised that women would exhibit greater frontal plane lower-extremity joint motion when compared to men, and that men would produce significantly greater magnitudes of GRF and temporal variables, namely, JAV, knee accelerations and peak vGRF. In agreement with these hypotheses, women exhibited greater frontal plane hip and knee motion, and greater ankle dorsiflexion at PvGRF when compared to men, whereas men displayed greater hip and knee flexion and ankle plantarflexion at PvGRF, coupled with significantly greater impact loading forces for all foot-drills when compared to women.

5.6.1 *Peak vertical ground reaction force and rate of force development*

It was expected that men would demonstrate significantly greater magnitudes of peak vGRF across foot-drill when compared to women, along with significantly greater magnitudes of vRFD in SaA, SaE, and halt. However, despite these differences, the magnitude of impact forces and loading rates of foot-drill reported for men and women were similar to those reported in previous experimental studies, and that of male and female soldiers (Carden *et al*., 2015). In addition, three men exhibited peak vGRF and vRFD in excess of 7.1 BW and 700 BW/s, respectively, providing evidence to suggest that some recruits may be at greater risk of tibial and femoral stress fractures when compared to others. However, it has been shown that acute bouts of high impact loading activity (i.e., hopping, drop-jumps), similar to the vGRF reported for foot-drill, may actually enhance bone density in the tibia and femoral neck, thus reducing risk of microdamage and subsequent fracture (Allison *et al*., 2013; Izard *et al*., 2016).

Nevertheless, the superior levels of physical fitness of soldiers in comparison to recruits provide the soldier with greater capacity to manage and cope with the high impact loading forces of foot-drill, in comparison to the poor initial physical fitness levels of recruits and subsequent increased risk of injury during BMT.

5.6.2 *Time to peak vertical ground reaction force*

The mean TTP relative to SaA, SaE, and halt are comparable to high impact loading activities that are routinely programmed in accordance with a periodised model of training due to the high risk of injury. For example, 61cm drop jumps (Bauer *et al*., 2001), land-based single-leg vertical jumps and countermovement jumps (Donoghue *et al.*, 2011), and extended-knee (straight-leg) gymnastic landings (Seegmiller and McCaw, 2003). The TTP of foot-drill ranged between 0.024 – 0.007s. According to research, the threshold range for muscle to actively respond to the landing/contact stimulus is between 0.05-0.07s (Donoghue *et al.,* 2011). Peak impact forces achieved below and/or between these ranges are referred to as passive forces, whereby the term 'passive' refers to the rapid onset of these forces and the inability of the neuromuscular system to apply a reaction response during the landing phase of the activity (Devita and Skelly, 1994). Based on this study, the TTP data representative of foot-drill, most notably, SaA, SaE and halt, have been found to be below this threshold range. Therefore, it is suggested that the passive forces of British Army foot-drill observed for untrained men and women may not be under sufficient neuromuscular control, reflecting an inability of lower-extremity musculature and/or impairments in specific neuromuscular systems to effectively attenuate the forces transmitted up the kinetic chain.

5.6.3 *Peak vertical knee joint impact acceleration and joint angular velocity*

Vertical tibial impact acceleration of foot-drill has been defined as the displacement of the tibial tuberosity after a portion of the load has been attenuated by footwear and/or surface characteristics (Carden *et al*., 2015), and is also considered an important factor for injury risk. More specifically, the magnitude of tibial shock has been linked to athletic overuse injuries including stress fractures (Milgrom *et al*., 1985) and medial tibial stress syndrome or 'shin splints' (Detmer *et al*., 1986). Peak tibial impact acceleration is frequently used as an indirect estimate of mechanical loading experienced by the tibia post impact and has been successfully used to discriminate between runners with and without a history of tibial stress fractures (Milner *et al*., 2006). As the foot contacts the ground, a positive upwards axial acceleration is observed. During walking, running, and jump-landings authors have reported peak positive impact accelerations ranging from 3g for walking, to 8g for jump-landing activities. Higher values of 9-11g have been reported for individuals running in more challenging conditions (i.e., muscle fatigue and increased stride length), or when running downhill (Coventry *et al*., 2006; Chu *et al*., 2004). However, in a study by Rice *et al*., (2018) peak positive tibial impact accelerations for foot-drill were found to be greater than those reported for walking, running and landing - exceeding very high thresholds (>15g). Additionally, significantly greater magnitudes of tibial shock were observed for male recruits and during the final weeks of Phase one training when compared to female recruits and week one of training, respectively.

The extremely high tibial shock values reported for foot-drill are considerably greater that those observed during other high impact loading activities such as running and jumping and may contribute to the high rate of lower-extremity injuries in recruits, particularly the high stress fracture incidence. The magnitude of peak vertical knee joint acceleration observed in this study for foot-drill may be associated with the high tibial shock reported by Rice *et al*., (2018).

Given that recruits are taught to forcefully stamp onto the surface of the ground and land with an extended-knee, it is likely that the velocity of the hip and knee joint (range: 391 – 1082°/s), and the peak vertical knee acceleration (range: 85 [8.7g] – 140m/s^2 [14.3g]) observed for both men and women of this study are key contributing factors to the overall magnitude of tibial shock observed during foot-drill. Although greater magnitudes of tibial shock have been shown to be associated with greater stress fracture risk in civilian populations (Milner *et al*., 2006), it is yet to be determined whether the magnitude of tibial shock during foot-drill has detrimental effects on bone health in male and female recruits, thus warranting further investigation.

Research indicates that the occurrence of a stress fracture is thought to be linked with a quantity, or 'dose' of loading, whereby the dose may be a combination of peak shock, GRF, and loading rate (Milner *et al*., 2006) – variables that are all dependent on the velocity and/or acceleration of movement prior to contact with the supporting surface. Considering that the principal feature of British Army foot-drill is to vigorously stamp down on to the surface of the ground with an extended (straight-leg) landing, the magnitude of acceleration and JAV are expected and have been implicated in the development of such lower-extremity MSK overuse injuries as bone stress fractures of the tibial, femur and pelvic girdle (Carden *et al*., 2015; Milner *et al*., 2006). Based on these results, it is suggested that knee joint accelerations and JAV be considered key parameters in which can be manipulated to reduce the magnitude of the loading 'dose' of British Army foot-drill on MSK structures of the lower extremities, thereby reducing the potential of lower-extremity MSK overuse injury in untrained recruits.

5.6.4 *Sagittal and frontal plane joint angles and moments*

Similar to that of the British Army, Australian, Canadian, and New Zealand Army recruits are all taught foot-drill to a common standard, which is to vigorously stamp down onto the surface of the ground with an extended-knee (straight-leg), whilst actively minimising the range of knee and hip flexion at ground contact. Although it is currently unknown whether other military nations have conducted similar research surrounding the potential biomechanical risk factors of foot-drill, it is possible that the data reported from the present thesis may be generalizable to Army recruits serving in different nations. Nevertheless, given the standardised and regimental movement patterns of British Army foot-drill, hip and knee flexion angles <90° for both men and women at PvGRF were expected.

Despite the regimental movement patterns of foot-drill, significant differences were observed between men and women across foot-drill, whereby it was observed that both male and female recruits adopted their own specific lower-extremity landing profile to best manage and/or influence the high impact forces, loading rates and regimental movement patterns (i.e., extended-knee) of foot-drill. For example, women demonstrated significantly reduced hip (mean angle: 19.6° vs 25.4°, Δ=6.7°) and knee flexion angles (mean angles: 24.7° vs 31.4°, Δ= 5.8°) for the SaA, SaE and halt foot-drills, along with significantly reduced hip (mean angle: 26.7° vs 39.4°, Δ=12.6°) and knee (mean angle: 18.1° vs 24.8°, Δ=6.7°) flexion angles for QM in comparison to men. Women also exhibited significantly greater frontal plane knee valgus angles (mean angle: 6.1° vs 1.6°, Δ= 4.5°) for the SaA, SaE and halt foot-drill when compared to men, whilst producing peak vGRF and vRFD values in excess of 3.5 BW and 250 BW/s. From these data, it is apparent that untrained men and women adopt different lower-extremity landing mechanics for the same military occupational activity (i.e., foot-drill), reflecting the impact of differences in lower-extremity physiology and anatomy between sex.

It has been well documented that women, in comparison to men are at a significant biomechanical and anatomical disadvantage during most aspects of physical training and are consistently found to exhibit distinct lower-extremity mechanics during activities that involve sudden deceleration of the body's centre of mass. In particular, women have shown to perform such athletic manoeuvres as high-level plyometric exercises (i.e., drop jumps) with decreased hip flexion, knee flexion, increased knee valgus angles, and greater internal knee adductor moments (Ford *et al.,* 2003; Kernozek *et al.,* 2008; Hewett *et al.*, 2002). These specific performance markers make-up a biomechanical profile that is somewhat similar to that observed in women for British Army foot-drill, and consistent with the anterior cruciate ligament (ACL) injury mechanism, potentially exposing female athletes and/or recruits to an increased risk of knee ligament injury. In addition, prospective studies have determined that the majority of recorded ACL disruptions (i.e., strains, tears and ruptures) within athletic female populations occur when the knee joint is near-full extension (<45°) (Yu *et al.*, 2011).

The extended-knee biomechanical profile representative of foot-drill is thought to be a key risk factor associated with the development of bone stress fractures and knee ligament disruptions in recruit/athletic populations. During flexed knee landings (>90°) the muscular system acts as the primary shock absorbing mechanism, whereas during extended-knee landings, the insufficiency of energy dissipation coupled with excessive vGRF is thought to substantially increase the risk of knee ligament damage and compressive lower-extremity fracture loads (Zhang *et al*., 2000). For instance, Makinejad *et al.*, (2013) conducted a finite element and simulation modelling analysis of the knee joint during extended-knee landings from 25cm and 50cm drop heights. The results indicated that the magnitude of stress and contact pressure distribution during extended-knee landings caused substantial depression of the tibial and femoral cartilage and meniscus, whereby contact pressures ranged from 23.1 - 128.7 MPa, resulting in a total depression of 48% between the tibia plateau and femoral condyle.

In addition, the peak vGRF reported for extended-knee landings of Makinejad *et al*., (2013) were similar to those observed for foot-drill (mean vGRF: 7.6BW vs 6.2BW), demonstrating that the forceful extended-knee landing of British Army foot-drill represents a substantial and potentially injurious mechanical load, and that recruits may be at greater risk of serious deformation of the meniscus and/or cartilage of the knee, coupled with bone-to-bone contact between the proximal tibia and distal femur. Considering the potential for injury linked to the biomechanics and contact stress distributions reported for extended-knee landings (Makinejad *et al*., 2013), coupled with the significantly reduced hip and knee flexions angles reported for women for the SaA, SaE and halt foot-drill, it is reasonable to suggest that whilst both men and women recruits may be at risk of injury associated with the biomechanics of foot-drill, the physiology and anatomy of women may expose them to greater risk of knee ligament injury, and may in fact contribute to the high incidence rates of knee MSK injuries observed during the initial weeks of BMT.

It is well recognised that for the majority of research studies (Cortes *et al.,* 2007; Devita and Skelly, 1992; Fowler *et* al., 1993; Hewett *et al.,* 2010 Pollard *et al.,* 2010; Myer *et al.,* 2004) women have consistently demonstrated significantly greater knee valgus angles and adductor moments during various jump-landing activities that involve a sudden deceleration when compared to their male counterparts. As such, the results of the current experimental chapter demonstrate similar findings, whereby women exhibited significantly greater knee valgus angles for the SaA, SaE and halt foot-drill, demonstrating a lower-extremity landing profile combining both reduced sagittal yet increased frontal plane knee motion whilst producing peak vGRF and vRFD values similar to that of high level plyometric activities (e.g., 60cm drop jumps (Wallace *et al*, 2010)) and parachute landings at descent velocities of 2.1m/s and 3.3m/s (Whitting *et al*., 2007). The combined greater frontal plane (knee valgus) and reduced sagittal plane (knee flexion) motion demonstrated by women in comparison to men, is a principal risk factor associated with the ACL injury mechanism, and has been a key finding within the current experimental study, as females are now operating in more physically demanding roles within the British Army, and thus the risk of injury is likely to increase (WGCC Interim report, 2016).

The results of the current experimental chapter are similar to those reported previously. Pollard *et al*., (2010) found that female soccer players exhibited significant reductions in knee flexion and increased knee valgus angles during 36cm drop landings. In addition, Laughlin *et al.,* (2011) investigated differences in sagittal plane knee kinematics and peak ACL force between self-selected 37cm soft and stiff-leg (<90°) landings, whereby 23% greater peak ACL force was associated with a more extended-knee landing in physically active females, thus increasing risk of rupture. Similarly, Podraza and White, (2010) quantified the effect of different degrees of knee flexion at landing during a sudden deceleration task. It was found that greater knee extensor moments were accompanied by greater degrees of knee flexion due to the orientation of the resultant force vector being greater relative to the knee joint centre, yet the greatest magnitudes of peak vGRF and loading rates were found for landings within a 0-25° knee flexion range, similar to that observed during foot-drill. It was further suggested that vGRF are more likely to be greatest and knee extensor moments smallest when adopting an extended-knee landing strategy. Thus, research proposes that greater ACL strain and/or injury from non-contact deceleration (i.e., foot-drill) may be linked to the rapid translational joint forces that propagate up the kinetic chain in the absence of sufficient impact absorption from muscle flexors/extensors (Podraza and White 2010). In agreement with research (Pollard *et al*., 2010; Laughlin *et al.*, 2011; Podraza and White 2010) the results of the current experimental chapter demonstrate reductions in knee flexion and increases in knee valgus angles for SaA, SaE and halt foot-drill for women in comparison to men, supporting the theory that females who actively limit sagittal plane motion employ a strategy of reliance on passive restraints in the frontal plane to best control deceleration of the body's centre of mass and manipulate the magnitude of loading transmitted up the kinetic chain.

Specific to the QM foot-drill, women exhibited significantly reduced hip (26.7° vs 39.4°, Δ=12.6°) and knee flexion angles (24.8° vs 18.1°, Δ=6.7°) in comparison to men, indicating that women adopted a more erect lower-extremity biomechanical profile at PvGRF. Regardless of sex, similar peak vGRF were observed for QM and a normal walk (mean vGRF: 1.35BW vs 1.26BW, Δ=6.7%), yet QM exhibited considerably greater peak vRFD values (mean vRFD: 34.51BW/s vs 9.4BW/s, Δ=72%), suggesting that the greater magnitudes of vRFD observed are associated with the exaggerated heel-strike of QM (figure 4.3), and when coupled with reduced sagittal plane hip and knee motion, recruits may be at an increased risk of marching-related injury.

Both U.S (Kelly *et al.*, 2000) and British (Hill *et al*., 1996) Army research has shown that QM is responsible for a large portion of pelvic and lower-extremity stress fractures in female recruits, whereby it has been determined that the impact of integrated physical training, specifically the standardised 30" stride-length, is a key aetiological factor that increases GRF and shear stress at the narrow isthmus resulting in fracture of the pubic rami. Since the work of Hill *et al*., (1996) and Kelly *et al*., (2000) both the U.S and UK Armed forces have reduced the standard 30" stride-length for women to 27" (U.S) and 26" (UK) and placed those women who are noticeably shorter in stature at the front of marching platoons. Despite Hill *et al.,* (1996) confirming a reduction in pelvic stress fractures following a reduction in marching stride-length, published communication regarding changes in lower-extremity kinematics and reductions in peak/cumulative impact loading forces between 30” and 26” stride-length remains elusive. Therefore, it is recommended that further empirical study is conducted to quantify the biomechanical differences associated with the 30” and 26” marching stride-length to better understand the implications of marching-related injury risk in British Army recruits.

There is increasing evidence to suggest that insufficient and/or altered neuromuscular control of the lower-extremities, in particular the knee joint during extended-knee (straight-leg) landing, significantly contributes to the risk of sustaining knee ligament injury and considered a key factor of the ACL injury mechanism (Hewett *et al.*, 2000; Hewett *et al.*, 2002). Empirical study has shown that repetitively impacting the ground with an extended-knee (straight-leg) landing, similar to that observed during foot-drill, may compromise knee joint stability from reduced knee excursion, resulting in decreased energy absorption by local musculature culminating in greater risk of injury (Nagai *et al.*, 2013; Schmitz *et al.*, 2007). In addition, Twist *et al.*, (2008) reported a latent impairment in lower-extremity neuromuscular function 24-hours proceeding an acute bout of plyometric training, a training modality shown to be biomechanically similar to the kinematics and GRF of British Army foot-drill. It was concluded that the reduction and/or impairment in neuromuscular control, as measured by unilateral static postural stability, was attributed to a complex interaction of central and peripheral mechanisms. Due to similarities in lower-extremity kinematics and impact loading forces between foot-drill and high level plyometrics, coupled with the implications of knee injury and/or damage associated with the extended-knee landings of SaA, SaE and halt, it is hypothesised that the physical demands of foot-drill training may alter and/or impair somatosensory and sensorimotor function in an untrained age-matched female population.

A limitation of the current experimental chapter was that 3-dimensional kinematic calculations are known to be influenced by a degree of soft tissue artefact (STA), defined as skin deformation/displacement causing marker movement with respect to the underlying bony structure (Leardini *et al*., 2005). This was illustrated by the high amounts of variation (SD) in kinematic measures, thus caution is recommended when interpreting these data. Thus, to reduce the magnitude of risk of STA on foot-drill data, all anatomical landmarks were clearly defined and in accordance with Visual 3D recommendations. Furthermore, marker-based analyses are highly dependent upon marker placement. Thus, to minimise inconsistency of marker placement, the lead researcher was responsible for all marker placement for both male and female participants. Furthermore, as a means of attenuating STA or “noise”, all marker-based kinematic data were low-pass filtered (removal of high frequency noise) based on *a priori* frequency content analysis from the FFT function in Matlab.

5.7 Conclusion

The regimental movement patterns of British Army foot-drill, namely the forceful extended-knee (straight-leg) landing of SaA, SaE and halt, coupled with the exaggerated heel-strike of QM has been shown to exhibit lower-extremity biomechanical profiles that are likely to contribute to greater risk of stress fracture and knee ligament disruptions (ACL injury). Women, in comparison to men, may be at greater risk of foot-drill related injury due to their reduced sagittal plane and increased frontal plane knee motion observed for SaA, SaE and halt, coupled with specific phenotypic traits that naturally disadvantage women in most aspects of physical performance (i.e., reduced muscle size and strength, more slender pelvic and tibial bones, and a wider pelvic width to femoral length ratio). Based on these results and that women are likely at greater risk of training-related injury due to the greater physical demands of close combat roles (WGCC Interim report, 2016), it is recommended that the magnitude (i.e., vGRF and vRFD), volume, and frequency of foot-drill training be structured accordingly to match the physical limitations of women (and men) as demonstrated in the current experimental chapter, along with the minimal performance requirements necessary to pass foot-drill assessments.

As previously mentioned, it has been hypothesised that the regimental movement patterns and high impact loading forces of foot-drill may alter and/or impair lower-extremity neuromuscular function and joint proprioception. Therefore, the aim of experimental chapter 5 – study 4 is to quantify such changes following an acute bout of British Army recruit foot-drill training. These results have the potential to better inform commanders (2* ranked personnel) of the implications of injury associated with the demands of foot-drill, and the risk of injury during subsequent military training.

6.0 Experimental Chapter 5 – Study 4

6.1 Changes in Ankle Joint Proprioception and Neuromuscular Function following an Acute Bout of British Army Foot Drill: Implications of Lower-Extremity MSK Injury Risk in Novice Female Foot-drill Performers.

6.2 Introduction

Per the Ministry of Defence Annual Medical Discharge report, 2016/17, the discrepancy in medical discharges between male (21.9 per 1,000 personnel at risk) and female recruits (26 per 1,000 personnel at risk, Δ=15.8%) is a reflection of the diverse and multi-factorial aetiology of occupational training-related injury risk factors, coupled with distinct phenotypic differences between men and women that inevitably expose women to greater risk of injury during arduous physical training. Therefore, it is suggested that lower-extremity MSK injury mechanisms and training-related injury risk factors be examined independent of sex, especially as women are now undertaking physical training for ground close combat (GCC) roles (i.e., infantry and armoured corps (WGCC Interim report, 2016)).

Coupled with recent foot-drill research (Rice *et al*., 2018), experimental studies 3, 4 and 5 have identified several biomechanical characteristics associated with the exaggerated heel strike of QM, and the forceful extended-knee (straight-leg) landing of SaA, SaE and halt. From these data, it was reported that women are likely at greater risk of lower-extremity stress fracture and knee ligament strain and/or injury due to reduced sagittal plane and increased frontal plane motion of the hip and knee joint, whilst producing similar peak vGRF and vRFD to that reported for high level plyometric exercises (>3.5BW and >350BW/sec). Furthermore, mean peak knee joint vertical accelerations and peak positive tibial accelerations of approximately 15g (130m/s^2) (experimental chapter 5 – study 3) and 20.8g (204m/s^2) (Rice *et al*., 2018) were observed for novice foot-drill performers and recruit personnel, respectively. In addition, the time to peak vGRF reported for women during SaA, SaE and halt (range: 0.016-0.020s) were achieved below the threshold range (50-70ms) for muscle to actively respond to the landing stimulus (Donoghue *et al.*, 2011). These data suggest that the passive forces of foot-drill may not be under sufficient neuromuscular control, potentially causing changes and/or impairments in neuromuscular function and lower-extremity joint proprioception, resulting in greater magnitudes of stress being applied to bone and connective tissue that may exceed the maximum tolerable stress for MSK structures to absorb and/or attenuate high impact loading forces.

Landing technique plays a key role in lower-extremity joint stability, whereby landing with an extended-knee has been shown to alter and/or compromise lower-extremity joint stability from reductions in kinetic energy absorption by local musculature (Fu *et al.*, 2005; Schmitz *et al*., 2007) and/or desensitisation of peripheral mechanoreceptors located in the muscle spindles and Golgi tendon organs of lower-extremity joints (Saxton *et al*., 1995). For instance, Twist *et al.*, (2008) reported a latent impairment in lower-extremity neuromuscular control as measured by static postural stability following a period of high intensity plyometric training; a training modality known to exhibit similar impact loading forces and 3-dimensional lower-extremity kinematics as foot-drill. It was found that healthy participants immediately, and 24r after a period of high impact loading activity demonstrated increased variability in static postural stability reflecting altered lower-extremity neuromuscular control, whereby it was suggested that the greater variability may increase the risk of injury following a period of high impact loading activity. The specific mechanism responsible for such changes in neuromuscular control was said to be attributable to a complex interaction of central and peripheral mechanisms. However, further research is required to identify the precise contribution of each mechanism to better understand the aetiological factors associated with reductions in somatosensory function.

Measures of static and dynamic postural stability are often utilised as a means of detecting lower-extremity landing and stability alterations, and/or deficiencies pre-post injury (Meardon *et al*., 2016) and between sex (Wikstrom *et al*., 2006). Studies have utilised non-linear measures of static and dynamic postural stability, namely Sample Entropy (SampEn) and the Dynamic

Postural Stability Index (DPSI) respectively, to quantify the magnitude of variability and complexity (irregularity) within time series data, namely displacements in centre of pressure (CoP) during a static (upright unilateral stance) or dynamic (single-leg-hop-stabilisation) setting to better understand the dynamics of somatosensory behaviours associated with disease and deficiencies in postural control systems following a particular physiological stress. For instance, Roerdink *et al*., (2011) quantified the effects of plantar-flexor muscle fatigue on the magnitude and regularity of CoP fluctuations during quiet unilateral static stance, whereby the magnitude of CoP fluctuations significantly increased with fatigued plantar-flexor muscles. Furthermore, more regular (i.e., less complex and possibly impaired) CoP fluctuations were observed with fatigue as illustrated by significantly lower SampEn values (pre-fatigue = 0.86, post-fatigue = 0.80, $p<.05$, $\Delta = 6.98\%$). Brown *et al*., (2010) reported that females with chronic ankle instability (CAI) demonstrated significantly greater vertical stability index and DPSI scores when compared to healthy controls, reflecting altered and/or impaired lower-extremity proprioceptive and neuromuscular function. It was suggested that the greater DPSI scores in CAI may have been attributable to increased laxity and/or damage to the anterior talofibular ligament – a key factor associated with lateral ankle instability.

Measures of static and dynamic postural control rely on proprioceptive feedback and pre-programmed muscle patterns, as well as reflexive and voluntary muscle responses. As such, joint position sense (JPS) has frequently been used as a functional measure of lower-extremity joint proprioception, whereby JPS is assessed by determining the error associated with active or passive reproduction of a joint angle (Deshpande *et al.,* 2003). Despite many studies using the threshold to detect passive motion as a means of quantifying proprioceptive capabilities (Deshpande *et al.,* 2003), previous reliability analysis demonstrated excellent intersession reliability for JPS of lower-extremity joints (ICC = 0.83) and as a result, is frequently used to detect knee and ankle proprioceptive deficiencies in various laboratory settings (Yokoyama *et al.*, 2008). For instance, Boyle and Negus (1998) quantified the magnitude of ankle JPS error between reoccurring ankle sprains and healthy controls, indicating that individuals suffering from functional ankle instability produced significantly greater magnitudes of JPS error in sagittal (plantarflexion) and frontal (inversion) plane ankle joint motion. In addition, Eils and Rosenbaum (2001) reported significantly reduced ankle JPS error, reflecting improved ankle joint proprioception in patients with CAI following a 6-week multi-station proprioceptive exercise programme.

It was hypothesised that the high impact loading forces and forceful extended-knee (straight-leg) landings of foot-drill, coupled with the known anatomical and physiological characteristics of the female MSK system may expose women to altered and/or impaired somatosensory (static and dynamic postural stability) and sensorimotor (joint proprioception) function following a bout of foot-drill training. To date, the relationship between a single period of British Army foot-drill and the associated cyclic high impact (extended-knee) landings on measures of neuromuscular function and ankle joint proprioception have not been explored. Rather, foot-drill research has focused primarily on analysing biomechanical risk factors in a laboratory setting of independent foot-drills in male and female trained soldiers and recruits, concluding that foot-drills such as SaA, SaE, halt, about turn and QM represent a substantial mechanical load (Carden *et al.*, 2015; Connaboy *et al.*, 2011). Research has yet to quantify the cumulative effects these regimental movement patterns have on predictors of injury risk in novice female drill performers immediately following an acute bout of British Army recruit foot-drill training. Quantifying the effects of foot-drill training in women on potential changes and/or impairments in somatosensory and sensorimotor function may be indicative of; the short-term implications of lower-extremity MSK injury, and its potential role in specific lower-extremity MSK injury mechanisms associated with ankle and knee ligament injuries/disorders in female recruits.

Therefore, the aims of the present study are two-fold: (i) examine the potential pre-post foot-drill training responses and/or impairments in static postural stability using SampEn and dynamic postural stability using the DPSI, and (ii) quantify the potential differences in ankle joint proprioception from JPS pre-post a period of foot-drill training in novice female foot-drill performers. Based on the results from Twist *et al.,* (2008), coupled with the potentially injurious biomechanical characteristics reported previously in experimental chapters 3 to 5, it was hypothesized that participants would exhibit greater regularity (i.e., reduced complexity) and increased DPSI and composite scores, along with greater JPS error post foot-drill training, reflecting impaired static and dynamic postural stability and ankle joint proprioception when compared to mean baseline and pre-test values.

6.3 Methods

6.3.1 *Participants*

Due to a lack of available resources and time it was not possible to collect pilot data prior to this study. Sample size was estimated using G*Power software (v3.1.9.2, Germany) for a repeated measures ANOVA (3[time]) to statistically determine differences in JPS and static and dynamic postural stability following a bout of foot-drill training. Only a standard G*Power function was used to determine sample size. With an estimated 20% probability (power=.80) of a type II error, an alpha level set at .05, and an estimated effect size of 0.3 (medium-to-large), it was estimated that a sample size of 20 female participants would be sufficient to detect a significant difference from zero. Due to time constraints and limited resources, only fourteen female foot-drill performers were recruited (n=14, 23.2 ± 2.5yrs, 169.7 ± 3.5cm, 68.2 ± 4.3kg) and self-reported no pathological lower-limb, hip or spinal conditions 48h prior to data collection.

All participants at the time of testing were taking part in moderate physical activity (gym training) and/or sport (soccer, rugby, badminton) 2-3 times per week (Decker *et al*., 2003) and were recruited from local Edinburgh Napier University sports teams. Forty-eight hours prior to testing participants refrained from high intensity activity as to eliminate potential fatigue effects on performance data. Ethical approval for the present study was gained from Edinburgh Napier University's ethics committee and written informed consent was obtained from each participant prior to data collection. Similar to previous experimental chapters of this thesis, study participants were defined as "novice drill performers" as they had no prior experience of British Army foot-drill prior to data collection and had similar anthropometric characteristics to that of female entry-level recruit populations (Blacker *et al*., 2009) (Women: Δ *n*, %: age = 3.4years, 14.6%; height = 0.04m, 2.3%, body mass = 8.2kg, 12%).

6.3.2 *Experimental Design and Procedures*

A within-participant repeated-measures design was utilised to quantify differences in ankle joint proprioception using JPS, and neuromuscular function from measures of static and dynamic postural stability (Centre-of-Pressure (CoP)) pre - post an acute bout of recruit British Army foot-drill training. The foot-drill training session was standardised across all study participants in terms of duration, number of different foot-drills, time taken on each individual foot-drill, total number of impacts, and recovery periods. Each participant performed a period of familiarisation as to eliminate potential learning and/or practice effects (Hopkins, 2000); involving multiple practice trials of ankle JPS and static and dynamic balance prior to collecting baseline measures. Ankle JPS and postural control data were collected and analysed from the dominant limb only; defined as the limb used to strike a ball (Brown *et al*., 2004).

Ankle JPS testing was performed first, reducing potential neuromuscular fatigue effects from postural control assessment (Brown *et al.,* 2004).

6.3.3 *Ankle Joint Positional Sense*

Frontal (Inversion/Eversion (IN/EV)) ankle JPS was assessed by using a Biodex dynamometer (Biodex Medical Systems, Shirley, New York, USA). Joint positional sense was analysed by the determination of the absolute error, calculated as the absolute difference between the test and reproduced angle - encompassing both systematic and random error; and variable error, calculated as the SD of the absolute error associated with the passive reproduction of the test angle(s). Participants were seated with the back rest inclined at 70° relative to the horizontal plane, with the ipsilateral knee joint flexed 45° (Sefton *et al.,* 2009). The axis of rotation of the foot/ankle apparatus for IN/EV passed through the fibula malleolus and the body of the talus at approximately 35°. Specific to the present thesis, the dominant ankle served as the testing limb for all JPS assessment, given that proprioception of the lower-limb has been shown not to be influenced by limb-dominance (Lephart *et al.*, 1996). Participants were restrained by a thigh and knee strap, with both arms folded across the chest preventing upper-body fixing (figure 6.0). Participants were blindfolded to eliminate any contribution of visual cues to the positioning of the dominant ankle. Frequent recovery periods were given throughout the test session to prevent fatigue and to assist with concentration.

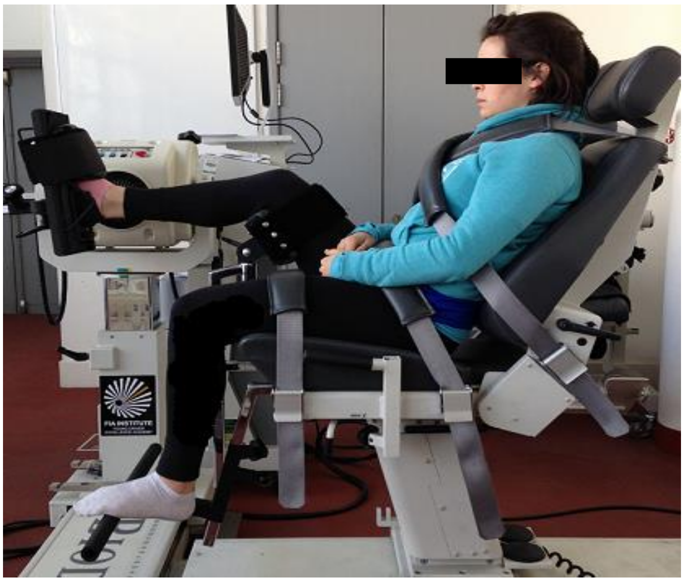

Figure 6.0: Joint positional sense (JPS) assessment of the dominant limb.

The dominant ankle was positioned in a clinically designated neutral or 0° position, achieving 90° between the foot and tibia (Brindle *et al.,* 2010). Ankle IN/EV range of motion (ROM) were determined prior to data collection, whereby 30% and 60% of each participant's full IN/EV ROM was calculated and utilised as JPS test angles; accounting for relative ankle joint flexibility and reducing the effect of additional sensory input from cutaneous receptors at extreme ROM (Burke *et al.,* 1988). The dominant ankle was randomly (RAND function in Microsoft Excel) moved passively into one of three test positions (°), namely, 30% and 60% inversion and 30% eversion. Each test angle was locked into position for 10secs (Brown *et al.,* 2004), followed by passively moving the ankle joint through its respective ROM (60°/sec) before returning to neutral (0°) (Sefton *et al.,* 2009). Participants would attempt to reproduce the test angle and orientation of the foot. Once completed, participants actively pressed a handheld trigger; recording the degrees of error (°) between the test and reproduced angle (South and George, 2007). The mean of three trials from each IN/EV JPS condition at baseline and pre-post foot-drill training was collected (total *n* trials = 9) and utilised for further statistical analysis.

6.3.4 *Static Postural Control*

Three axis (X, Y, Z) ground reaction forces (GRFs) of static and dynamic postural stability were collected at 1000Hz using a Kistler force plate (Kistler Instruments AG, 9281CA, Switzerland). Static postural stability trials were counterbalanced (RAND function in Microsoft Excel) and determined from two tasks; 1) eyes open (EO), and 2) eyes closed (EC). Prior to static and dynamic postural stability data collection, participants were issued a size specific pair of British Army in-service combat boots and worn them throughout data collection for this study. In accordance with previous studies (Sell, 2012) participants assumed a single-leg stance on the dominant (stance) limb only with hands placed on hips. The non-stance limb was flexed at the knee joint as to bring the non-stance foot to the height of the contralateral malleoli. Trials were discarded and repeated if the participant's non-stance limb contacted the stance limb or the ground around the force plate. Participants were asked to look straight ahead during EO to standardise visual influence on balance. A total of five 30sec trials were collected from each static task, with 60sec recovery between trials. All participants performed the EC condition prior to EO condition as this specific protocol has demonstrated good reliability (ICC = >0.71) in previous studies (Sell *et al.*, 2007).

6.3.5 *Dynamic Postural Stability*

Dynamic postural stability trials were determined from two tasks (i.e., anterior-posterior (A-P) jump, and medio-lateral (M-L) jump), performed in a counterbalanced manner (RAND function in Microsoft Excel) and analysed using the DPSI. Specific to the A-P and M-L jump, participants stood bilaterally at a distance of 40% and 33% of their standing height from the middle of the force plate, respectively (Sell *et al.*, 2007). When instructed, participants jumped anteriorly (A-P jump) or laterally (M-L jump) off both legs, over a 30cm (A-P jump) or 15cm (M-L jump) hurdle and landing on the force plate with the dominant-limb (single-leg landing).

Participants were asked to stabilize immediately after landing, placing both hands on hips and balancing for 13sec (McGuine *et al*., 2000). Upper-limb movement was not restricted during the take-off or flight phase of each task (Figure 6.1). Dynamic trials were discarded and repeated if the participants' non-stance limb contacted the stance limb or the ground out-with the force plate. Anterior-posterior, M-L and vertical GRF data were extrapolated from the force plate using Bioware ® (5.3.0.7 systems) for subsequent analysis.

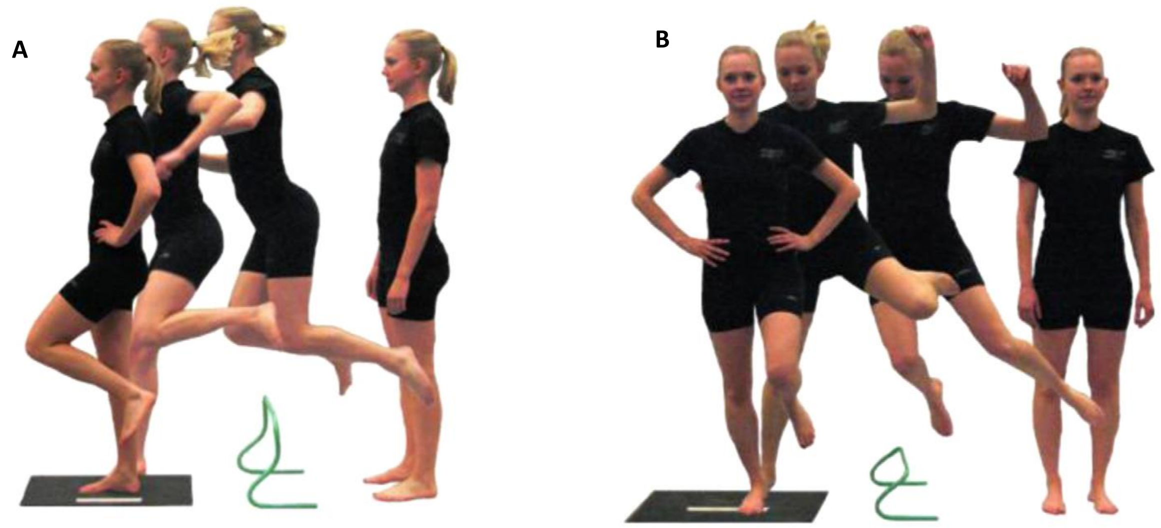

Figure 6.1 (A) Anterior-posterior jump over 12" hurdle assessing DPSI (B) Medio-lateral jump over 6" hurdle assessing DPSI. Permission granted from Sell T (2011).

6.3.6 *British Army Foot-drill Session Plan*

A British Army foot-drill instructor conducted each standardised foot-drill session. Each session lasted approximately 70min (table 6.1) with JPS and postural control assessment conducted pre and immediately post each foot-drill session. All participants wore the CB during their respective foot-drill session. Foot-drills are characterised by their own unique key performance markers (BADIM, 2009). For example, QM involves marching at two paces per second whilst impacting the ground with an exaggerated heel strike. The SaA, SaE, right-turn, about-turn (left-leg), left-turn, and Halt foot-drill (right-leg) involves raising the active limb approximately 90° hip flexion and forcefully stamping onto the ground repeatedly with an extended-knee (straight-leg) landing.

Entry-level British Army foot-drill session plan.

Foot-Drill	Standard entry-level recruit British Army foot-drill session		
Order of execution	Duration(mins)	*n* left foot impacts	*n* right foot impacts
SaA	11	42	-
SaE	9	28	-
Right-turn	12	48	-
Left-turn	9	-	32
About-turn	10	26	-
Halt	18	-	39
March	12	-	-
Rest	7	-	-
Total	88	144	71

Table 6.0: Condensed version of foot-drill session plan. Illustrates the frequency (repetitions), duration (time) and the total *n* of impacts performed with the right and left foot. SaA=stand-at-attention, SaE=stand-at-ease, QM=quick-march. This represents a typical entry-level recruit British Army foot-drill training session performed frequently during the initial phase of BMT.

6.4 *Statistical Analysis*

Statistical means and standard deviations for each variable were calculated. Each independent variable was analysed for the assumption of normality (Field, 2012). The JPS IN30% (W = .902, p = .004), ML (W = .835, p<.001) AP (W =.844, p<.001) stability indices for the AP jump condition, and ML (W = .978, p<.001) and AP (W = .875, p<.001) stability indices for the ML jump condition were found to violate the assumption of normality. In addition, the static balance eyes-open x (ML) condition (W = .988, p <.01) was also found to violate the assumption of normality. Therefore, a non-parametric one-way repeated measures ANOVA equivalent (i.e., Friedman test) was used to analyse differences between measurement event (DV: BL – Pre – Post) and JPS test angle (IV: IN30% - IN60% - EV30%), dynamic postural stability jump condition (IV: ML [2 levels], AP [2 levels], and static postural stability sensory condition (IV: EO [2 levels], EC [2 levels]). Post hoc analysis was conducted using Wilcoxon signed-rank tests with a Bonferroni correction applied, resulting in a significance level set at p=0.017 (Field, 2012). All remaining data were statistically analysed using parametric one-way ANOVAs, with Bonferroni adjusted multiple comparisons (p=.05). Effect sizes were calculated using Cohen's (1973) criteria.

6.5 Data Analysis

6.5.1 *Determination of Sample Entropy Input Parameters*

The magnitude of variability in the anterior-posterior (AP) and medio-lateral (ML) directions of human postural sway during quiet unilateral stance were quantified using the SampEn algorithm; defined as more reliable for short data sets, less sensitive to data length, possess greater relative consistency, and does not contain the inherent bias associated with other entropy algorithms, namely, approximate entropy (Yentes *et al.,* 2013). In addition, SampEn has shown to successfully discriminate between two sensory conditions, namely, EO and EC (Ramdani *et al.,* 2009). Prior to the computation of SampEn, important analysis considerations were made to investigate and determine the most appropriate selection of specific input parameters, namely, m and r values; defined as the template length of sequences to be compared, and the tolerance level for accepting matches (Ramdani *et al.,* 2009; Richman and Moorman, 2000), respectively. With no clear consensus established for the proper selection of SampEn input parameters, reports indicate that multiple m and r values be examined prior to the selection of final parameters, with the appropriate selection of r considered the most challenging aspect of SampEn analysis (Yentes *et al.,* 2013). The CoP data remained unfiltered during the analysis process as previous reports have shown that filtering CoP data dampens the dynamic characteristics of the CoP signal (Rhea *et al.,* 2015). Furthermore, CoP data were down sampled to 120Hz (Ramdani *et al.*, 2009) from the same Matlab script used previously.

Similar to that of Ramdani *et al.,* (2009) an empirical approach was utilised to estimate and determine the most appropriate SampEn input parameters for the present study, coupled with the SampEn values for EO and EC conditions using a custom Matlab (v7.11.0, Natick, MA) script file. The EOx, ECx, ECy and EOy represent each condition in the ML and AP direction, respectively. Due to known fluctuations in CoP data between the x and y-axes (Ramdani *et al.*, (2009), the present study estimated the SampEn values for both directions independently. To determine the most appropriate input values for parameters *m* and *r* for both x and y-axes, the median SampEn values for a random subset of CoP data was taken from each event (BL-pre-post), whereby a total of 150 CoP data files each containing 3,600 data points for both axes were utilised for several values of *m*. At this point, the SampEn values for *r* ranging from 0.01 to 0.4 in increments of 0.01, and for m = 1-4 were estimated (figure 6.2).

Similar to Ramdani *et al.*, (2009) it was observed that increasing *m* resulted in a concomitant reduction in SampEn estimates. Furthermore, these data revealed that the SampEn curves globally "converge" for $m \geq 3$, thus, such values of *m* were chosen for further analysis. For both ML and AP axes, m =3 curve exhibited values of error that were lower than the threshold of 0.05 (Ramdani *et al.*, (2009), which lead to the selection of $m = 3$, whereby the choice of *r* was simply determined by the minimum of the error curve corresponding to the chosen *m* thereafter. The present study obtained a value of $r = 0.09$ for both x and y-axes (figure 6.3).Thus, the selection of $m = 3$ and $r = 0.09$ were used to compute the SampEn values for all CoP data.

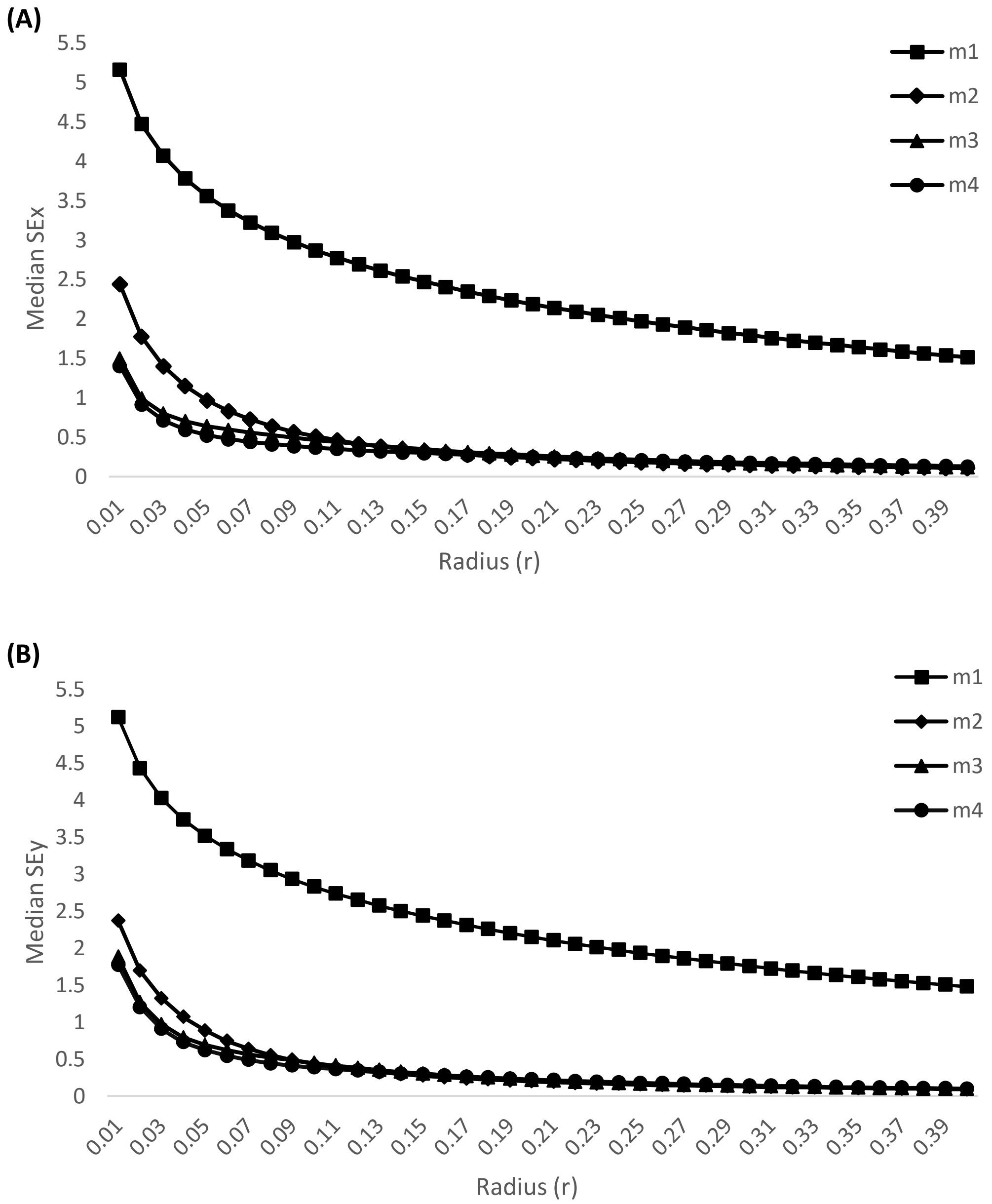

Figure 6.2: The median SampEn values for ML (a) and AP (b) for m = 1-4 and r = 0.01-0.4. The curves of the median of the SampEn estimation as a function of r and for m = 1-4 for both x and y-axes. Figure a and b illustrates the median calculated for 150 randomly selected CoP files across event (BL-pre-post). As shown, the highest curve represents m = 1, whereby $m \geq 1$ shifts the curves down and converges proceeding r = 0.09.

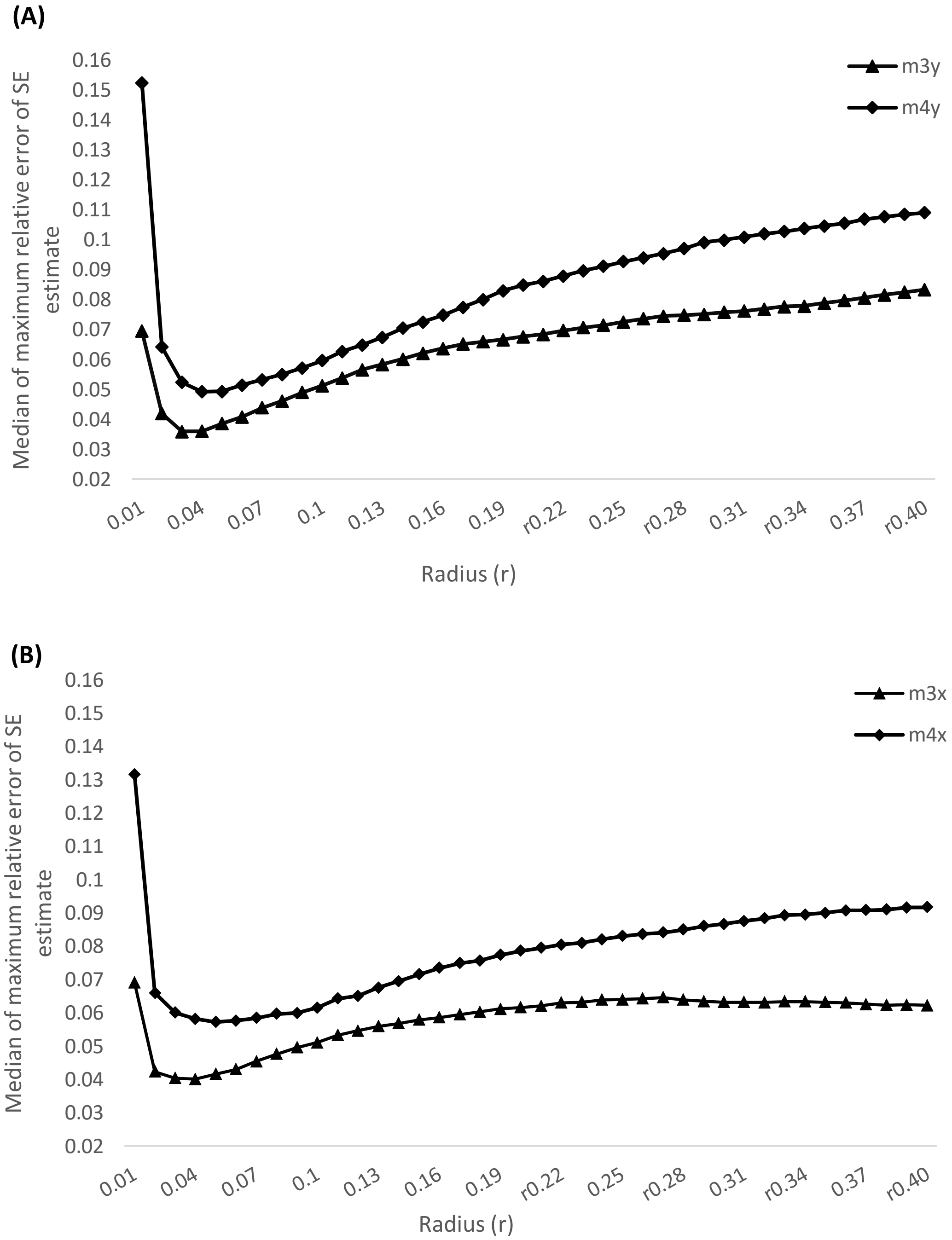

Figure 6.3: The median of the maximum relative error for m = 3 – 4. The curves of the median of the maximum relative error of the SampEn estimate as a function of *r* for *m* = 3 - 4. Figure a and b represents the calculated median values for 150 randomly selected CoP files across event relative to the x and y-axes, respectively. An *m* of 3 represents the lowest curve, whereby increasing *m* shifts the magnitude of the curve up. For both axes the *m* = 3 curve illustrates a minimum relative error lower than 0.05 – achieved at *r* = 0.09 for both axes.

6.5.2 Dynamic Postural Stability Index

All dynamic postural stability data were treated from a 4th order (zero-lag) low pass Butterworth filter with a cut-off frequency of 20Hz (Wikstrom *et al.*, 2006). The primary variable for A-P jump and M-L jump was DPSI (Eq. 4). The DPSI and its directional components (stability index (MLSI, APSI, VSI)) were processed and analysed using a custom Matlab script file. The MLSI and APSI directional components analyse fluctuations from zero along the X (A-P) and Y (M-L) axis, whereby VSI assess the fluctuations along the Z (vertical) axis of the force plate (Eq 1-3). The DPSI is a composite of the M-L stability index, A-P stability index, and vertical stability index, and was computed from the initial 3sec of the GRFs following initial contact, defined as the instant the vGRF exceeded 5%BW (Sell *et al.,* 2013) and shown to produce good test-retest reliability (Hopkins, 2001: Model 3, 1) (ICC = 0.96) (Wikstrom *et al.,* 2005). Greater SI scores reflect altered dynamic postural stability, with MLSI, APSI, VSI, and DPSI calculated as;

$$\text{MLSI} = \sqrt{\left(\frac{\sum(0 - GRFx)^2}{number\ of\ data\ points}\right)} \div \text{BW} \qquad \text{Eq 6.1}$$

$$\text{APSI} = \sqrt{\left(\frac{\sum(0 - GRFy)^2}{number\ of\ data\ points}\right)} \div \text{BW} \qquad \text{Eq 6.2}$$

$$\text{VSI} = \sqrt{\left(\frac{\sum(BW - GRFz)^2}{number\ of\ data\ points}\right)} \div \text{BW} \qquad \text{Eq 6.3}$$

$$\text{DPSI} = \sqrt{\left(\frac{\sum(0 - GRFx)^2 + \sum(0 - GRFy)^2 + \sum(0 - GRFz)^2}{number\ of\ data\ points}\right)} \div \text{BW} \qquad \text{Eq 6.4}$$

where, BW is the bodyweight of the individual in Newtons.

6.6 Results

6.6.1 *Joint Positional Sense*

There was a statistically significant difference for JPS test angle IN30%, χ^2 (2) = 6.04, p = 0.29. Post hoc analysis demonstrated a statistically significant increase in absolute JPS error for the IN30% test angle between pre and post measurement event (Z= -2.3, p=.024, d = 0.8) (Figure 6.4). No statistically significant main effects for JPS test angle IN60% ($F_{1.9}$, 0.63, p = .534) and EV30% ($F_{2.1}$, 2.2, p = .140) were found between measurement event. Post hoc power calculations using G*Power were conducted and confirmed that the total sample size of 14 female participants did not provide sufficient power (0.64) for this analysis. Therefore, it is possible that the inadequate sample size may have influenced these findings.

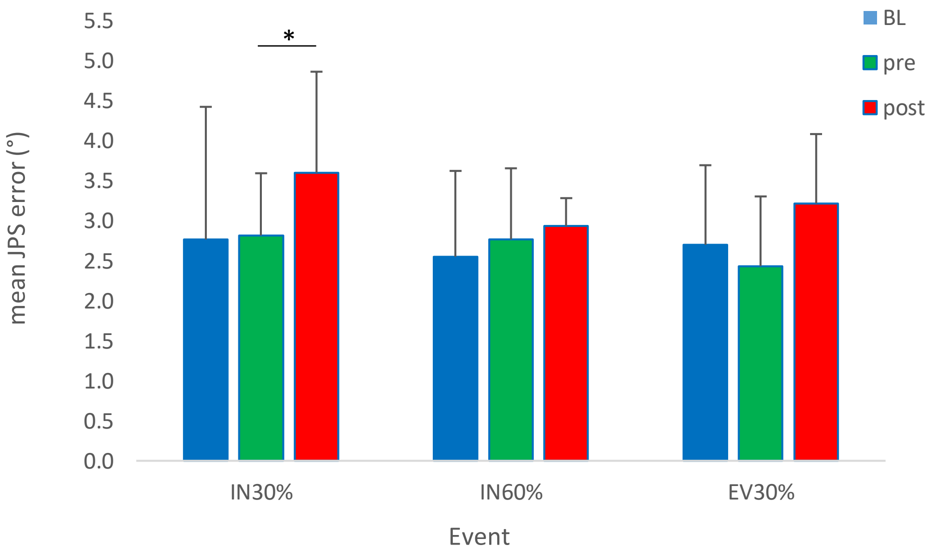

Figure 6.4 Mean JPS error (°) between events for each percentage IN/EV ROM test angle: mean JPS error (°) for each of the three percentage IN/EV ROM test angles at baseline (BL), pre, and post an acute bout of British Army foot-drill training. *denotes p<.05.

6.6.3 *Dynamic postural stability Index*

The DPSI and its directional components quantified dynamic postural stability during a single leg forward (AP) and lateral (ML) jump-landing condition (Figure 6.2). Statistically significant main effects were found for the AP jump condition (MLSI: χ^2 (2) = 54.2, p <.001, APSI: χ^2 (2) = 54.5, p <.001, DPSI: F_2 = 5.9, p = .004, ηp^2 = 0.15), and for the ML jump condition (MLSI: χ^2 (2) = 55.3, p <.001, APSI: χ^2 (2) = 54.1, p <.001, DPSI: F_2 = 4.5, p = .023, ηp^2 = 0.11) (table 6.3). Post hoc analysis demonstrated significantly greater stability index scores. The MLSI, APSI, and DPSI for both the AP and ML jump-landings demonstrated significant differences between events (table 6.2), whereby greater stability index scores were observed at post-test when compared to pre-test measures, demonstrating a reduction in dynamic postural stability. These results indicate that untrained females may have adopted different and/or impaired neuromuscular landing strategies following an acute bout of foot-drill training.

			Mean						
Condition	SI	BL[a]	PRE[b]	POST[c]		Post-hoc		Es (d)	
AP_Jump	MLSI	0.01a	0.01b	0.03c	.765[ab]	<.001[ac]	<.001[bc]	>1.0[ac]	>1.0[bc]
	APSI	0.02a	0.02b	0.12c	.649[ab]	<.001[ac]	<.001[bc]	>1.0[ac]	>1.0[bc]
	VSI	0.31a	0.30b	0.31c	-	-	-	-	-
	DPSI	0.31a	0.31b	0.33c	.823[ab]	.020[ac]	.003[bc]	0.6[ac]	0.6[bc]
ML_Jump	MLSI	0.02a	0.02b	0.09c	.745[ab]	<.001[ac]	<.001[bc]	>1.0[ac]	0.8[bc]
	APSI	0.01a	0.01b	0.04c	.937[ab]	<.001[ac]	<.001[bc]	>1.0[ac]	>1.0[ac]
	VSI	0.29a	0.29b	0.28c	-	-	-	-	-
	DPSI	0.29a	0.28b	0.31c	.744[ab]	.198[ac]	.047[bc]	0.5[ac]	0.6[bc]

Table 6.3: The mean and statistical data for the ML and AP jump condition and each directional component for each event. SI=stability index, AP=anterior-posterior, ML=medio-lateral. [ab]= represents the significance value and effect size (Es) using Cohen's criteria (d) between BL and PRE. [ac]= indicates the significance value and effect size (Es) using Cohen's criteria (d) between BL and POST. [bc]= signifies the significance value and effect size (Es) using Cohen's criteria (d) between PRE and POST.

6.6.2 *Sample Entropy – Static postural stability*

The SampEn statistic was used as a means of quantifying the complexity in terms of irregularity within CoP time series data between measurement events (i.e., BL-Pre-Post) and visual perception conditions (EO and EC) for the medio-lateral (x) and anterior-posterior (y) directions. Statistically significant main effects were observed between measurement events, whereby significantly greater regularity (reduced complexity) was observed for the EOx (χ^2 (2) = 8.8, p = .012) and ECx (F_2 = 3.3, p <.01, ηp^2 = .09) following foot-drill training when compared with pre-test values. These data demonstrate greater regularity, reflecting poorer static postural stability post following a bout of British Army foot-drill. In addition, a paired samples t-test was conducted to determine the effects of visual perception on static postural stability measures. Significantly lower SampEn values (i.e., greater regularity and reduced complexity) were observed for the EC condition when compared with the EO condition for the ML (t_{107} =2.6, p=.011) and AP (t_{107} =7.6, p<.001) directions, confirming the commonly proposed view that a loss of complexity in physiological systems is observed when the number of their structural components (i.e., visual input parameters) is reduced (Ramdani *et al.*, 2009).

Condition	Mean BL^a	PRE^b	POST^c	Main Effect Sig	Post-hoc			Es (d)
EOx	0.48^a	0.49^b	0.46^c	0.012*	.294^{ab}	.219^{ac}	.003^{bc}	0.7^{bc}
ECx	0.50^a	0.49^b	0.48^c	0.044*	<.05^{ab}	.297^{ac}	.007^{bc}	0.6^{bc}
EOy	0.50^a	0.51^b	0.49^c	0.495	<.05^{ab}	1.00^{ac}	.599^{bc}	-
ECy	0.42^a	0.43^b	0.41^c	0.525	<.05^{ab}	1.00^{ac}	.767^{bc}	-

Table 6.4 Mean SampEn data for EO and EC conditions for each event. Illustrates the mean and statistical data for the EO (eyes-open) and EC (eyes-closed) condition across each event (BL: baseline) for both the x and y-directions, calculated from the SampEn algorithm determined from a template length of m=3 and a tolerance level of r=0.09. *=indicates p<.05 between event within condition.

6.7 Discussion

This study is the first to quantify the effects of an acute bout of British Army foot-drill training on predictors of lower-extremity MSK injury risk using measures of neuromuscular function and ankle joint proprioception of untrained recruit-aged women. The objective of the current experimental chapter was to examine the potential pre-post adaptations and/or impairments in lower-extremity neuromuscular function across three constructs, namely, static and dynamic postural stability, and ankle joint kinaesthesia as measured by the SampEn statistic, DPSI and its directional components, and active JPS error, respectively. The results of the current experimental chapter revealed significantly greater JPS error and DPSI scores, reflecting greater magnitudes of variability when compared to BL and pre-test values. In addition, significantly lower SampEn values were observed for the EO and EC condition relative to the ML jump-landing condition, reflecting a more regular and less complex system, signifying a potentially compromised postural control system in untrained female personnel following an acute bout of British Army foot-drill training.

6.7.1 *Ankle Joint Positional Sense (JPS): Frontal plane (Inversion/Eversion)*

The control of movement is highly dependent on the quality of the afferent information originating from the various somatosensory systems involved in proprioception (Forestier *et al*., 2002). Joint proprioception and accompanying neuromuscular feedback mechanisms provide an important component for the establishment and maintenance of functional joint stability and awareness, derived from several sources, namely, articular mechanoreceptors, cutaneous afferents, muscle, and visual and vestibular receptors (Mohammadi *et al.*, 2013). It is well recognised that deficiencies in ankle joint proprioception, as measured by joint kinaesthesia (JPS), are associated with repeated lateral ankle sprain (Fu *et al*., 2005), chronic functional ankle instability (Hertel, 2008), exercise-induced muscle damage (Mohammadi *et* *al*., 2013) and dysfunctional static and dynamic postural stability control mechanisms (Lephart *et al.,* 1998), all of which play a key role in the susceptibility of lower-extremity injury and/or re-injury during physical performance.

Error in the reproduction of position (°) (i.e., JPS) is a reliable measure (ICC=0.86) with which to quantify deficiencies in the quality of ankle proprioception (Deshpande *et al*., 2003) and has been used in many athletic populations to diagnose and/or track the quality of somatosensory functions following injury and/or training interventions. This study investigated changes in active angle reproduction error in healthy active females following an acute bout of foot-drill training. Significantly greater JPS error was found for IN30% when compared to post-test values (2.77° vs 3.60°, Δ= 23.1%), with no significant differences observed for IN60% or EV30%. Excessive dynamic inversion of the ankle joint has been shown to alter ankle joint proprioception and increase the risk of ligamentous injury - defined as a key aetiological factor of lateral ankle sprain and subsequent functional ankle instability (Yokoyama et al., 2008). The increased frontal plane ankle JPS error observed for untrained women post foot-drill training may be attributable to greater (in comparison to men) inversion ankle angles observed in experimental chapter 4 – study 3 for the SaA (mean: 14.2° vs 11.4°, Δ= 19.7%), SaE (mean: *17.9° vs 12.6°, Δ= 29.8%), and halt foot-drill (mean: 9.6° vs 6.7°, Δ= 30.1%). Although the precise mechanism(s) responsible for greater JPS error observed in untrained women post foot-drill training could not be established, similar empirical study reported that greater JPS error and subsequent loss of proprioceptive sensibility post an acute bout of high impact loading activity, may be linked to the desensitisation of muscle spindles and Golgi tendon organs of the ankle joint, leading to modifications in afferent receptor activity, and thus deterioration in ankle joint proprioceptive measures (Twist *et al*., (2008).

Following an exercise-induced lower-extremity fatiguing protocol (Forestier *et al.*, 2002), it was reported that changes in firing patterns of compensatory muscle groups were responsible for greater ankle JPS error, predisposing individuals to an increased risk of ligamentous injury and subsequent functional ankle instability. More specifically, epidemiologic evidence shows that military specific exercise-induced fatigue may lead to deficits in JPS in recruits and soldiers, resulting in an increased risk of lower-extremity injury during military training (Mohammadi *et al* 2013). Although measures of lower-extremity muscle fatigue were not considered in this study, it is possible that untrained women may have been in a state of reduced muscular capacity (i.e.., fatigue) immediately post foot-drill training, which may have inhibited proprioceptive mechanisms in their ability to actively reproduce IN30% test angle, resulting in greater absolute JPS error following foot-drill.

As measures of ankle joint proprioception were limited to immediately after foot-drill training, it is unknown whether untrained women continued to exhibit altered ankle joint proprioception in the hours after completing foot-drill training. Nevertheless, in accordance with previous research, the significantly greater frontal plane ankle JPS error post foot-drill may predispose untrained women to an increased risk of ankle injury during subsequent military training. However, further empirical study is required to determine whether deficiencies in ankle joint proprioception are prolonged, as this may have implications relating to impaired performance and increased risk of injury during subsequent physical training. Based on these data, it is suggested that the magnitude of the vertical GRF vector produced by untrained women during foot-drill, coupled with significantly reduced knee flexion angles and greater ankle inversion angles at PvGRF, may have imposed greater mechanical stress on the lateral aspect of the ankle joint within a limited joint range of motion (due to footwear), leading to acute trauma of the lateral ankle ligaments and supporting musculature (Docherty *et al.*, 1998; Yokoyama *et al.*, 2008), resulting in an increased risk of impaired and/or modified neuromuscular and proprioceptive function (McKeon *et al.*, 2008).

6.7.2 *Dynamic Postural Stability Index (DPSI)*

As a reliable (ICC= 0.96) and precise (SEM= 0.03) measure of dynamic postural stability (Wikstrom *et al*., 2006), researchers have utilised the DPSI to better understand the magnitude of differences and variance in dynamic postural control between individuals suffering from chronic ankle instability and healthy controls (Brown *et al.*, 2010), sex differences (Wikstrom *et al*., 2006), the acute effects of vibration training amongst soccer players (Cloak *et al*., 2014), the effectiveness of home-based balance training (Ridder *et al*., 2014), and the effects of stable and unstable training surfaces (Kirby, 2011). However, to the best of the author's knowledge, this is the first study to utilise the DPSI and its directional components to quantify changes in dynamic postural stability pre-post a cyclic high impact loading military occupational activity of foot-drill. The results of this study reveal significantly greater stability index scores for all stability indices (excluding VSI) for both AP and ML jump-landing conditions following an acute bout of foot-drill training. Based on the traditional interpretation of variability from linear dynamics, these data illustrate greater magnitudes of task difficulty to stabilise the centre of mass when transitioning from a dynamic to a static state. Factors reported to influence static and dynamic measures of postural stability include sensory information gathered from the somatosensory system, along with motor responses that can affect coordination, awareness, and joint range of motion. Although the precise mechanism responsible for altered and/or impaired balance performance remains in question, experts agree that modifications in motor systems are responsible for changes and potential impairments in balance performance within clinical and laboratory settings (Bressel *et al*., 2007).

The magnitude of DPSI and VSI for the ML and AP jump condition post foot-drill training are similar to those reported for females with chronic ankle instability (CAI) in two separate studies (Brown *et al*., 2010; Ridder *et al*., 2014), whereby both studies reported similar mean DPSI and VSI scores (mean range: 0.32-0.36) when compared to the current study (mean range: 0.31-0.33). In Brown *et al.*, (2010), it was concluded that females with CAI had decreased postural stability and increased GRF as demonstrated by greater vertical stability index scores. These results were found to be attributable to laxity or damage in the anterior talofibular ligament, which has the lowest failure load out of all the lateral ankle ligaments and is responsible for reducing the anterior translation of the lateral side of the talus. However, when stressed beyond its failure load threshold, the function of the anterior talofibular ligament is comprised and said to be attributable to the increased DPSI and VSI scores observed in women with CAI. Based on these results, the significantly greater stability index scores observed post foot-drill training may have been attributable to repetitive inversion motion of the ankle joint (as demonstrated in experimental chapter 4 – study 3), coupled with the rapid rise in vGRF as demonstrated by significantly greater vRFD and shorter TTPvGRF when compared to QM and other impact-related activities (Wallace *et al*., 2010).

Greater GRF as supported by higher stability index scores were observed for MLSI, APSI, and DPSI for both the ML and AP jump-landing conditions post foot-drill. The magnitude of difference between pre - post dynamic postural stability values are similar, and in some cases greater than those reported for soldiers landing with 13kg of additional load (Sell *et al.*, 2013). For instance, participants of the current study exhibited 66.7%, 83.3% and 6.1% greater GRF relative to MLSI, APSI, and DPSI, respectively, whereas Sell *et al.*, (2013) reported 10% increase for the MLSI and APSI, and 7% increase for the VSI and DPSI. The magnitude of all GRF components relative to the AP jump condition post foot-drill, were shown to be comparable to those reported for soldiers landing with 13kg of additional load, with a mean unit difference of 0.04; indicating that recruit-aged women produced similar magnitudes of anterior GRF post foot-drill to those exhibited by highly trained US soldiers carrying an additional 13kg of external load.

Traditionally, these results would indicate that the physical demands of an acute bout of foot-drill on untrained women significantly impairs dynamic postural stability, leading to an increased risk of lower-extremity MSK injury. However, it should be noted that all untrained female participants of the current experimental chapter were healthy and injury free at the time of testing, and were able to successfully complete each jump-landing condition at BL, pre and post foot-drill training. As such, the current study cannot confirm whether untrained women exhibited significantly impaired dynamic postural stability post foot-drill training in comparison to baseline and pre-test values, as research in non-linear dynamics (Rhea *et al*., 2011), commonly referred to as the chaos theory, has challenged the traditional perspectives that associate greater variability with impaired performance and pathology (Wikstrom *et al*., 2006). Therefore, rather than an impaired dynamic postural control system, it is suggested that the increased DPSI and composite scores observed post foot-drill are a reflection of different functional lower-extremity landing strategies, acting to stabilise and attenuate the kinetic energy exhibited during the single-leg-hop-to-stabilisation task of the ML and AP jump-landing condition. Unlike Twist *et al.*, (2008) whereby measures of postural stability were measured at 24-hours post activity, the current study only collected data immediately after foot-drill training. Therefore, it is unknown whether increased dynamic stability index scores, reflecting different neuromuscular landing strategies remain consistent over time.

6.7.3 *Static Postural Stability*

The upright stance of a healthy individual is known to be unstable, requiring a complex system of control loops to maintain a balanced position over the base of support (Ramdani *et al.,* 2009; Rhea *et al.,* 2015; Twist *et al.,* 2008). During quiet standing, the displacements of the centre of pressure (CoP) have shown highly irregular and non-stationary fluctuations (Ramdani *et al.,* 2009), whereby the complexity of such data has directed research to focus on the analysis of their temporal dynamics to characterise the effects of a wide range of functionally relevant factors on postural stability, namely, visual perception, cognitive task, and specific physical activity. Traditionally, a less variable CoP is considered a more stable system. However, it has been demonstrated that increased variability may not be synonymous with impaired postural stability, whereby increased variability may actually serve a functional purpose (Rhea e*t al.,* 2015). In general, it has been shown that entropy measures such as SampEn provide researchers and clinicians with information regarding health, stability and adaptability of the postural system that is not captured when using more traditional methods (Rhea *et al*., 2011). Therefore, to better characterise system variability, many studies, such as chapter 5 – study 4, have utilised non-linear metrics, namely the SampEn algorithm to quantify both the magnitude and structure of CoP time series in clinical (Busa *et al.,* 2014) and athletic populations (Cavanaugh *et al*., 2005).

Postural stability testing has been employed in previous studies examining the relationship between impaired postural stability and risk of lower-extremity MSK injury, whereby some have indicated that postural stability deficits can predict an increased risk of ankle sprains in high school basketball players, (McGuine *et al.,* 2000; Willems *et al.,* 2005), while others have not (Baynon *et al.,* 2001; Willems *et al.,* 2005). The lack of agreement between studies is most likely attributable to divergent research designs and measures utilised making comparisons difficult. Nevertheless, postural stability deficiencies have been identified as predictors of altered neuromuscular control, and shown to be a key factor in lower-extremity injury mechanisms in athletic and military populations (i.e., chronic ankle instability, ACL and lateral ankle injury) (Sell *et al.,* 2013). As such, the current experimental chapter demonstrated significantly lower SampEn values (greater regularity) for the EO and EC condition relative to the x-direction at post-test when compared to pre-test values, with no significant differences observed for the y-direction. However, lower SampEn values were observed at post-test when compared to pre-test values for the EOy and ECy, indicating that participants exhibited greater regularity, reflecting altered static postural stability in the frontal and sagittal plane post an acute bout of British Army foot-drill. Furthermore, independent of jump-landing condition, significantly greater regularity (less complexity) was observed for the EC condition when compared to the EO condition in the current experimental chapter. These results are in agreement with previous studies (Ramdani *et al.,* 2009), whereby a loss of complexity of physiological and behavioural systems is apparent when the number of structural components is reduced, and/or the combination of these components is altered.

Research reported deficiencies in neuromuscular function using static postural stability following an exercise-induced fatiguing exercise, namely an acute bout of cyclic high impact loading activity (Twist *et al.,* 2008), whereby it was reported that static balance performance was impaired up to 24h, after which the stability index recovered. The results reported by Twist *et al*., (2008) demonstrated significant impairments in static postural stability following plyometric exercise, a training modality similar to that of foot-drill in terms lower-extremity joint kinematics (Benjaminse *et al.*, 2008) and the magnitude of the cyclic high impact loading forces (Connaboy *et al*., 2011; Wallace *et al*., 2010). However, as mentioned previously, a limitation of the current experimental chapter was that measures of JPS, dynamic and static postural stability were only collected immediately post foot-drill. Therefore, it is not known whether alterations and/or deficiencies in postural control systems continue to expose untrained female personnel to greater risk of injurious jump-landing characteristics, potentially leading to an increased risk of lower-extremity injury during subsequent military physical training. Nevertheless, mechanoreceptors located within the musculotendinous unit are developed from muscle spindles and Golgi tendon organs, acting as a mechanism by which joint positon and motion are regulated to equilibrate stressors and maintain upright posture. Research indicates that muscle spindles and Golgi tendon organs become desensitised following an acute bout of rigorous physical activity (Johnston *et al.*, 1998). Thus, given the importance of intramuscular receptors maintaining joint position and motion, the short-term effects of British Army foot-drill may have potentially modified afferent receptor activity, resulting in a reduction in system complexity, reflecting greater regularity (poor postural stability) in untrained women post foot-drill.

This study demonstrated significant changes in ankle joint proprioception and in static and dynamic postural stability post an acute bout of foot-drill. These alterations and/or impairments in system complexity could potentially be the result of acute trauma to the ankle ligaments and supporting musculature associated with the cyclic high GRFs and excessive inversion, but also to sensory nerve fibres contained within the joint capsule, responsible for stabilisation of the ankle joint during locomotion (Docherty *et al.*, 1998). Other authors suggest that metabolic acidosis associated with acute rigorous physical activity and the concomitant reduction in muscle pH, subsequently reducing the acuity of muscle spindle and Golgi tendon organ responses, may have impaired the sensorimotor function of lower-extremity joints post foot-drill (South and George, 2006). However, the significantly greater JPS error in IN30% only, DPSI, and regularity in static measures of postural stability demonstrate altered and/or impaired sensorimotor function post an acute bout of British Army foot-drill, which may be a contributing risk factor associated with high incidence rates of lower-extremity MSK injuries/disorders reported for British Army recruit women during basic training.

6.8 Conclusion

Recruit-aged women exhibited significant changes in sensorimotor function post an acute bout of British Army foot-drill, demonstrating significantly greater JPS error and dynamic postural stability index scores (excluding VSI) for both AP and ML jump conditions. Furthermore, significantly greater regularity in static postural stability was observed from non-liner dynamic analysis (SampEn), possibly reflecting impaired postural stability and neuromuscular control. These results could have potentially been attributed to a complex interaction of central and peripheral mechanisms, however the present study was not able to distinguish the precise contribution of each. Overall, the findings of the present study have implications for British Army commanders and physical training instructors who should be conscious of the use of British Army foot-drill during the initial weeks of basic training, and for increased risk of lower-extremity MSK injury and potential medical discharge.

7.0 General Discussion, Summary, and Conclusion

It is essential that British Army personnel develop and maintain a state of physical readiness, allowing them to meet the physical demands of training and when operating in theatre. Unfortunately, high rates of training-related lower-extremity MSK overuse injuries are reported during basic military training, resulting in a significant financial burden and negatively impacting on the trained strength of the British Army. Unlike other military occupational activities, namely marching, load carriage, and various physical fitness tests, foot-drill has received limited empirical study (Connaboy *et al.*, 2011; Carden *et al.*, 2015) and is poorly understood in terms of its potential for MSK injury in entry-level recruit populations. The aim of the present thesis was to conduct a biomechanical analysis of British Army foot-drill, quantifying lower-extremity MSK injury risk factors and predictors of injury risk associated with the cyclic mechanical loading of foot-drill in age-matched civilian men and women.

The research aims of the thesis are categorised into their respective experimental chapters. The aims of experimental chapter one were three fold: (i) determine the magnitude of any systematic bias among British Army foot-drill session(s) and between trial(s), (ii) establish the within-subject variation of such biomechanical variables as vGRF and vertical RFD; and (iii) analyse the test-retest reliability to determine the necessary number of sessions and/or trials required to maximise the possibility of identifying changes in the vGRF and vertical RFD of British Army foot-drill between different conditions, and over time.

Based on the magnitude of loading identified in experimental chapter 3 – study 1, coupled with the lack of existing load reduction strategies (i.e., shock absorbing footwear) aimed at mitigating the high impact loading forces of foot-drill in novice foot-drill performers, it was hypothesised that the use of a specific type of in-service footwear may act to marginally reduce the magnitude of loading profiles specific to foot-drill. Therefore, the aims of experimental chapter 4 - study 2 were as follows; compare the magnitude of the vGRF and temporal parameters of foot-drill, namely, peak vGRF, peak vertical RFD, and TTP across three different types of standard issue British Army footwear: the CB, ammunition (ammo) boot (AB), and Hi-Tech Silver Shadow training shoe (TR).

Due to the magnitude of mechanical loading of foot-drill observed across all three types of footwear, combined with the exaggerated heel-strike of marching, and the vigorous extended-knee landing of SaA, SaE and halt, this thesis hypothesised that both male and female novice foot-drill performers may be exposed to sex- specific kinematic, kinetic and temporal lower-extremity injury risk factors that may contribute to a greater risk of injury as a consequence of the regimental loading characteristics of foot-drill. Thus, experimental chapter 5 – study 3 quantified differences between male and female novice foot-drill performers in frontal and sagittal (hip, knee) and transverse (ankle) plane kinematics, kinetics (hip, knee, and ankle joint moments) and GRF profiles of specific British Army foot-drills; as well temporal occurrences of peak events of these parameters.

Experimental chapters 3-6 identified lower-extremity injury risk factors associated with the biomechanics of individual British Army foot-drills. These results provided evidence to investigate whether the accumulative mechanical loading representative of a single British Army foot-drill training session in novice foot-drill performers would impair specific neuromuscular control systems, thus providing key information regarding the potential risk of injury specifically related to foot-drill training, along with the risk of injury during subsequent military training. Therefore, the aims of chapter 5 – study 4 examined the potential pre-post adaptations and/or impairments in static and dynamic postural stability and quantified the potential differences in ankle joint proprioception pre-post an acute bout of recruit British Army foot-drill training in female novice foot-drill performers.

Despite the limited empirical study of British Army foot-drill, two studies have reported on the impact loading forces and tibial accelerations in trained soldiers and untrained recruits (Carden *et al.*, 2015), and age-matched civilians (Connaboy *et al.*, 2011). However, the number of trials chosen to accurately assess foot-drill performance was selected arbitrarily, with no evidence regarding the requirement for any familiarisation sessions and/or trials prior to data collection, and no rationale for the mean number of trials used to represent the forces achieved. Therefore, to ensure the stability and reproducibility of mean values used to represent the magnitude of foot-drill impact loading forces, this thesis sought to determine the necessary number of trials required to obtain accurate and stable measures of foot-drill performance, along with the requirement of any familiarisation sessions and/or trials prior to data collection. Based on these results, it was recommended that a single familiarisation session consisting of 10 trials per foot-drill be conducted prior to the collection of test data as a means of preventing and/or reducing the effects of a systematic bias. These results also indicated that the mean of eight-trials was sufficient to achieve moderate to strong levels of reliability when analysing the impact loading forces of foot-drill in a population of novice foot-drill performers, and that diminishing returns were observed with reductions in %CVte (within-subject variation) data beyond eight-trials.

In comparison to a sample of novice foot-drill performers, it is likely that fewer test data and/or familiarisation trials/sessions will be required when assessing foot-drill GRF variables of a trained sample, as the greater training age and levels of experience performing timetabled foot-drill sessions conducted as part of their basic training programme is thought to improve the efficiency and consistency of repeated performances. However, additional reliability analysis of foot-drill performance within a trained (and untrained) sample may be needed to elucidate these conclusions. These results have provided this thesis and other foot-drill research studies with useful information regarding how to improve and maintain moderate to strong levels of accuracy and reproducibility of foot-drill test-data. Additionally, it is recommended that a pragmatic approach be adopted when determining the total number of trials used to represent foot-drill data, whilst considering the requirement of high test-retest reliability and acceptable levels of within-subject variation concurrently with the economic, practical, and logistical concerns of collecting repeated sessions and/or trials (Connaboy *et al.*, 2010; Hopkins *et al.*, 2000).

As part of the reliability analysis, peak impact forces and loading rates were analysed and were shown to be similar in magnitude to those reported in previous foot-drill studies (Carden *et al.,* 2015; Connaboy *et al*., 2011) and that of high level plyometric exercises (Ebben *et al.,* 2007; Sinclair and Taylor, 2014); a training modality more commonly associated with more experienced and better conditioned athletes, suggesting that foot-drill represents a substantial mechanical load on the MSK structures of the lower-extremities. A select number of participants produced peak impact forces and loading rates in excess of 6.9 BW and 825 BW/sec, respectively. These individuals had slightly more trained experience participating in sporting activities that require high levels of coordination, balance and reactive agility. Therefore, it was hypothesised that these particular individuals in comparison to those who did not participate in such activities would have better motor learning and control (Aydin *et al*., 2002; Schmidt *et al*., 2018), resulting in more efficient foot-drill specific movement patterns and thus, greater impact loading forces. Although no pre-test physical performance measures were conducted, these results suggest that despite minimal foot-drill training, the magnitude of impact loading forces of foot-drill within a sample of novice foot-drill performers are high and are likely to be greater for those who are slightly more physically conditioned.

In accordance with previous *in vivo* (Milgrom *et al*., 2012) and foot-drill research (Carden *et al*., 2015), the magnitude of impact forces and loading rates reported for foot-drill are suggested to play a key role in the development of lower-extremity stress fractures. Generally, a stress fracture represents the inability of a bone to withstand cyclic bouts of mechanical loading, resulting in structural fatigue (fatigue failure) and resultant signs and symptoms of localised pain and tenderness (Warden *et al*., 2005). The pathogenesis of bone stress fracture is considered multifactorial, whereby intrinsic risk factors such as hormonal disturbances and irregular menstrual cycle in women, muscle fatigue, and irregularities and/or deficiencies in androgens such as testosterone in men (Clarke and Khosla, 2009), are known to be key contributory factors that influence skeletal health, and increase the susceptibility of lower extremity ligament injury and stress fracture risk, especially in female athletic and recruit populations (Boden *et al*., 2010; Feingold, 2006; Jeffrey *et al*., 1992; Souza and Williams, 2014; Rozzi *et al*., 1999).

Submaximal forces commonly experienced during activities such as running and jump-landing (Boden *et al*., 2000) do not usually result in bone fracture, provided that there is enough time for reinforcement through the remodelling process. Instead, each loading cycle incrementally damages the bone, and these incremental damages accumulate with every cycle. It is believed that when the magnitude and frequency of loading is low (i.e., low impact running and/or landing with large degrees of knee and hip flexion) and is combined with adequate recovery, there is sufficient time for osteoblastic activity to generate new bone whilst removing old damaged bone. However, when the magnitude and frequency of loading is high as identified during British Army foot-drill, the rate of bone resorption by osteoclastic activity exceeds the rate of bone generation resulting in weakened bone. Under certain conditions of continued cyclic loading of the weakened bone, fracture occurs (Välimäki *et al.,* 2005; Zadpoor *et al.,* 2011).

Based on the cyclic high impact loading forces of foot-drill, coupled with the general aetiology of stress fracture, it was suggested that foot-drill may contribute to the incidence rates of stress fractures during basic training due to the cyclic high impact loading characteristics. However, owing to its positive effect on bone density, weight-bearing physical activity such as plyometric training (i.e., jump-landings) has shown to significantly increase total body and regional bone mass in pre, peri, and postpubertal men and women (Fredericson *et al.*, 2007; Witzke and Snow, 2000). However, despite both foot-drill and plyometric jump-landing activities demonstrating similar peak vGRF, specific foot-drill exhibits considerably greater vertical RFD. As a means of better understanding associations between vertical RFD and stress fracture risk/occurrence, researchers have compared GRF characteristics of control and stress fracture groups (Hennig *et al.*, 1993; Milner *et al.*, 2006; Zadpoor *et al.*, 2011). While some have reported no significant differences between GRF of stress fracture groups in comparison to control groups, others have reported substantial differences. However, the majority of these studies were retrospective in design, and therefore were not able to determine causality. However, in a prospective study conducted by Beck *et al.*, (2000) it was found that Army recruits who sustained a stress fracture exhibited a tendency of reporting a history of stress fracture as a potential consequence of having bone with smaller cross-sectional areas (CSA).

The importance of better understanding the associations between GRF characteristics and history of stress fracture lead to a systematic review aimed at determining the associations between GRF characteristics and lower-limb (i.e., tibial/metatarsal) stress fractures (Zadpoor *et al*., 2011). From this systematic review, it was found that the magnitude of the GRF was not significantly different between stress fracture and control groups. However, the vertical RFD was found to significantly differ between stress fracture and control groups. These findings are consistent with the results of mechanical tests performed on bone samples showing that the fatigue strength of bone is significantly less when the load is applied at higher strain rates. (Milgrom *et al.*, 2012; Schaffler *et al*., 1989). The lack of significance between the GRF and stress fracture groups are likely due to differences that exist in the geometry and/or strength of bones of different individuals, or that the GRF cannot fully represent the loading experienced by bones due to the different types of loading (i.e., internal and external) on the skeleton and the contribution of the MSK system in the attenuation of loading forces.

The role of muscular fatigue in muscle strain injury indicates that fatigued muscles are able to absorb less energy prior to reaching a threshold that causes injuries (Mair *et al*., 1996). In this thesis, participants were in a rested state prior to data collection. However, during the last experimental study involving measures of joint proprioception and neuromuscular function pre-post foot-drill training, no fatiguing measures were captured. Therefore, it is unknown whether the reduced neuromuscular function reported was due to the high loading forces of foot-drill, muscular fatigue, or a combination of both. Milgrom *et al.,* (2007) indicated that the majority of stress fractures in military recruit epidemiological studies occur between the fourth and eighth week of basic training, yet an insufficient number of loading cycles would have occurred necessary to fatigue mechanically tested cortical bone (Yoshikawa *et al*., 1994). Therefore, it was hypothesised that bone strain rates may increase markedly during the muscular fatigue phase, reaching levels exceeding that recorded *in vivo* from non-fatiguing exercise (Yoshikawa *et al*., 1994).

Milgrom *et al*., (2007) provided evidence in support of their hypothesis, in that being in a fatigued state, as determined by a significant reduction in maximum gastrocnemius torque and achieved following an unloaded 30km desert terrain march, increases the magnitude of bone strain on the tibia. Therefore, it can be suggested that training in a fatigued state may be a significant contributing risk factor for stress fractures in military recruit populations, and that recruits and/or soldiers marching with additional load over similar distances (30km) are likely to experience greater tibial strains than those reported by Milgrom *et al*., (2007). It is likely that recruits during the initial weeks of basic training will be in a fatigued state due to the rapid rise in training load during the initial 4- to 6-weeks of phase one training. Therefore, activities such as foot-drill that produce significantly greater impact loading forces than running (Sinclair and Taylor, 2014), marching (Windle *et al*., 1999), and jump-landing activities (Wallace *et al*.,

2010) performed in a fatigued state may be a major risk factor for tibial stress fracture. However, empirical research similar to that of Milgrom *et al.*, (2007) is required to determine whether the high cyclic impact loading forces of foot-drill in a non-fatigued vs a fatigued state significantly increases tibial bone strains, thus greater risk of stress fracture. Following which would necessitate a review of training activities, and methods of reducing the high loading forces of foot-drill in British Army recruits if the hypotheses were met.

It is well-recognised that the shock absorbing capabilities of specific footwear play a key role in the attenuation of impact loading forces generated at the foot ground interface (Sinclair and Taylor, 2014; Snyder *et al*., 2009). However, specific types of standard issue military footwear have undergone scrutiny in terms of their inability to provide the wearer with adequate shock absorbency, altering lower-extremity kinematics, and thereby potentially increasing the risk of MSK injury (Sinclair and Taylor, 2014). In an effort to determine the influence current in-service footwear has on the high impact loading forces of foot-drill, and whether a specific type of in-service footwear could be utilised as a means of reducing these high loading forces, the present thesis sought to biomechanically analyse differences in peak impact forces and loading rates across three different types of commonly worn in-service footwear. It should be noted that the black leather CB and TR are no longer standard issue and have been replaced by the new brown boot series. However, the AB remains standard-issue and is currently worn when on parade in full dress uniform and during ceremonial and/or drill duties (MoD Announcement, 2012).

The magnitude of impact loading forces relative to the CB were found to be similar to those reported previously in untrained recruits whilst wearing the current in-service Defender Combat Boot (DCB) (Carden *et al.*, 2015). One key feature of the DCB superior to the CB is the inclusion of a micro-shock absorbing midlayer, providing dismounted soldiers with greater levels of shock absorbency at the foot-ground interface (MoD Announcement, 2012). However, the similar impact loading forces reported for foot-drill between the present thesis and that of Carden *et al*., (2015), suggests that the micro-shock absorbing midlayer of the DCB may not be sufficient in reducing the large impact loading forces of foot-drill. However, following on from this thesis, human performance and mechanical footwear research is currently underway to accurately determine the capacity of shock absorbency of the DCB and other relevant in-service footwear when exposed to impact loading forces equal to foot-drill, thus providing an informed evidence-based approach to the development and implementation of effective load reduction strategies.

This thesis has confirmed that when performing foot-drill in greater shock absorbing footwear, namely the TR, significant reductions in peak vGRF, peak vRFD and significantly greater times to peak impact force (TTP) were achieved in comparison to the CB and AB, thus potentially reducing the magnitude of loading transmitted up the kinetic chain. Based on the structural design on the AB, namely the iron heel toe-plate, and the hobnailed-studded outer-midsole, it was hypothesised that the AB would exhibit significantly greater impact forces and loading rates when compared to the CB. Rather, the CB and AB exhibited similar magnitudes of impact loading force when analysed statistically. Previous footwear research has reported significant changes in dynamic postural stability, peak impact loading forces, and lower-extremity kinematics dependent on footwear type (Browser *et al.,* 2017; Sinclair and Taylor, 2014). It is thought that due to the AB's rigid structure, participants were less likely to impact the ground with as much force and may have acutely altered their lower-extremity landing mechanics to compensate for the rigid structural properties of the AB. However, additional lower-extremity 3D kinematic analysis of foot-drill and marching comparing the AB with other in-service footwear is required to quantify the influence of the AB on gait and lower-extremity biomechanics.

It is hypothesised that the substantial mechanical loading reported for foot-drill whilst wearing boots other than the AB may differ when analysed in real-time in the field. Recruits are taught to impact the ground and make a 'loud noise' – a factor of tradition in the British Army and carried by drill sergeants (Carden *et al.*, 2015). This is achieved with ease wearing the AB due to its structure but considered more challenging in the DCB. Therefore, during foot-drill training recruits wearing the DCB may consciously impact the ground with substantially greater force in an attempt to make a 'loud noise' as instructed by their drill sergeant, thereby exposing recruits to greater and potentially more injurious mechanical loading. Data from the Army Recruiting and Initial Training Command (ARITC) indicate that trained soldiers performing foot-drill in the field produce peak positive (vertical) accelerations (g) in excess of 20g whilst wearing the DCB (Rice *et al.*, 2018). It is recommended that similar field testing be conducted to determine peak and cumulative impact loading forces of foot-drill whilst wearing the AB as to compare with the DCB, and other in-service footwear (Karrimor SF, Haix Combat boot) worn during foot-drill training.

Regardless of the type of footwear worn, mean foot-drill TTP values reported by the present thesis ranged from 18ms to 14ms for untrained men, which are considerably lower than the threshold range (50-70ms) for muscle to activity respond to the landing/contact stimulus (Donoghue *et al.,* 2011; Pollard *et al*., 2010). These passive forces (<70ms) of foot-drill are similar to those reported for other high impact lower-extremity activities such as drop jumps, parkour and gymnastic landings (Donoghue *et* al., 2011; Milner *et al*., 2006) suggesting limited and/or altered neuromuscular joint control at foot-ground contact, resulting in potentially greater stress being applied to the cartilage, ligament, tendon and bone of the lower-extremity

(Makinejad *et al.*, 2013; Milner *et al.*, 2006). The influence of footwear on the impact loading forces of foot-drill were only calculated within an untrained male sample, thus given the distinct neuromuscular control strategies and specific anatomical factors between men and women (Gehring *et al.*, 2008), it is unlikely that these results can be generalised to an untrained female population. Therefore, additional empirical research is needed to elucidate potential changes and associated injury risk factors in GRF parameters of foot-drill within trained and untrained women.

Despite significantly greater shock absorbing capabilities observed for the TR when compared to the CB and AB, the impact loading forces of foot-drill across each footwear represent a substantial mechanical load. The large impact forces and loading rates reported by this thesis are likely related to the specific regimental manoeuvres of foot-drill, namely impacting the ground with an extended-knee whilst actively minimising the range of hip and knee flexion at ground contact. Due to the passive, high impact and potentially injurious loading forces of foot-drill, coupled with the unique extended-knee movement patterns, a 3-dimensional lower-extremity comparative analysis was conducted between untrained men and women, demonstrating distinct temporal, kinetic, and kinematic lower-extremity profiles at PvGRF.

In agreement with previous foot-drill research (Carden *et al.*, 2015), significantly greater vertical knee acceleration was observed for men, coupled with greater hip and knee angular velocity when compared to women. However, women exhibited knee accelerations and joint angular velocities in excess of $100 m/s^2$ and 1010°/s which are similar to those reported for trained personnel (Carden *et al.*, 2015) and other high impact loading activities (Decker *et al.*, 2003). Foot-drills SaA, SaE and halt elicited significantly greater accelerations and joint angular velocities when compared to QM and walk, suggesting that the large peak impact loading forces observed for SaA, SaE and halt are likely associated with the effective mass of the active limb travelling at a higher velocity than QM and walk prior to initial ground contact. Additional statistical analysis (i.e., multiple regression analysis) is required to determine any potential significant relationship between temporal and GRF parameters, and whether peak vertical knee acceleration and joint angular velocity are significant predictors of the high impact loading forces of foot-drill observed in trained and untrained men and women.

Considering that British Army recruits are instructed to forcefully stamp onto the ground with an extended, straight-leg landing whilst actively reducing sagittal plane hip and knee motion at impact, the magnitude of hip and knee flexion at PvGRF was expected to be small. As such, men demonstrated hip and knee flexion angles ranging from 23°-27°, and 27°-34° at PvGRF respectively; whereas women demonstrated peak hip and knee flexion angles ranging from 15°-22°, and 20°-27° for the SaA, SaE and halt foot-drill at PvGRF, respectively. In addition, women demonstrated significantly lower hip and knee flexion angles for QM when compared to men, with marginal differences observed for the walk. Further analysis indicated that women produced considerably greater frontal plane knee motion and ankle inversion at PvGRF across foot-drill when compared to men. Despite the standardised and regimental movement patterns of foot-drill, differences in lower-extremity kinetics and kinematics at PvGRF were observed between untrained men and women, such that women adopted a more erect sagittal plane lower-extremity profile, whereas men exhibited a more erect frontal plane lower-extremity profile.

The results from this thesis suggest that women conform better to the regimental movement patterns of foot-drill when compared to men, as demonstrated by the reduced hip and knee flexion angles observed at PvGRF. Whether this was linked to the specific anatomy of the female or a function of foot-drill instruction is unknown. However, as a result, women exhibited greater frontal plane knee motion at PvGRF – a key biomechanical risk factor associated with the ACL injury mechanism. Although resting Q-angles were not measured, it is well-recognised that women have a greater pelvic width to femoral length ratio in comparison to men, and that the greater frontal plane knee motion reported for women during foot-drill is likely associated with these specific anatomical characteristics. Previous research suggests that women who land with a greater extended-knee employ a strategy of reliance on passive restraints in the frontal plane, as demonstrated by greater knee abduction/adduction joint motion. This shock attenuation strategy is thought to mediate and/or reduce the rate of deceleration of the body's centre of mass, thus reducing the magnitude of kinetic energy transmitted to lower-extremity joints. Although knee abduction has been reported as the predominant risk factor for non-contact knee ligament injury in female athletes, the specific phase of the menstrual cycle and the identification of estrogen and progesterone at the time of injury has been linked with the ACL injury mechanism. The identification of estrogen and progesterone receptors in the fibroblasts of the human and animal ACL indicates that pregnancy-related hormones may alter the structure (i.e., laxity) of this, and potentially other ligaments (Heitz *et al*., 1999; Liu *et al*., 1997).

Huston *et al*., (2002) investigated the association between ACL injury occurrence and the phase of the menstrual cycle in 60 female athletes, reporting significantly greater incidences of ACL injury during the ovulatory phase in comparison to the late follicular and luteal phase, corresponding with the surge in estrogen levels observed prior to ovulation (follicular phase) (day 1 of cycle: mean 45.5µg; day of injury: mean 80.2µg; Δ = 34.7µg, d = >1.0, p<.001). Additionally, Heitz *et al*., (1999) reported greater ACL laxity with increasing levels of circulating estrogen during the late follicular and ovulatory phase of the menstrual cycle, supporting the theory that hormonal changes experienced during the menstrual cycle are likely to alter the laxity and structure of the ACL. It is unclear as to whether the high cyclic impact forces and loading rates of foot-drill, along with the greater knee abduction/adduction observed in novice female foot-drill performers are a consequence of altered and/or increased laxity of the ACL due to increasing levels of circulating hormones as per the menstrual cycle. Therefore, further investigation is warranted.

There is evidence to suggest that the biomechanical demands of high impact lower-extremity activities along with exercise-induced muscle damage may reduce and/or impair neuromuscular efficiency – as measured by a reduction in static and dynamic postural stability (Brown *et al*., 2010), and altered proprioceptive function (Saxton *et al.*, 1995). Impairments in somatosensory function are suggested to occur as a result of disturbances in muscle receptors, muscle spindles, and tendon organs (Twist *et al*., 2008). Accordingly, it was hypothesised that the cumulative mechanical loading from an acute bout of foot-drill training, coupled with the regimental movement patterns of British Army foot-drill may incur adaptations in ankle joint proprioception and neuromuscular function, thereby potentially exacerbating the risk of foot-drill related lower-extremity injury in untrained women. Therefore, the present thesis sought to examine potential pre-post adaptations in neuromuscular function and ankle joint proprioception from measures of static and dynamic postural stability and ankle joint positional sense (JPS). The results of the present thesis demonstrate significantly greater JPS error, DPSI and composite scores, and significantly lower SampEn values for static postural stability specific to the lateral jump condition post a standardised foot-drill training session. Reduced ankle joint proprioception is a well-known predictor of ankle injury and chronic functional ankle instability from excessive dynamic ankle inversion (McGuine *et al*., 2000; South and George, 2006; Gabbett, 2000). The present thesis identified significantly greater ankle inversion JPS error for untrained women post foot-drill training, whereby the percentage of total error was 17.8% greater than pre-test values. In addition, results of experimental chapter

3 indicated that women exhibited significantly greater ankle inversion angles at PvGRF when compared to men. As excessive ankle inversion is a key aetiological factor associated with ankle sprain and subsequent deficiencies in ankle joint proprioception (McGuine *et al*., 2000), it was suggested that the greater inversion ankle angles observed for untrained women in the present thesis may have contributed to reduced ankle joint proprioception following foot-drill training. It should be noted that originally, the present thesis aimed to quantify ankle joint proprioception by conducting threshold to detect passive motion using the isokinetic dynamometer (biodex) based on recommendations from research (Nagai *et al*., 2013). However, the specific research toolkit required for this particular measure was not readily available and required additional funding. Therefore, JPS or active-to-active reproduction was chosen to analyse changes in ankle joint proprioception as research has shown excellent test re-test reliability (r = .88) for this method (Deshpande *et al.*, 2003).

The DPSI in comparison to other measures (time-to-stabilisation (TSS)) is more informative, and a reliable (ICC=.96) and precise (SEM= .03) measure of dynamic postural stability. It is considered a functional measure of neuromuscular control due to the single-leg-hop-to-stabilisation manoeuvre, whilst allowing a multi-plane examination of dynamic stability (Wikstrom *et al*., 2006). Therefore, due to the limitations of TTS (single plane examinations, and a lengthy and time-consuming data reduction analysis process) DPSI was used to determine potential changes in dynamic postural stability pre-post foot-drill training. These results showed that when compared with baseline and pre-test values, untrained women exhibited significantly greater DPSI and composite scores (excluding VSI) for the ML and AP jump-landing conditions proceeding a standardised foot-drill training session. No significant differences were observed between baseline and pre-test values for DPSI or for any stability indices specific to the ML or AP jump-landing condition, suggesting that jump protocol direction does not affect dynamic postural stability in a healthy untrained female sample.

Typically, greater DPSI scores observed for untrained women post foot-drill training would indicate a compromised or potentially impaired neuromuscular control system. However, it should be noted that women were able to successfully complete each jump-landing condition at pre and post assessment. Therefore, the current thesis cannot state whether women exhibited significantly worse dynamic postural stability when compared to baseline and pre-test values, as research in non-linear dynamics, commonly referred to as the 'chaos theory', has challenged the traditional perspectives that associate greater variability with impaired performance and pathology (Wikstrom *et al*., 2006). Consistent with Wikstrom *et al.*, (2006), and considering that all participants were healthy and injury free, it was suggested that untrained women utilised different landing strategies following foot-drill training to stabilise and attenuate kinetic energy during the landing phase of each jump-landing protocol.

Specific to the present thesis, differences in DPSI and stability indices may be a function of neuromuscular fatigue, resulting in altered jump-landing biomechanics and providing a possible explanation for the increased dynamic postural stability post foot-drill training. Previous studies indicate that recreational active women demonstrate changes in the control mode of postural stability proceeding a fatiguing activity (Corbeil *et al*., 2002), whereby others reported altered lower-extremity kinematics and increased tibial impact accelerations (Moran and Marshall, 2006). It was not feasible to collect lower-extremity kinematic data whilst assessing DPSI in this study. However, given the physiological, anatomical and biomechanical disadvantages of women associated with greater risk of lower-extremity injury during jump-landing activities, it is reasonable to suggest that greater DPSI scores post foot-drill are likely a result of modified landing strategies, placing greater demands on postural control systems by increasing the frequency of actions required to regulate upright unilateral stance. Physiotherapists could use DPSI as a reliable and objective measure to return recruits to training proceeding a unilateral lower-extremity injury (Wikstrom *et al.,* 2006).

Typically, static postural stability has been garnered from computerised posturography, whereby traditionally, a less variable static CoP is considered a more stable system. However, research over the past three decades suggests increased variability may not be synonymous with a dysfunctional system, rather some variability may serve a functional purpose (Rhea *et al*., 2015). Therefore, to more fully characterise the complexity and variability of static postural stability pre-post foot-drill training, the sample entropy (SampEn) statistic (m=3, r=.09) was employed. Sample entropy is a statistic developed from approximate entropy (ApEn), designed to quantify the regularity and complexity of a wide variety of physiological and clinical time series data, namely, heart rate variability (Lake *et al*., 2002; Richman and Moorman, 2000; Rigoldi *et al.,* 2012), endocrinological study (Pincus, 2000), and human postural sway (Ramdani *et al.,* 2009; Rhea *et al*., 2015; Rhea *et al*., 2014).

When statistically compared to baseline and pre-test values, untrained women exhibited compromised static postural stability post foot-drill training, as demonstrated by lower SampEn values for the EC condition. Greater regularity infers a less complex yet compromised physiological system, whereas greater irregularity suggests a more complex system, inferring normative physiology (Pincus and Goldberger, 1994). This capability offers flexibility when exposed to unexpected perturbations and/or constraints, and is considered a primary source of variability that is regularly utilised to determine healthy and adaptable physiological systems (Wikstrom *et al*., 2006). In accordance with the present thesis, greater regularity (lower SampEn values) was observed for static postural stability, suggesting that the integrity of neuromuscular control mechanisms may be compromised following an acute bout of foot-drill training. Similarly, Twist *et al*., (2008) reported latent impairments in neuromuscular control in unilateral balance performance up to 24hrs proceeding a bout of plyometric training, which has implications for both use of skill-based activities and for increased risk of MSK injury following high impact loading activity.

Although the precise mechanism(s) responsible for changes and/or impairments in proprioception and neuromuscular function could not be established, it was suggested that peripheral mechanoreceptors located in the muscle spindles and Golgi tendon organs of lower-extremity joints may have become acutely desensitised as a result of neuromuscular fatigue. Considering the importance of these intramuscular receptors in controlling joint position and movement, it is reasonable to suggest that the cumulative loading and unique kinematic profiles of foot-drill may have led to modified receptor activity (Brockett *et al.*, 1997; Saxton *et al.*, 1995), resulting in modified jump-landing strategies due to deterioration of balance and JPS performance specific to untrained women.

Results of the current thesis are limited such that only the acute effects of foot-drill training on measures of proprioception and neuromuscular function were analysed. It is currently unknown whether the unique loading and kinematic lower-extremity profiles of foot-drill result in prolonged alterations in balance and JPS performance, or demonstrate an immediate deterioration followed by a rapid recovery. Furthermore, measures of static and dynamic postural stability and JPS pre-post foot-drill training were calculated specific to an untrained female sample. Therefore, given the anatomical and physiological differences observed between men and women resulting in distinct neuromuscular landing strategies (Greeves, 2015; Wikstrom *et al.*, 2006), it is unlikely that these results can be generalised to an untrained male population. Future research is required to determine the potential continual reductions in lower-extremity joint proprioception and neuromuscular function following foot-drill training in trained and untrained male and female military personnel, as these results may have strong implications for increased risk of lower-extremity MSK injury during subsequent military training. Given the implications of knee MSK injury associated with the forceful extended-knee landing of foot-drill, and that injuries/disorders of the knee are one of the leading causes of medical discharge reported by recruits during the initial weeks of basic training (Annual medical discharge report, 2017), it is recommended that future research investigate the influence of the high impact loading forces and regimental movement patterns of foot-drill on measures of knee proprioception and neuromuscular function post a standardised British Army foot-drill training session.

In summary, the results of this thesis provide substantial empirical evidence to suggest that the biomechanical demands of British Army foot-drill expose untrained men and women to increased risk of developing such lower-extremity MSK overuse injuries as bone stress fractures, and joint connective tissue injury. Given specific physiological and anatomical factors such as a greater pelvic width to femoral length ratio, higher oestrogen levels resulting in reduced lean muscle mass, and an over-reliance on passive restraints resulting in greater frontal plane knee motion during jump-landing activities, it was reasonable to suggest that the rigorous mechanical load and unique regimental movement patters of foot-drill are likely to expose women, more so than men, to greater risk of developing a foot-drill related lower-extremity MSK overuse injury during the initial weeks of basic training.

Results of the present thesis demonstrated that the use of a shock absorbent in-service footwear was capable of significantly reducing the magnitude and rate of British Army foot-drill. It was suggested that the superior shock absorbing properties of the TR (and equivalent) may act to marginally reduce the magnitude of force transmitted up the kinetic chain. However, regardless of footwear type, the magnitude of mechanical loading remained high and potentially injurious.

Although the use of shock absorbent footwear has been reported as an effective load mitigating strategy during running and marching activities (Sinclair and Taylor, 2014; Windle *et al*., 1999) these loads are considerably lower than those reported for foot-drill (Carden *et al.,* 2015; Connaboy *et al*., 2011). Despite these results, it is thought that the magnitude and rate of impact loading produced during foot-drill may be too severe for the shock absorbent properties of footwear to be considered an effective load reduction strategy. However, based on the results of the present thesis and those of others (Carden *et al*., 2015; Connaboy *et al.,* 2011) it is vital that an effective load mitigation strategy be developed and implemented as a means of reducing the risks of such potential foot-drill related lower-extremity MSK overuse injuries as bone stress fractures.

The implementation of specific periodisation models have shown considerable success in the prevention of injury whilst maintaining high levels of physical and tactical performance in various training components, namely, aspects of plyometric training (Baechle and Earle, 2008). Thus, as a means of preventing and/or reducing the injurious high impact loading forces of foot-drill observed for untrained and trained male and female military personnel, the present thesis recommends that the structure and timetabling of foot-drill be strategically managed and/or manipulated within the basic training syllabus in accordance with a periodised model of training, such that the frequency and duration of foot-drill sessions, total number and type of drills, repetitions and sets of drills, recovery and intensity of drill sessions, and total number of foot-contacts are managed in such way that reduces the injurious cumulative high impact loading forces of foot-drill, whilst minimally impacting on the recruits ability to learn and maintain high levels of foot-drill performance.

To conclude, the results of this thesis provide the British Army with a better and more empirically informed knowledge and understanding of the potential kinetic, kinematic and neuromuscular lower-extremity injury risk factors associated with the cyclic high impact loading forces and regimental movement patterns of British Army foot-drill in an untrained, age-mated civilian male and female population. Furthermore, these data have the potential to better inform current and/or future British Army standard operating procedures and policies specific to the priorities of the ARITC - reducing rates of injuries that result in preventable medical discharge, whilst maintaining retention of trained strength in the British Army.

8.0 Future research considerations

The present thesis has identified a series of biomechanical lower-extremity injury risk factors linked to the high impact loading forces and regimental movement patterns of popular British Army foot-drills. Furthermore, these data also indicate that the cumulative effects of foot-drill training significantly alter and/or impair the function of joint proprioception and neuromuscular function from measures of JPS and postural stability. Based on these results, it cannot be confirmed whether foot-drill significantly contributes to the high rates of lower-extremity MSK injury sustained by recruits during Phase one training, only that a number of identified injury risk factors may contribute to rates of injury. Therefore, additional empirical study is warranted, namely a Randomised Control Trial (RCT) (group 1 – normal foot-drill training vs group 2 – no foot-drill training) analysing a series of physiological variables (i.e., anthropometrics, physical performance measures, HR pQCT, lower-limb loading (IMU's), injury rates, rehabilitation times, and medical discharges)) at week 1 (baseline) and week 11/12 of basic training. It is hypothesised that a significant reduction in injury rates and medical discharges would be observed in the "no drill" group when compared to the "drill" group based on the results of the present thesis. Furthermore, these data could be used to develop bespoke foot-drill training programmes aimed at reducing the magnitude of injury rates and medical discharges in male and female recruit populations.

8.0 References

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Appendix 1: British Army Foot-Drill Instructor Manual – Chapter 3

Appendix 2

BRITISH ARMY FOOT DRILL INSTRUCTOR MANUAL

CHAPTER 3 - FOOT DRILL

BASIC FOOT DRILL

During the initial stages of training in foot drill, instruction is to be given in open order.

Exercises are to be taught first by numbers and when proficient, judging the timing. A pause equal to one pace in quick time is to be observed between successive movements except where otherwise stated.

Bend the knee. One particular movement of foot drill, to be described as "Bend the Knee", will frequently form part of a sequence. "Bend the Knee" should be demonstrated to trainees before all others. In this movement, while one leg is kept braced back with the foot flat on the ground, the other leg is bent in front of the body so that the thigh is parallel to the ground with the foot hanging naturally below the knee. The leg is then straightened, and the foot placed on the ground so that on contact the ball of the foot reaches the ground first.

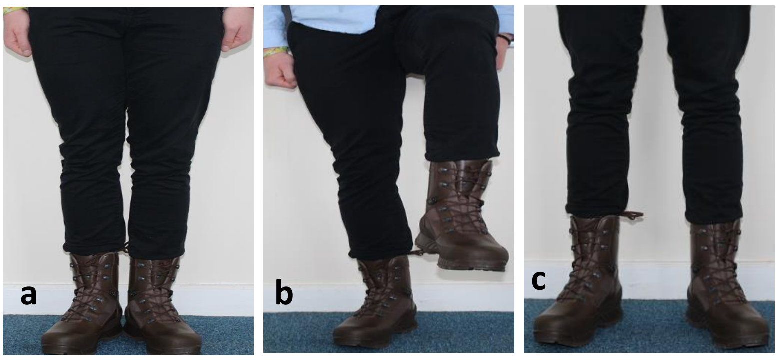
THE POSITION OF STANDING AT EASE

4. On the command*:*

Stand at - EASE

The feet are to be approximately 30cms (12 ins) apart at the heels and turned outwards 45°. The knees are to be straight. The weight of the body is to be balanced on both feet and is to be evenly distributed between the heels and the fore part of the foot. The body is to be erect and the shoulders (which are to be level and square to the front), are to be drawn down and backwards without strain or stiffness, so as to bring the chest to its natural position. The arms are to hang easily to their fullest extent, at the same time holding the hands behind the back. The back of the right hand being positioned in the palm of the left hand, the thumbs are to be crossed right over left. Although standing at ease is a relaxed position, no movement is to be made.

Diagrams for SaE: The three main phases of SaE are depicted below.



SaE: Starting from the SaA position (a), on command, the recruit lifts the left leg until the thigh is parallel to the ground (b), followed by a forceful stamp on the ground with legs approx 30cm apart (c).

Timing - One

5. When equipped in marching order without weapons, the arms are to be kept at the side (see position of attention).

STANDING EASY

6. On the command:

stand - EASY

The limbs, head and body may be moved, but not the feet. If the feet are moved the dressing may be lost. Slouching, talking and unnecessary movements are not allowed.

Timing - One

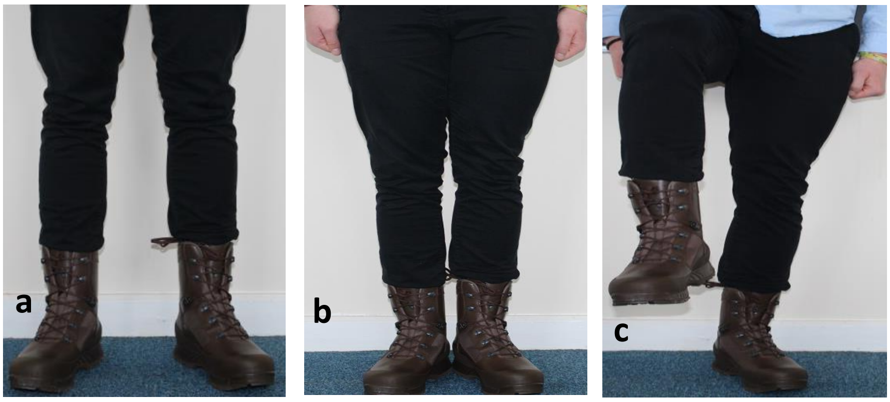
7. Personnel standing easy are to assume the position of Stand at Ease as soon as a cautionary word of command is given, so as to be ready to carry out the next command (for example Squad/ Flight).

ATTENTION

8. On the command:

Shun

While keeping the right foot still and the leg braced, bend the left knee and bring the left foot smartly into a position beside the right foot. At the same time pull the arms to the sides of the shortest possible route.



SaA: Starting from the SaE position (a), on command, the recruit lifts the left leg until the thigh is parallel to the ground (b), followed by a forceful stamp on the ground with legs together ad toes turned out approx 45 degrees (c).

Timing - One

The heels are to be together in line. The feet are to be turned outwards at an angle of 45° approximately, to give a comfortable stance. The knees are to be straight. The weight of the body is to be balanced on both feet and is to be evenly distributed between the fore-part of the feet and the heels. The body is to be erect and is to be carried evenly over the thighs. The shoulders (which are to be level and square to the front), are to be drawn down and backwards without strain or stiffness so as to bring the chest to its natural position. The arms are to hang easily from the shoulders and are to be as straight as the natural bend of the arms (when the muscles are relaxed), will allow. The wrists are to be straight and the palms of the hands are to be turned towards the thighs. The fingers are to be lightly clenched and the thumbs are to be to the front, touching the forefingers. The thumbs and tips of the fingers are to rest lightly on the thighs with the thumb on the side seam of the trousers. The neck is to be erect, the head is to be straight, and the chin is to be drawn in. The eyes are to look straight to the front (except when an individual is being personally addressed then he is to look at the person addressing him, without turning the head). Breathing is not to be restricted and no part of the body is to be stiff, tense or strained.

The position of attention is one of alertness in readiness for a word of command and the muscles are, therefore, to be controlled to await any orders which may be given. Unless stated all drill movements follow from the position of attention.

STANDING AT EASE FROM ATTENTION

11. On the command:

stand at - EASE

While keeping the right foot still and the leg braced, bend the left knee and place the left foot smartly on the ground 30cms (12 ins) to the left of the right foot. At the same time the hands are to be placed behind the back to assume the position of stand at ease with the weight of the body resumed evenly on both feet.

<u>FORMATION OF A SQUAD</u>

A right marker is to be detailed.

On the command:

right - MARKER

The marker is to come to attention, march out in quick time and Halt, facing the instructor at a distance of 3 paces, and stand at ease.

On the command:

on - PARADE

The marker (already in position), and the squad (at their off-parade position), are to come to attention. The squad is to observe a pause, and is then to march forward and form up in 3 ranks with 2 persons covering the marker to form the first file; the remainder are to form up on the left of the first file. Once still, and after observing a further pause each file, with the exception of the right file, are to turn their head and eyes to the right; at the same time personnel in the front rank are to raise their arms fully extended with hands clenched and the back of the hand upward, knuckles touching the shoulder of the person immediately to their right. Each file is then to observe a further pause and take up their dressing in line by moving with short quick paces until they are just able to see the lower part of the face of the second person beyond. The shoulders are to be kept square to the front without bending the body or the head either backwards or forwards. Personnel in the centre and rear ranks are to cover the person in the front rank of their file at a distance of one pace behind each other. (At this distance personnel are in close order.)

When the right hand person of the second file is satisfied that the squad is steady, he/she is to turn their head and eyes to the front. At the same time personnel of the front rank are to lower their arms to their sides. Again, after a pause each file from the right to left is to stand at ease.

On the command:

Parade/Flight/Squad - **right** - DRESS

First Movement. Whereupon all personnel, except the right hand person of each rank, is to turn their head and eyes smartly to the right. Personnel in the front rank are to raise their right arms sharply to the right to a horizontal position, hands clenched, backs of hands upwards, each with knuckles just touching the person immediately to their right. (The elbow is bent briefly when bringing up the arm. The clenched hand is driven to the right and rear of the person next to them, taking care not to strike them on the shoulder.)

Second Movement. After a pause (equal to one pace in quick time), each person is to take a dressing in line as quickly as possible by moving with short, quick paces until they are able to see the lower part of the face of the second person beyond. (The shoulders are to be kept square to the front without bending the body or head forward or backwards.) Personnel in the centre and rear ranks are to cover, at one pace distance, those in the front rank.

The distance of one pace between ranks is measured by the right-hand person in the centre and rear ranks who, at the same time as the front rank, are to raise their arms, hands clenched, to just touch the shoulder of the person in front.

Timing - Up, Pause, Dressing

19. In some instances the command given will be:

Left - DRESS. Exactly the same procedure is followed, except that the left arms are to be raised and head and eyes turned to the left.

EYES FRONT FROM DRESSING

20. On the command:

eyes - FRONT

Each person, except the right (or left) hand person of each rank, is to turn their head smartly to the front. All those with raised arms are to drop their arms smartly to their sides without bending the elbow or striking their thighs, thereby resuming the correct position of attention.

Timing - One

DRESSING WITHOUT INTERVALS

21. On the command:

Without intervals - **right** - DRESS

The general procedure is the same as given in Paras 17 - 18 except that the arms of the front rank are not to be fully extended. Instead, the clenched hand is to be rested on the person's own right hip at belt level, with the back of the hand towards the body, thumb to the rear. The bent elbow is to just touch the left arm of the person to the right.

22. Dressing is made without intervals when space is limited when, say, an address is to be given or on some other special occasions, eg when a guard of honour is in 2 ranks.

OPEN AND CLOSE ORDER

23. On the command:

open order - MARCH

The front rank is to take 2 paces forward and the rear rank 2 paces backward.

Timing - One, One, Two

24. On the command:

close order - MARCH

The front rank is to take 2 paces backward and the rear rank 2 paces forward.

Timing - One, One, Two

25. When in 2 ranks, the rear rank only moves on each occasion. (Note: During these movements, the arms are held steady at the sides.)

TURNING WHEN HALTED

The detail for turning (and inclining) to the left is the same as for the movements to the right, except that the word "left" is to be substituted for the word "right" and vice versa. During all turning movements the arms are to be kept close to the sides as for the position of attention. Turning at the halt is divided into 2 movements.

On the command:

right - TURN

First Movement. A turn is to be made to the right, through 90°, on the right heel and left toes by raising the left heel and right toes; both knees are to be kept straight and the body erect. On completion of this preliminary movement the right foot is to be flat on the ground and the left heel raised, knees are to be straight and the thighs locked and the weight of the body is to be on the right foot.

Second Movement. After a pause, bend the left knee and resume the position of attention facing the new direction.

Timing - One, Pause, Two

INCLINING

Inclining is similarly carried out in 2 movements.

On the command:

right in - CLINE

First Movement. A movement is made similar to that of the first movement for a right turn, except that the turn is to be made to the half right (45°).

Second Movement. As for the second movement for the turn.

Timing - One, Pause, Two

TURNING ABOUT

The About Turn is always to be made by turning to the right, unless specifically detailed otherwise for certain instances. The About Turn is also carried out in 2 movements.

On the command:

about - TURN

First Movement. A movement is made similar to that of the first movement for a right turn except that the turn is to be to the rear (180°).

Second Movement. As for the second movement for the right turn.

Timing - One, Pause, Two

SALUTING TO THE FRONT WHEN HALTED

Saluting to the front when halted is always carried out in 2 movements.

On the command:

to the front - SALUTE

First Movement. The right hand is to be brought smartly, with a semi-circular motion, to the side of the head. The palm of the hand is to be to the front with the thumb and fingers fully extended and held closely together. The fore-finger is to be placed 2cms (1 in) behind and to the right of the eye. The wrist is to be straight and the elbow in line and square with the right shoulder.

Second Movement. After a pause equal to 2 paces in quick time, the right arm is to be brought smartly down to the side of the body by the shortest route, resuming the position of attention, without striking the thigh.

Timing - Up, Two, Three, Down

SALUTING TO THE FLANK WHEN HALTED

Saluting to the flank when halted is similarly carried out in 2 movements.

On the command:

to the left/right - SALUTE

First Movement. A movement is made similar to that of the first movement for saluting to the front except that at the same time the head and eyes are to be turned sharply in the direction ordered.

Second Movement. In this case a pause equal to 4 paces in quick time is to be observed before carrying out the movements to return the hand to the side of the body and the head and eyes to the front.

Timing - Up, Two, Three, Four, Five, Down

FALLING OUT AND DISMISSING

The order to Fall Out is to facilitate dispersal from the formal formation, to attend a task or to rest, prior to being required to fall in again. There is no salute during the Fall Out.

On the command:

fall - OUT

Personnel carry out a right incline, and after a pause march off individually in accordance with any instructions they have been given.

Timing - One, Pause, Two, Pause, Forward

The order to Dismiss implies completion of the parade and personnel are to disperse to their next duty or off duty, as required.

On the command:

dis - MISS

The same action is to be carried out as for the Fall Out.

Timing - One, Pause, Two, Pause, Forward

If an officer is present, the orders given and actions carried out will change.

On the command:

Officer on parade - **dis** - MISS

Personnel carry out a right incline, pause, salute to their front for a pause equal to 2 paces in quick time, discontinue the salute and, after a further pause, are to disperse to their next duty or off duty, as required.

Timing - One, Pause, Two, Pause, Up, Two, Three, Down, Pause, Forward

Annexes:

Instructors' Check Points.

Marching.

ANNEX A TO

CHAPTER 3 TO ACP 19

INSTRUCTORS' CHECK POINTS

Instructors should check for the following common faults during drill:

1. Position of Attention and Stand at Ease

A strained position which constricts breathing.

Allowing the body to sag and the shoulders and arms to creep forward.

Roving eyes.

Bending the wrist and failing to close the hands.

Feet and body not square to the front, heels not together.

2. Standing at Ease from Attention (and vice versa)

Bending the waist when moving.

Allowing the arms to bend or to move too far from the body when going behind the back or coming to the sides.

Moving the right foot.

Moving left foot less than 30cms (12 ins) and not at the correct angle.

3. Standing Easy

Moving the feet.

Adjusting clothing etc, without an order.

4. Dressing

A sluggish movement of the arm or head.

Looking up or down or not square to the side while dressing off.

Craning forward.

Not keeping the shoulders square to the front.

A - 1

Shuffling movements with the feet.

Unnecessary movement.

5. Turnings

The weight not being on the leading foot in the first movement.

Not completing the turn with the body and shoulders in the first movement.

Moving the arms, particularly during the second movement.

Bending at the waist during the second movement.

6. Saluting

The body and head not remaining erect.

Allowing the elbow to come forward.

Saluting hand not straight and in an incorrect position.

Allowing the left arm to creep forward.

Failing to turn head and eyes fully in the direction ordered.

A - 2

ANNEX B TO

CHAPTER 3 TO

ACP 19

MARCHING/Quick marching

QM: Starting from a static position such as SaA (a), on the QM command recruits step forward with the left foot first (b) followed by the opposite leg (c). The QM is taught in such a way that recruits are to keep the legs extended from toe-off, transition and to heel contact. The heel of the leading leg is driven into the ground whilst the torso and head remain erect.

BALANCE STEP

The Balance Step is an effective method of teaching personnel to control the muscles and limbs and to acquire correct balance and erect carriage. It is also a useful preliminary method of instruction in training personnel in drill movements. When the person has made enough progress to carry out each separate movement of the balance step correctly, the interval between the successive words of command is to be reduced until each movement forward is made after only a short pause.

On the command:

Balance step - **left foot** - FRONT

The head and the body are to be in the position of attention with the arms steady at the sides. The left foot is to be advanced smartly to the front about 38cms (15 ins), and turned outward at the same angle as when halted, with the toes pointing towards, and 5cms (2 ins) from the ground. The left leg is to be kept straight and the body is to be balanced on the right foot.

On the command:

for - WARD

The left foot is to be advanced in an even movement to complete a pace of 75cms (30 ins), ensuring the small toe of the foot touches the ground first. At the same time the weight of the body is to be transferred to the left foot, keeping the right foot at its original position with the knee bent and the toes on the ground.

On the command:

Right foot - **for** - WARD

The right foot is to be advanced smartly 75cms (30 ins) beyond the left foot. The leg is to be bent sufficiently to enable the foot to clear the ground, and is to be straightened as it comes forward. The foot is to be stretched and turned outwards at the same position as when halted. The toes are to be pointed towards and about 5cms (2 ins) from the ground. The small toe of the foot touches the ground first, the weight is transferred to that foot and the left foot remains 75cms (30 ins) behind it with the knee bent and the toe on the ground.

5. The sequence of commands at Para 3 is then continued as necessary.

B - 1

6. On the command:

Flight/Squad - HALT

Which is given when the right foot is forward and on the ground, a pace of 38cms (15 ins) is to be completed with the left foot, bend the right knee, and then place the right foot smartly down in line with the left foot; movement ceases at the position of attention.

Halt: Starting from the QM (a), on command the recruit checks one, two with the left leg (b), plants the left and raises the right leg until parallel with the ground (c), followed by a forceful stamp onto the ground finishing in the SaA position (d).

<u>TURNINGS ON THE MARCH</u>

7. On the command:

Balance Step - **right** - TURN

Which is to be given when the left foot is forward and on the ground, a full forward pace is to be completed with the right foot. The left foot is to be turned diagonally to the right and is to be placed on the ground with the instep about 8cms (3 ins) in front of the right toe. The weight of the body is to be turned to the right (through 90°). At the same time, the right foot is to be advanced smartly about 30cms (12 ins) in the new direction, and is to be held clear of the ground with the foot stretched and the toes pointing downwards. (In this position both knees are to be straight and the arms are to be steady at the sides.)

8. On the command:

for - WARD

A forward pace of 75cms (30 ins) is to be completed with the right foot, and marching resumed.

Note: Details for the balance step movement to the left are the same except that the words left and right should be counter changed.

Appendix 2a: Dynamic Postural Stability Code (DPSI)

```
function varargout = DPSI(varargin)
% DPSI M-file for DPSI.fig
%      DPSI, by itself, creates a new DPSI or raises the existing
%      singleton*.
%
%      H = DPSI returns the handle to a new DPSI or the handle to
%      the existing singleton*.%% singleton: a dimension of 1 (columns)
%
%      DPSI('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in DPSI.M with the given input arguments.
%
%      DPSI('Property','Value',...) creates a new DPSI or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before DPSI_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to DPSI_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help DPSI

            %%%Changed lines 182-186%%%%

% Last Modified by GUIDE v2.5 07-Feb-2011 10:20:03

%%%%%%%%%%USER DISCRETION: This program has been modified (7FEB2011) from its
%original version to process NMRL DPSI, DOD DPSI data, and SWCC DPSI data. The calculations
%are valid for single-leg jump landings in the AP and ML directions as well as for single-leg balance.
%Also use discretion in further modification of this
%program for its inteded use.%%%%%%%%%%

% V2: Coefficient of variation added to output. Output filename changes to
%    OutputV2_.... (Jon Akins, April 2012)

% V3: corrected AP and ML direction detection using the max value of the
% absolute GRF vector. output changed to OutputV3_... (Nick Heebner, Nov
% 2012)

% V4: Eliminated Task selection. Only AP DPSI is used at the remote labs.
% This version also statically defines the force plate directions (AP/ML)
% beasure the DoD Labs do not move platform. The previous version was not
% 100% identifying direction correctly. Lastely this version modified the
% weight input to accept either kg or lbs.

% V4: Modified for portable force plate. (Mallory Sell and Heather Bansbach, September 2015)
```

```
% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @DPSI_OpeningFcn, ...
                   'gui_OutputFcn',  @DPSI_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
   gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
   [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
   gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before DPSI is made visible.
function DPSI_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to DPSI (see VARARGIN)

% Choose default command line output for DPSI
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes DPSI wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = DPSI_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

function BWBox_Callback(hObject, eventdata, handles)
% hObject    handle to BWBox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
% Hints: get(hObject,'String') returns contents of BWBox as text
%       str2double(get(hObject,'String')) returns contents of BWBox as a double
handles.BW = str2double(get(hObject, 'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function BWBox_CreateFcn(hObject, eventdata, handles)
% hObject    handle to BWBox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%      See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end

function IBABox_Callback(hObject, eventdata, handles)
% hObject    handle to IBABox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of IBABox as text
%       str2double(get(hObject,'String')) returns contents of IBABox as a double
handles.IBAW = str2double(get(hObject, 'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function IBABox_CreateFcn(hObject, eventdata, handles)
% hObject    handle to IBABox (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%      See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in Process.
function Process_Callback(hObject, eventdata, handles)
% hObject    handle to Process (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

fs = 1000;
kg = get(handles.kgbutton,'Value');
lbs = get(handles.lbsbutton,'Value');

if kg == 1
   BW = (handles.BW)*9.81; % Input kg and convert to N
```

```
elseif lbs == 1
   BW = (handles.BW)/2.2; %Convert to Kg
   BW = BW*9.81; %Convert to Newtons
else
   error('ERROR... You did not select whether KG or LBS for Weight input. Please select one and re-
run');
end

IBA = (handles.IBAW)*9.81;

if (get(handles.LoadCondition, 'Value')) == (get(handles.LoadCondition, 'Min')) % no load trial
   TestWeight = BW;
else
   TestWeight = BW + IBA;
end

weight = BW + IBA; % Total weight
output = [];

[JumpForcefilename,JumpForcepathname] = uigetfile('*.txt','Please select all DPSI file to
process.','MultiSelect','on');
cd(JumpForcepathname);
if ~iscell(JumpForcefilename)
   JumpForcefilename = {JumpForcefilename};
end

dynamicmessage = ['Choose trial type from the pop-up window'];
set(handles.dynamictext, 'String', dynamicmessage);
%whichtest = menu('What task was this test?', 'Balance','Anterior/Posterior', 'Medial/Lateral');
%%%%%%%% Version 4 %%%%%%%%%%%%%
whichtest = 2;% automatically selects AP DPSI
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for fn=1:length(JumpForcefilename)
   %Original Commands
   JumpForcedata = dlmread(JumpForcefilename{fn},'\t',19,0);
%    if sum(JumpForcedata(:, 10)) > sum(JumpForcedata(:, 22)) % If jump onto forceplate 1
%       FP = -12; % Shift data reading left for 12 columns to read the forceplate 1 data
%    else
%       FP = 0; % Default
%    end

%    %Check to see if fs == 1200Hz
%    if length(FP(:,1)) == 12000
%    elseif length(FP(:,1)) == 10000
%       fswarning = menu('WARNING! ... Sampling Frequency of force plates may not be at 1200 Hz.
You may have it set at 1000Hz. Please correct before continuing...','OK');
%    else
%       fswarning = menu('WARNING! ... Sampling Frequency of force plates may not be at 1200
Hz','OK');
%    end
```

```
% %--------------------------------
  if whichtest == 1;

    testtask = 'Balance';
    dynamicmessage = ['Processing balance trials'];
    set(handles.dynamictext, 'String', dynamicmessage);
    %assign variables
    APforceRAW = JumpForcedata (:, 3);
    MLforceRAW = JumpForcedata (:, 2);
    VertforceRAW = JumpForcedata (:, 4);
    APcop = JumpForcedata (:, 6)./1000;
    MLcop = JumpForcedata (:, 5)./1000;
%      sampleperiod = 10;

  elseif whichtest == 2;

    testtask = 'AP';
    dynamicmessage = ['Processing A-P trials'];
    set(handles.dynamictext, 'String', dynamicmessage);
    %assign variables
%      if max(abs(JumpForcedata(:, 20+FP))) > max(abs(JumpForcedata(:, 21+FP)))
%        APforceRAW = JumpForcedata (:, 20 + FP);
%        MLforceRAW = JumpForcedata (:, 21 + FP);
%      else
%        APforceRAW = JumpForcedata (:, 21 + FP);
%        MLforceRAW = JumpForcedata (:, 20 + FP);
%      end
    %%%%%%% Version 4 %%%%%%%%
    APforceRAW = JumpForcedata (:, 3);
    MLforceRAW = JumpForcedata (:, 2);
    VertforceRAW = JumpForcedata (:, 4);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    APcop = JumpForcedata (:, 6)./1000;
    MLcop = JumpForcedata (:, 5)./1000;
%      sampleperiod = 10;

  else whichtest == 3;

%      testtask = 'ML';
%      dynamicmessage = ['Processing M-L trials'];
%      set(handles.dynamictext, 'String', dynamicmessage);
%      %assign variables
%      if max(abs(JumpForcedata(:, 2))) > max(abs(JumpForcedata(:, 3)))
%        APforceRAW = JumpForcedata (:, 3);
%        MLforceRAW = JumpForcedata (:, 2);
%      else
%        APforceRAW = JumpForcedata (:, 2);
%        MLforceRAW = JumpForcedata (:, 3);
%      end
%      VertforceRAW = JumpForcedata (:, 4);
%      APcop = JumpForcedata (:, 10)./1000;
```

```
%       MLcop = JumpForcedata (:, 9)./1000;
%       sampleperiod = 10;
   end

   %filter data
      [a,b] = butter (2, 20/600);

      APforcefilt = filtfilt (a,b,APforceRAW);
      MLforcefilt = filtfilt (a,b,MLforceRAW);
      Vertforcefilt = filtfilt (a,b,VertforceRAW);

      APforce = APforcefilt;
      MLforce = MLforcefilt;
      Vertforce = Vertforcefilt;

   %Identify offset >5N in force data.
   for k = 1:100
     if abs(Vertforce(k)) > 5
        VertOffset = mean(Vertforce(1:100));
        APOffset = mean(APforce(1:100));
        MLOffset = mean(MLforce(1:100));

        %If there is an offset, normalize by subtracting offset from
        %each data point.
        Vertforce = Vertforce - VertOffset;
        APforce = APforce - APOffset;
        MLforce = MLforce - MLOffset;
     else
        k = k + 1;
     end
   end


   Verttotaltime = 0:1/fs:(length(Vertforce)-1)/fs;

   cla;
   plot (Verttotaltime, Vertforce);
   title ('Total GRFz data set');
   xlabel ('time (s)');
   ylabel ('GRF (N)');

   %identify stance phase based on 5% BW
   ICvalue = ceil(.05*TestWeight);
   [stancepos] = find (Vertforce > ICvalue);
   ICtime = Verttotaltime (stancepos(1));
   VertIC = Vertforce (stancepos(1));
   timestance = 0:1/fs:(length (stancepos)-1)/fs;
   Vertstance = Vertforce (stancepos);
   MLstance = MLforce (stancepos);
   APstance = APforce (stancepos);
   APcopstance = APcop (stancepos);
```

```
MLcopstance = MLcop (stancepos);
hold on;
plot (ICtime, VertIC, 'ro');

whichconfirm = menu('Is IC identified correctly?', 'Yes','No');
 whichconfirm = 1;
if whichconfirm == 1;
   testconfirm = 'YES';


   %Calculate APSI
   APSIsumsquared=0;
   for i=1:((fs*3)-1);
      %First section sums the squared differences from 0
      APSIdatapoint=(0-APstance(i))^2;
      APSIsumsquared= APSIsumsquared + APSIdatapoint;
   end
   %Second section takes the square root of the sum/number of data
   %points
   APSI= sqrt((APSIsumsquared)/(fs*3))/weight;

   %Calculate MLSI
   MLSIsumsquared=0;
   for i=1:((fs*3)-1);
      %First section sums the squared differences from 0
      MLSIdatapoint=(0-MLstance(i))^2;
      MLSIsumsquared= MLSIsumsquared + MLSIdatapoint;
   end
   %Second section takes the square root of the sum/number of data points
   MLSI= sqrt((MLSIsumsquared)/(fs*3))/weight;

   %Calculate VSI
   VSIsumsquared=0;
   for i=1:((fs*3)-1);
      %First section sums the squared differences from 0
      VSIdatapoint=(TestWeight-Vertstance(i))^2;
      VSIsumsquared= VSIsumsquared + VSIdatapoint;
   end
   %Second section takes the square root of the sum/number of data points
   VSI= sqrt((VSIsumsquared)/(fs*3))/weight;

   %Calculate DPSI
   %3 seconds of data is 3600 points
   DPSIsumsquared=0;
   for i=1:((fs*3)-1);
      %First section sums the squared differences from 0
      DPSIdatapoint=((TestWeight-Vertstance(i))^2)+((0-MLstance(i))^2)+((0-APstance(i))^2);
      DPSIsumsquared=DPSIsumsquared+DPSIdatapoint;
   end

   %Second section takes the square root of the sum/number of data points
```

```
	DPSI= sqrt((DPSIsumsquared)/(fs*3))/weight;

	%Calculate standard deviations IC - sampleperiod sec
	stdevAPstance = std(APstance(1:end));
	stdevMLstance = std(MLstance (1:end));
	stdevVertstance = std(Vertstance(1:end));
	stdevAPcop = std(APcopstance(1:end));
	stdevMLcop = std(MLcopstance(1:end));

	%Calculate sway length
	for i = 1:(length(APcopstance)-1)
	   APdist(i) = APcopstance(i+1)-APcopstance(i);
	   MLdist(i) = MLcopstance(i+1)-MLcopstance(i);
	   swaydist(i) = sqrt(APdist(i)^2 + MLdist(i)^2);
	end

	TOTALswaylen = sum(swaydist);
	AVGswayvel = TOTALswaylen/(length(APcopstance)/fs);

	%Claculate sway range
	MAX_APcop = max(APcopstance(1:end));
	MIN_APcop = min(APcopstance(1:end));
	RANGE_APcop = MAX_APcop - MIN_APcop;

	MAX_MLcop = max(MLcopstance(1:end));
	MIN_MLcop = min(MLcopstance(1:end));
	RANGE_MLcop = MAX_MLcop - MIN_MLcop;

	output = [output; fn MLSI APSI VSI DPSI stdevMLstance stdevAPstance stdevVertstance
stdevAPcop stdevMLcop TOTALswaylen AVGswayvel RANGE_APcop RANGE_MLcop];

%	%form output and compile data
%	xcell = {1};
%	xcell{1,1} = 'MLSI';
%	xcell{1,2} = 'APSI';
%	xcell{1,3} = 'VSI';
%	xcell{1,4} = 'DPSI';
%	xcell{1,5} = 'MLstdev(N)';
%	xcell{1,6} = 'APstdev(N)';
%	xcell{1,7} = 'Vertstdev(N)';
%	xcell{1,8} = 'stdevAPcop(m)';
%	xcell{1,9} = 'stdevMLcop(m)';
%	xcell{1,10} = 'TOTALswaylen(m)';
%	xcell{1,11} = 'AVGswayvel(m/s)';
%	xcell{1,12} = 'RANGE_APcop(m)';
%	xcell{1,13} = 'RANGE_MLcop(m)';
%	xcell{2,1} = MLSI;
%	xcell{2,2} = APSI;
%	xcell{2,3} = VSI;
%	xcell{2,4} = DPSI;
%	xcell{2,5} = stdevMLstance;
```

```
%       xcell{2,6} = stdevAPstance;
%       xcell{2,7} = stdevVertstance;
%       xcell{2,8} = stdevAPcop;
%       xcell{2,9} = stdevMLcop;
%       xcell{2,10} = TOTALswaylen;
%       xcell{2,11} = AVGswayvel;
%       xcell{2,12} = RANGE_APcop;
%       xcell{2,13} = RANGE_MLcop;
%
%    Tempfilename = JumpForcefilename{fn};
%    SaveFilename = ['Output_',Tempfilename(1, 1:end-4),'.xls'];
%    xlswrite(SaveFilename, xcell);



  elseif whichconfirm == 2;
     testconfirm = 'NO';
     close gcf;
     error ('\n\nPlease identify why IC is incorrect before continuing');
  end




end

averages = [];
stdev = [];
CoV = [];
for p=2:14
  averages = [averages mean(output( :, p))];
  stdev = [stdev std(output( :, p))];
  CoV = [CoV (std(output(:,p)/abs(mean(output(:,p)))))];
end

averages = num2cell(averages);
stdev = num2cell(stdev);
CoV = num2cell(CoV);

averages = ['Average' averages];
stdev = ['SD' stdev];
CoV = ['CoV' CoV];


output = num2cell(output);

      xcell = {};
      xcell{1,1} = 'Trial';
      xcell{1,2} = 'MLSI';
      xcell{1,3} = 'APSI';
      xcell{1,4} = 'VSI';
      xcell{1,5} = 'DPSI';
```

```
        xcell{1,6} = 'MLstdev(N)';
        xcell{1,7} = 'APstdev(N)';
        xcell{1,8} = 'Vertstdev(N)';
        xcell{1,9} = 'stdevAPcop(m)';
        xcell{1,10} = 'stdevMLcop(m)';
        xcell{1,11} = 'TOTALswaylen(m)';
        xcell{1,12} = 'AVGswayvel(m/s)';
        xcell{1,13} = 'RANGE_APcop(m)';
        xcell{1,14} = 'RANGE_MLcop(m)';

FinalOutput = [xcell; output; averages; stdev; CoV];

SaveFilename = JumpForcefilename{fn};
SaveFilename = ['OutputV4_',SaveFilename(1, 1:end-5),'.xlsx'];
xlswrite(SaveFilename, FinalOutput);
dynamicmessage = ['Done! Data exported: ' SaveFilename];
set(handles.dynamictext, 'String', dynamicmessage);

clear all

% --- Executes on button press in LoadCondition.
function LoadCondition_Callback(hObject, eventdata, handles)
% hObject    handle to LoadCondition (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of LoadCondition
if (get(hObject,'Value') == get(hObject,'Max'))
   set(handles.dynamictext, 'String', 'To Process IBA Trials');
   % checkbox checked, IBA trial
else
   set(handles.dynamictext, 'String', 'To Process No Load Trials');
   % checkbox not checked, no load trial
end
```

Appendix 2b: Sample Entropy Code

```
% Nonlinear Postural Stability Measures

% This code was wrtiten by Heather Bansbach on 11/16/2016
% This code was written to process force plate data collected via Bioware
% Software during a double leg stance postural stability task. It reads in
% text file and outputs for min and max path excursion, total COP path
% distance, mean velocity, and sample entropy.

function varargout = NonlinearPS(varargin)
% NONLINEARPS MATLAB code for NonlinearPS.fig
%      NONLINEARPS, by itself, creates a new NONLINEARPS or raises the existing
%      singleton*.
%
%      H = NONLINEARPS returns the handle to a new NONLINEARPS or the handle to
%      the existing singleton*.
%
%      NONLINEARPS('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in NONLINEARPS.M with the given input arguments.
%
%      NONLINEARPS('Property','Value',...) creates a new NONLINEARPS or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before NonlinearPS_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to NonlinearPS_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help NonlinearPS

% Last Modified by GUIDE v2.5 29-Nov-2016 12:41:16

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @NonlinearPS_OpeningFcn, ...
                   'gui_OutputFcn',  @NonlinearPS_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
```

```
   gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before NonlinearPS is made visible.
function NonlinearPS_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to NonlinearPS (see VARARGIN)

% Choose default command line output for NonlinearPS
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes NonlinearPS wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = NonlinearPS_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

function weight_Callback(hObject, eventdata, handles)
% hObject    handle to weight (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of weight as text
%        str2double(get(hObject,'String')) returns contents of weight as a double
handles.Weight = str2double(get(hObject, 'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function weight_CreateFcn(hObject, eventdata, handles)
% hObject    handle to weight (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
```

```
end

% --- Executes on button press in ProcessPS.
function ProcessPS_Callback(hObject, eventdata, handles)
% hObject    handle to ProcessPS (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

mpathname = mfilename('fullpath');
mpath = mpathname(1:length(mpathname)-length(mfilename()));
addpath([mpath filesep 'CircStat2012a']);

fs = 1000; % sampling frequency
g = 9.81;
% BW = (handles.Weight)*g; %Convert body weight from kg to Newtons
% unloaded = get(handles.Unloaded,'Value'); %Get radio button values from GUI
% BW50 = get(handles.BW50,'Value');
% BW70 = get(handles.BW70,'Value');
%
% if unloaded == 1 %if radio button is checked, value should equal 1 and adjust BW accordingly
%     BW = BW;
% else
% end
%
% if BW50 == 1
%     BW = BW + (BW*.5);
% else
% end
%
% if BW70 == 1
%     BW = BW + (BW*.7);
% else
% end

% Load .txt force plate data files
[PSfilename,PSpathname] = uigetfile('*.txt','Please select trials to process.','MultiSelect','on');
 cd(PSpathname);
 if ~iscell(PSfilename)
    PSfilename = {PSfilename};
 end

 filenumber = length(PSfilename);
 Output = [];

 for j = 1:filenumber

    % Read .txt files and extract GRF x,y,z,r
    data = dlmread(PSfilename{j},'\t',19,0);
    fpTime = data(:,1);
    Data = data(1:length(data),2:3);
    % Leave data unfiltered for nonlinear measure. Unfiltered data is not
```

```
    % shown to have a significant effect on time domain measures when
    % sampled at 100 Hz. (Rhea, 2015)

    grfData = zeros(size(Data));
    % Zero Mean and Unit variance x,y, and z GRF
    for i = 1:2
      MgrfData = Data(:,i)-mean(Data(:,i));
      grfData(:,i) = MgrfData;
      grfData_unitVAR(:,i) = MgrfData/std(Data(:,i));
    end

    % Root Mean Square
    RMSap = 0;%rms(grfData(:,1));
    RMSml = 0;%rms(grfData(:,2));
%     RMSv = rms(grfData(:,3));
%     RMSr = rms(grfData(:,4));

    % Stnadard Deviation
    STDap = 0;%std(grfData(:,1));
    STDml = 0;%std(grfData(:,2));
%     STDv = std(grfData(:,3));
%     STDr = std(grfData(:,4));
%
    % Peak to Peak
    P2Pap = 0;%range(grfData(:,1));
    P2Pml = 0;%range(grfData(:,2));
%     P2Pv = range(grfData(:,3));
%     P2Pr = range(grfData(:,4));

    % Normalized Path Length
    for i = 1:(length(grfData)-1)
       dap(i) = abs(grfData((i+1),1) - grfData(i,1));
       dml(i) = abs(grfData((i+1),2) - grfData(i,2));
%         dv(i) = abs(grfData((i+1),3) - grfData(i,3));
%         dr(i) = abs(grfData((i+1),4) - grfData(i,4));
    end
    NPLap = sum(dap)/(length(grfData)/fs); %N/sec
    NPLml = sum(dml)/(length(grfData)/fs); %N/sec
%     NPLv = sum(dv)/(length(grfData)/fs); %N/sec
%     NPLr = sum(dr)/(length(grfData)/fs); %N/sec
    clear dap dml %dv dr

    % Sample Entropy
    % m=3 data point and r=0.3xSD of the heading change were selceted for
    % the resultant magnitude and direction time series, while m=3 and
    % r=0.07xSD for the independent analysis of
    % both the AP and ML time series. (Rhea, 2014)

    % Displacement between two successive CoP positions
    for i = 1:(length(grfData)-1)
       dap(i) = (grfData((i+1),1) - grfData(i,1));
```

```
      dml(i) = (grfData((i+1),2) - grfData(i,2));
    end
    dap = dap';
    dml = dml';

    % atan2(y,x) specifies that the x-coordinate is on the horizontal (ML)
    % axis
    arctan = atan2(dap,dml);
    for i = 1:length(arctan)
      if arctan(i) < 0
         arctan(i) = arctan(i) + 2*pi;
      else
      end
    end

    heading = arctan*(180/pi);

    deltaHeading = circ_dist(heading,0);
    stdevHeading = circ_std(arctan,[],[],1);

    grfData_unitVAR = resample(grfData_unitVAR,100,1000);
    m = 3;
    rx = 0.3; %0.15 based on Rhea et al 2015 Gait and Posture..... Alt%0.3; %0.07*stdevHeading;
    ry = 0.3;
    [ex,se_x,A_x,B_x] =
sampen(grfData_unitVAR(:,1),m,rx,1,0,1);%%%https://www.physionet.org/physiotools/sampen/
    [ey,se_y,A_y,B_y] = sampen(grfData_unitVAR(:,2),m,ry,1,0,1);

    Output = [Output; ex(length(ex)) ey(length(ey)) se_x(length(se_x)) se_y(length(se_y))];

end

   datasize = size(Output);
   filenumber = length(PSfilename);
   for k = 1:datasize(2)
      Output(filenumber+1, k) = mean(Output(1:filenumber, k));
      Output(filenumber+2, k) = std(Output(1:filenumber, k));
      Output(filenumber+3, k) = std(Output(1:filenumber, k)) / abs(mean(Output(1:filenumber, k)));
   end

   PSfilename1 = PSfilename';
   PSfilename1{filenumber+1, 1} = 'Average';
   PSfilename1{filenumber+2, 1} = 'SD';
   PSfilename1{filenumber+3, 1} = 'CoV';

   Output = num2cell(Output);
   Output = [PSfilename Output];

   header{1} = 'Trial';
   header{2} = 'Sampenx';
   header{3} = 'Sampeny';
```

```
    header{4} = 'REx';
    header{5} = 'REy';

    Output = [header;Output];

    filename = char(PSfilename(1));
    SaveFilename = ['OutputV1_',filename(1:end-6),'.xlsx'];
    xlswrite(SaveFilename, Output, 'Sheet1');
   % dynamicmessage = ['Done! Data exported: ' SaveFilename];
   % set(handles.dynamictext, 'String', dynamicmessage);

clear all;

% --- Executes on button press in Unloaded.
function Unloaded_Callback(hObject, eventdata, handles)
% hObject    handle to Unloaded (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of Unloaded


% --- Executes on button press in BW50.
function BW50_Callback(hObject, eventdata, handles)
% hObject    handle to Unloaded (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of Unloaded


% --- Executes on button press in BW70.
function BW70_Callback(hObject, eventdata, handles)
% hObject    handle to Unloaded (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of Unloaded
```

Appendix 2c: Fast Fourier Transform

```
%%[filename,pathname] = uigetfile ('*.txt','Please choose files to process','MultiSelect','on');
cd(pathname);
disp('processing files');
processing files
data = dlmread(data',',');
x = data;
size (x)
N=3000;
fs=1000;
ts=1/fs;
tmax=(N-1)*ts;
t=0:ts:tmax;
plot (t,x)
f=-fs/2:fs/(N-1):fs/2;
z=fftshift(fft(x));
figure
plot (f,abs(z))
```

Appendix 3a: Reliability of the Kinetics of British Army Foot-drill in Untrained Personnel – Publication. Accepted. DOI: 10.1519/JSC.0000000000001492

Running head: Reliability of the Kinetics of Foot-Drill

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ABSTRACT

The purpose of this study was to quantify the reliability of kinetic variables of British Army foot-drill performance within untrained civilians and report the magnitude of vertical ground reaction force (vGRF) and vertical rate of force development (RFD) of foot-drills. Fifteen recreational active males performed three testing sessions across a 1-week period, with each session separated by 24 h. Within each testing session participants (mean ± SD; age 22.4 ± 1.7 years; height 177 ± 5.6cm; weight 83 ± 8.7kg) completed ten trials of stand-at-attention (SaA), stand-at-ease (SaE), halt, quick-march (QM) and a normal walking gait, with vGRF and vertical RFD measured on a force plate. Between and within session reliability was calculated as systematic bias, coefficient of variation calculated from the typical error (CV_{te}%) and intra-class correlation coefficient (ICC). Significant ($P \leq 0.05$) between session differences were found for the vGRF SaA, SaE and vertical RFD SaA, SaE conditions. Significant ($P \leq 0.05$) within session differences were found for the vGRF SaA and SaE conditions. A mean vGRF CV_{te}% ≤10% was observed across all foot-drills. However, the mean vertical RFD CV_{te}% observed was ≥10% (excluding SaE) across all foot-drills. The ICC analyses indicated that the vGRF Halt, QM, SaA and Walk condition achieved moderate to large levels of test-retest reliability, with only SaE failing to achieve an ICC value ≥0.75. The vertical RFD QM, SaE, and Walk condition achieved moderate levels of test-retest reliability, with Halt and SaA failing to achieve an ICC value ≥0.75. It was determined that a single familiarization session and using the mean of eight-trials of vGRF are required to achieve acceptable levels of reliability.

KEY WORDS: Military, Training, systematic bias, within-subject variation, test-retest reliability

INTRODUCTION

Lower-limb musculoskeletal (MSK) overuse injuries are defined as the single most significant medical impediment to the physical readiness of recruits within the British Armed Forces [23] and the most common cause of medical discharge from the British Army (MOD, 2015). Training status specific rate of medical discharges for untrained recruits (52.2 per 1,000 personnel) is significantly greater in comparison with trained personnel (11.8 per 1,000 personnel) [1]. The high rates of medical discharge of untrained personnel reflect both the intensive physical nature of basic military training (BMT), and lack of exposure to the rigorous physical demands of high training loads specific to the BMT course [1]. Efforts to reduce and/or minimise the incidence of lower-limb MSK overuse injuries and disorders is of primary focus for many military organisations worldwide.

British Army foot-drill is a fundamental military occupational activity, routinely practised by recruits during BMT, and utilised to enhance discipline, co-ordination, and body awareness [7]. Organised foot-drill sessions for recruits have been reported to range from 40 min to 80 min sessions per day [30] up to a total of 13h per week [5]. Each foot-drill contains a number of key performance markers which define that particular foot-drill. For example, quick march (QM) requires marching at two paces per second whilst repeatedly impacting the ground with an exaggerated heel strike. Other regimented movements performed while marching involve an exaggerated stamp of the dominant or non-dominant foot (depending on foot-drill performed) onto the surface of the ground. Foot-drills such as stand-at-attention (SaA), stand-at-ease (SaE) and Halt, involve flexion at the hip to 90° followed by an exaggerated stamping of the foot onto the ground, landing with the knee in an extended position. Selective British Army foot-drill has previously been shown to produce high impact loading forces within soldiers who have been trained in foot-drill (trained) [5] and recruits who have not (untrained) [5, 9]. To date, only two biomechanical studies have quantified the impact loading forces of selected foot-drills within an untrained sample. Using the mean of 3 trials, Carden *et al.,* [5] reported high vertical ground reaction forces (vGRF) for march, halt, stand-at-attention (SaA) and stand-at-ease

(SaE); ranging from 1.3BW to 4.4BW, and high loading rates; ranging from 70BW/s to 499BW/s. Connaboy *et al.,* [9] reported similar mean vGRF (3.06 ± 1.16BW) and vertical rate of force development (RFD) (187.7 ± 94.2BW/s) values for the same foot-drills using the mean of 5 trials. Both studies illustrate impact loading forces similar to those experienced during high level plyometric exercises; a modality of training more commonly associated with highly trained athletic populations [4].

However, although Connaboy *et al.,* [9] and Carden *et al.,* [5] investigated the impact loading forces of foot-drill, the number of trials utilised to accurately assess ground reaction force (GRF) variables of foot-drill was selected arbitrarily, with no justification regarding the requirement for any familiarisation sessions and/or trials prior to data collection, and no rationale for the mean number of trials used to represent the forces achieved. Using too few trials to assess biomechanical variables of foot-drill may not reliably represent the individual's true performance. Consequently, the stability and reproducibility of mean values could be questioned as the magnitude and influence of variability within previous foot-drill data was not calculated. The sources of error that contribute to the overall reliability of the measure primarily consist of biological, and technological – with a reliable test characterised by low within-subject variation and high test-retest correlation [16, 22]. Analysing the magnitude of a systematic bias, within-subject variation, and test-retest correlation of foot-drill will provide valuable information that will better inform future biomechanical studies of foot-drill in terms of the necessary number of trials required to obtain accurate and stable measures of foot-drill performance, and the requirement of any familiarisation sessions and/or trials prior to analysing the impact loading forces of foot-drill within an untrained sample.

Therefore, the aims of the present study were three fold: (i) to determine the magnitude of any systematic bias among session(s) and between trial(s), (ii) to establish the within-subject variation of key biomechanical variables; and (iii) to analyse the test-retest reliability to indicate the number of sessions and/or trials required to maximise the possibility of identifying changes in the kinetics of British Army foot-drill between different conditions, and over time.

It was hypothesized that similar to other locomotor and landing tasks, several trials would be necessary to achieve high levels of performance stability during British Army foot-drill, and that familiarisation sessions and/or trials would be required prior to collecting stable foot-drill biomechanical data. In addition, it was hypothesized that as random error decreased, test-retest correlation scores would increase when using the average of multiple trials.

METHODS

Experimental Approach to the Problem

A within-participant repeated-measures study design was employed to assess measures of reliability; establishing the requirement for familiarisation sessions and/or trials to determine within-subject variation and test-rest reliability.

Participants

An a *priori* power analysis (G*Power, v 3.1.9.2, Germany) was conducted as a means of detecting population effect size, with sample size computed as a function of power (1 – β) with significance set at 0.05. From this analysis it was determined that a total sample size of 15 achieved a power of 0.812 with a medium-to-large effect size ($f = 0.35$). Thus, fifteen recreational active healthy males (mean ± SD; age 22.4 ± 1.7 years; height 177 ± 5.6cm; body mass 83 ± 8.7kg) with no pathological lower-limb, hip or spinal conditions volunteered to participate in the present study. Study participants were recreationally active, taking part in moderate physical activity and/or sport a minimum of two-to-three times per week over the previous three years [11]. Ethical approval for the present study was gained from the local ethics committee. Written informed consent was obtained from each participant prior to data collection. Study participants were defined as “untrained” as they did not obtain any previous training of British Army foot-drill prior to this study. Nevertheless, the study participants obtained similar anthropometric characteristics and training histories when compared with male entry-level recruits [21, 28].

Procedures

During each of the three 90 min testing sessions, ten acceptable trials [20] of five British Army foot-drills involving; SaA, SaE, QM, Halt and a normal walking gait were collected from each participant independently. Acceptable trials were those that conformed to the key performance markers as described in the British Army Drill Instructors Manual (BADIM) [2]. Furthermore, if obvious adjustments in foot-drill movements were identified, those trials were discarded and repeated. Ten trials of a normal walking gait were collected on each day of testing to act as a comparison with QM. Foot-drill data was collected on three non-consecutive days. All three test sessions were conducted at the same time of day and performed under the guidance of the same instructor. Participants were asked to avoid practicing foot-drill throughout the testing period and to refrain from strenuous, high impact loading activity 24 hours prior to each test session.

Each participant was fitted with a size-specific pair of Hi-Tech Silver Shadow™ training shoes (TR) to reduce the influence of different shock absorbing properties of different footwear on force plate data [12]. Each participant performed a standardised 10 min warm up whilst wearing the TR, consisting of 5 min on a cycle ergometer (Monark Exercise AB, 824-E, Sweden), cycling between 60-70 revolutions per minute under a 1.5kg breaking force, followed by various dynamic lunging and squatting movements prior to each test session [27]. Foot-drill and walk were performed on two embedded (side-by-side) Kistler force plates (Kistler Instruments AG, 9281CA, Switzerland) - interfaced with BioWare 3.2.5 software to record and analyse the vGRF and vertical RFD of each foot-drill and walk. The force plate was set at a sampling frequency of 1000Hz with a 3 sec capture period [13, 25]. Force data were collected using an eight channel 16-bit analogue to digital converter (Qualisys, 8128, Sweden). The vGRF values were normalised to bodyweight (BW) to enable direct comparison across participants.

Representative of an entry-level recruit, foot-drill was a novel task for all participants prior to data collection. Furthermore, a combination of action observation and physical practice in accordance with the BADIM [2] was utilised as a means of demonstrating and teaching foot-drill. Study participants were given a 3 sec countdown prior to the execution of each foot-drill. Specific to QM, participants were instructed to QM with an exaggerated heel strike across the 10-m walkway [6]. During the execution of SaA, SaE, and Halt, study participants were instructed to flex their hip to 90° and land with an exaggerated stamp onto the surface of the force plate with the knee in an extended position. Study participants kept their head and eyes forward as to minimise visual fixation (targeting) of the force plate during all foot-drill trials [6]. During the initial testing session only, study participants were given 15 min to practice the five foot-drills prior to data collection and become familiar with the TR.

A 90 sec recovery period between each of the 10 trials and a 15 min recovery between foot-drills was employed to reduce the risk of fatigue on foot-drill performance [4]. Ten trials were collected for each of the five foot-drills during each of the 3 test sessions. A total of 30 trials were analysed for each of the five foot-drills. Accumulatively, 150 (acceptable) trials were collected and analysed per participant. As a means of enhancing the internal validity of the present study whilst minimising an order effect, foot-drill was counterbalanced for each participant across all three testing sessions [6].

Key performance markers of British Army foot-drill

A comprehensive description of each foot-drill analysed within the present study can be found in the BADIM [2]. The foot which strikes the force plate during each of the foot-drills is referred to as the active limb with the opposite limb referred to as the support limb (table 1).

Table 1 - Regimented foot-drill manoeuvres (BADIM, 2009)

Foot drill	from QM	from SaE	from SaA	active Limb
QM				*R*
Halt	*X*			*R*
SaA		*X*		*L*
SaE			*X*	*L*
Walk				*R*

Table 1 illustrates the regimented foot-drill manoeuvres completed from their respective foot-drill, identified by *X*. The active limb refers to the left (L) or right (R) limb that is used in each foot drill.

Ten trials of a normal walking gait were included in the analysis for each participant as to compare with the biomechanical variables of QM. Walking, performed by each participant at their preferred walking speed, was measured in meters per second and was standardised for each individual participant via timing gates (Fusion sport, SmartSpeed, Australia) located at 0-m, 5-m and 10-m along the 10-m walkway. The velocity of walking was monitored across each test session and a maximum deviation of +/- 5% was allowed from each participants walking velocity [28]. Foot-drill vGRF data were exported via BioWare 3.2.5 system and filtered via a low-pass 4th order zero-lag (single bi-directional) Butterworth filter, using a cut off frequency of 50Hz based on previous power spectrum analysis, ensuring 95% of the signal content was retained [32].

The BW normalized vGRF was calculated as,

$$BW_{Norm} = \frac{\mathrm{Fz}_{peak}}{BW} \qquad [1]$$

where, BW_{Norm} is the normalized vGRF expressed in BW, Fz_{peak} is the peak vertical ground reaction force measured in Newtons (N), and BW is the participant's bodyweight expressed in N determined via the force plate. The kinetic variables of interest were defined and calculated as follows: Fz_{peak} - defined as the highest (Peak) vertical ground reaction force (measured in Netwons (N)) of each foot-drill.

Time to Fz_{peak} - defined as the time to reach Fz_{peak} expressed in milliseconds (ms).

$$\textit{Time to } Fz_{peak} = t_{max} - t_{min} \quad [2]$$

where, t_{min} represents the time point of the initial onset of vGRF and t_{max} represents the time point of Fz_{peak}, measured in sec. The initial onset of vGRF was defined as when the vGRF component exceeded a threshold of 20N [24]. The vertical RFD was calculated as;

$$RFD = \frac{\Delta F}{\Delta T} \quad [3]$$

where, *RFD* is the rate of force development measured in N per second (N/s), ΔF represents the change in force measured in N and, ΔT represents the change in time measured in sec [2].

Vertical RFD was normalised relative to participant's BW calculated as,

$$Norm\ RFD = \frac{RFD}{BW} \quad [4]$$

where, *Norm RFD* is the vertical RFD normalised to the participant's bodyweight, measured in N.

Statistical Analyses

Prior to calculating systematic bias, within-subject variation and, test-retest correlation, each of the biomechanical variables was examined for heteroscedasticity [3]. If heteroscedasticity was not present and showed no departures from a normal distribution, the raw data were used in the reliability calculations. However, if the data were found to be heteroscedastic, and shown to violate the assumption of normality, then data were log transformed in SPSS 20 using 100x natural logarithm of the observed value [3, 16]. To isolate the effects of the between-session and within-session systematic bias only the remaining two testing sessions and the initial 8 trials from each session were included in the subsequent reliability analyses (within-subject variation and test-retest correlations).

Systematic bias was determined using a repeated-measures analysis of variance (RM ANOVA) design. Multiple (n = 5) one-way RM ANOVA's with Bonferroni adjusted multiple comparisons were conducted for each of the predictor variables (vGRF and vertical RFD) for each of the foot-drills. This analysis was utilised as a means to determine whether the magnitude of difference among the mean values for each session (n = 3) and trial (n = 10) was statistically significant. Alpha (α) value was set at 0.05. Where any statistically significant differences between-session and/or within-session occurred, those sessions and/or trials were removed from further calculations of reliability (within-subject variation and test-retest correlations). The within-subject variation was calculated for the remaining marching drill trials that did not contain any systematic bias. The within-subject variation was reported for the remaining trials as both the typical error and coefficient of variation of the typical error (CV_{te}). The within-subject variation was expressed as a percentage of the coefficient of variation of the typical error (CV_{te}%). The CV_{te}% was calculated using the methods proposed by Hopkins, [16] and were calculated as;

$$CVte\% = \left(\frac{\mathrm{TE}n}{\mathrm{M}n}\right) X\ 100 \qquad [5]$$

where TE_n is the typical error of n number of trials and M_n is the mean value from the same n repeated trials.

Test-retest reliability was calculated for all acceptable trials for each foot-drill and evaluated using the ICC (Model 3,1) [3, 17]. The stability of the variation in each predictor variable was assessed using methods proposed by James *et al.,* [20]. Trials that contained a systematic bias were removed with the remaining trials used to calculate maximum ICC values. Initial ICC was calculated for all data to establish maximum ICC values and 95% confidence intervals (CI). An iterative process was then conducted by which ICC values were calculated for the initial 3 trials up to the maximum number of acceptable trials per foot-drill [17]. To assess the stability of each predictor variable, the minimum number of trials required to achieve maximum levels of ICC were calculated. Furthermore, to determine the minimum number of trials necessary to achieve a stable representation of the variation within each predictor variable, the number of trials required to achieve an ICC value of 0.75, 0.80 and 0.85 were calculated.

RESULTS

Systematic Bias

Statistically significant between-session differences were found for the vGRF and vertical RFD in the following foot-drills: vGRF SaA condition ($F_{2, 28}$ = 9.603, P = 0.001, Np^2 = .407), vertical RFD SaA condition ($F_{2, 28}$ = 7.152, P = .003, Np^2 = .338), vGRF SaE condition ($F_{2, 28}$ = 7.242, P = .003, Np^2 = .341), and for the vertical RFD SaE condition ($F_{2, 28}$ = 9.615, P = .001, Np^2 = .407). Follow up Bonferroni comparisons indicated a systematic bias between session 1 and the two remaining testing sessions for the vGRF SaA and SaE, and vertical RFD SaE conditions, with the vertical RFD SaA condition illustrating a systematic bias between session 1 and 3 only (figure 1). No further statistically significant between-session systematic bias was observed for the remaining conditions.

Statistically significant within-session (between-trial) differences were found in the vGRF in the following foot-drills: vGRF SaA condition ($F_{9, 126}$ = 6.133, P < 0.01, Np^2 = .305), vGRF SaE condition ($F_{9, 126}$ = 4.408, P < 0.01, Np^2 = .239), and vGRF Halt condition ($F_{4.9, 68.7}$ = 2.406, P = .046, Np^2 = .147). Bonferroni comparisons revealed a systematic bias in trials 10 for the aforementioned conditions. No further statistically significant within-session systematic bias was observed for the remaining conditions.

Figure 1 – Reliability (systematic bias) of the vGRF and RFD SaA and SaE condition

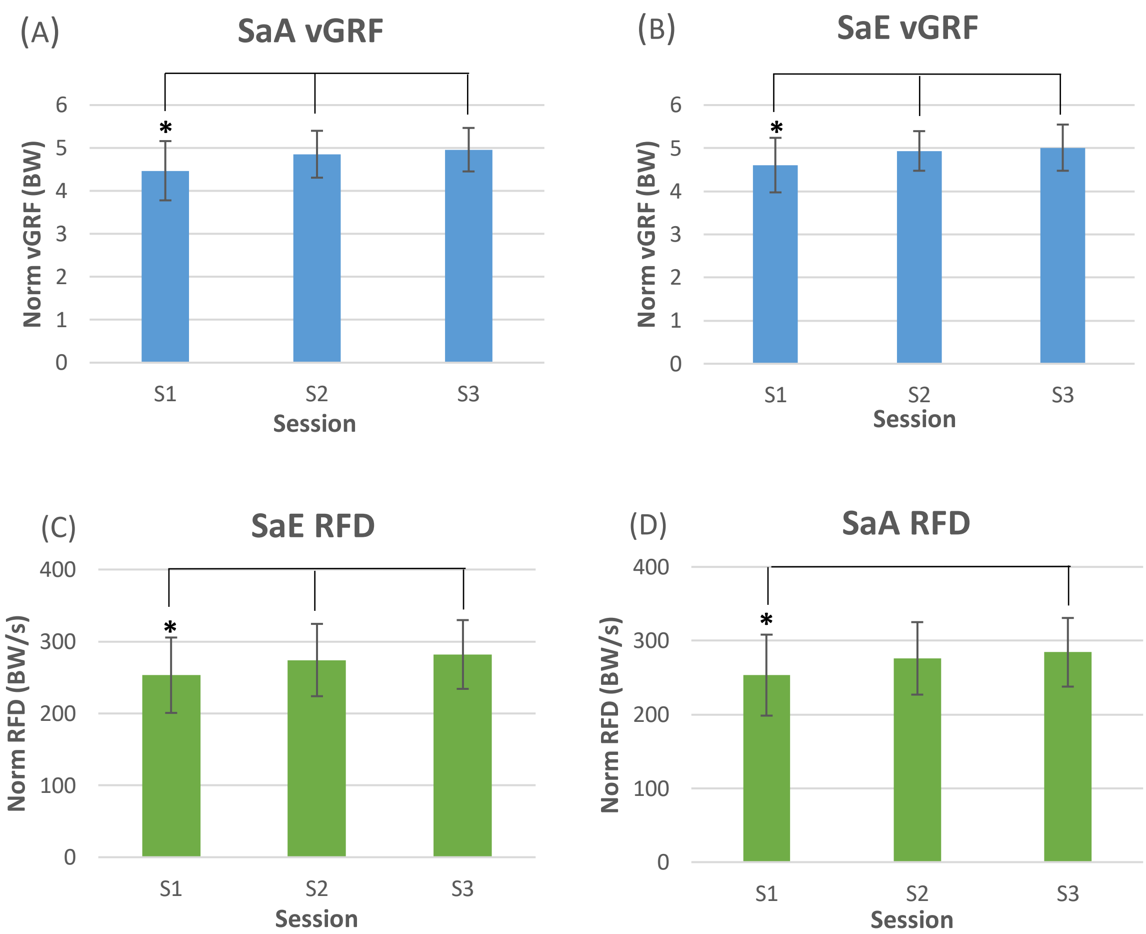


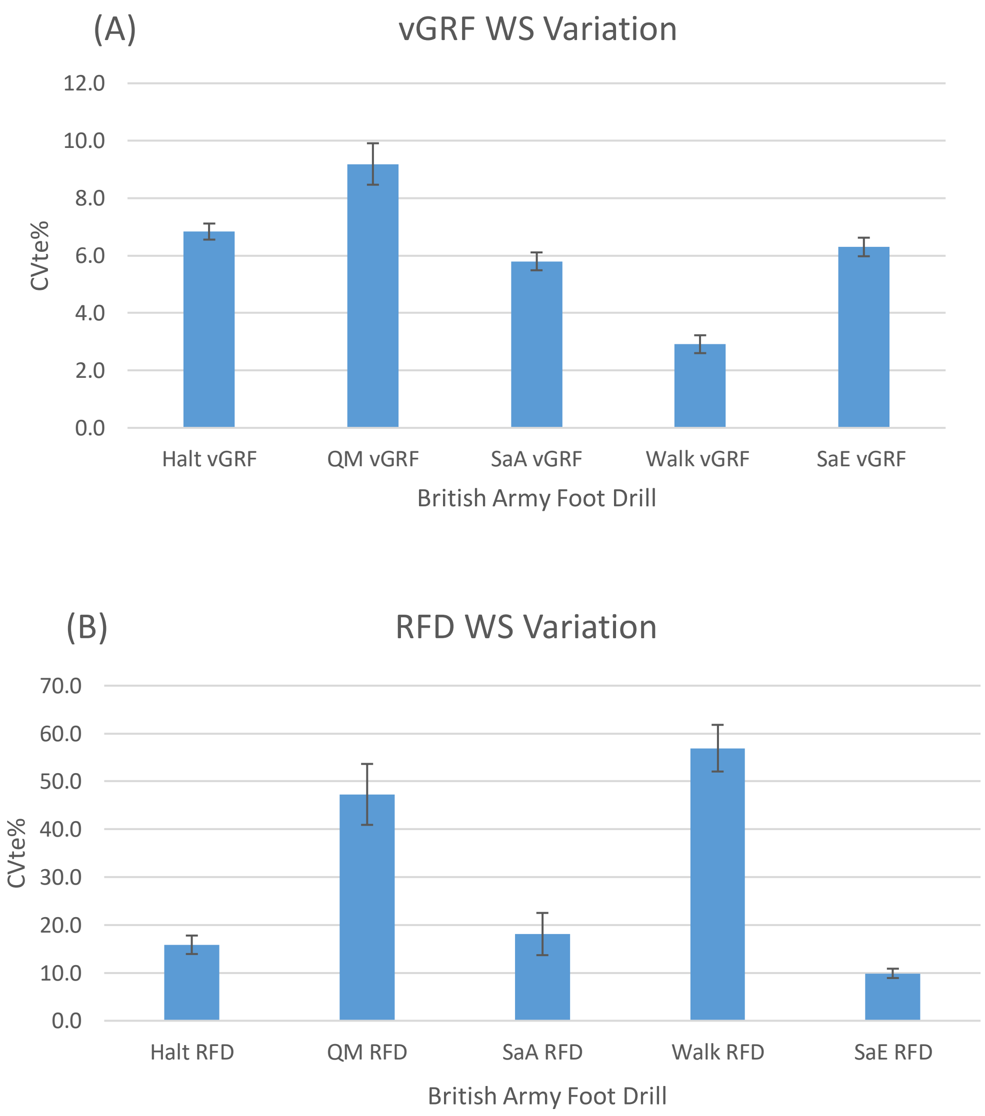
Figure 1: Reliability (systematic bias) of the vGRF and RFD SaA and SaE condition. Mean values for session (1 – 3) for vGRF SaA (A), vGRF SaE (B), RFD SaE, and RFD SaA (D).*Statistically significant difference (*P*>0.05). Values are session means; bars are SD.

Within-Subject Variation

Table 2 illustrates the magnitude of the $CV_{te}\%$ found within repeated measurements of foot-drill data. Depending on the existence of heteroscedasticity, data were expressed in absolute form (preceded by ±) or ratio form (preceded by x/÷) [3, 16]. Figure 2 indicates the magnitude of $CV_{te}\%$ relative to the vGRF variable, showing a mean $CV_{te}\%$ ≤10% across all foot-drills (mean±SD = Halt: 6.8 ± 0.3, QM: 9.2 ± 0.72, SaA: 5.8 ± 0.31, Walk: 2.9 ± 0.3, SaE: 6.3 ± 0.32) demonstrating low within-subject variability indicating good reliability. Note however, that in figure 2 the vertical RFD variable expressed a mean

CV_{te}% ≥10% (excluding SaE) across foot drills (mean ± SD = Halt: 15.9 ± 1.93, QM: 47.3 ± 6.37, SaA: 18.1 ± 4.4, Walk: 56.9 ± 4.9, SaE: 9.9 ± 1.0) demonstrating poor levels of within-subject variability [16].

Figure 2 – WS variation expressed as a CV_{te}% of the vGRF and RFD across all foot drills



(A): vGRF WS variation, (B): RFD WS variation for all foot drills. Values are session means; bars are SD

.

Table 2 – vGRF and RFD foot-drill WS variability results

Variable (Units or Ratio)	Trials (n)		TE(n)	TE_{LCL}	TE_{UCL}		%CV	CV_{LCL}	CV_{UCL}
Halt	3	x/÷	1.08	1.06	1.11	x/÷	7.5	5.9	11.2
	4	x/÷	1.07	1.06	1.09	x/÷	7.0	5.6	9.5
	5	x/÷	1.07	1.05	1.09	x/÷	6.6	5.5	8.5
	6	x/÷	1.07	1.06	1.09	x/÷	6.9	5.8	8.6
	12	x/÷	1.07	1.06	1.08	x/÷	7.0	6.3	8.3
	18	x/÷	1.07	1.06	1.08	x/÷	6.8	6.2	7.8
	24	x/÷	1.07	1.06	1.07	x/÷	6.6	6.2	7.4
Halt RFD	3	x/÷	1.23	1.18	1.36	x/÷	23.5	18.0	35.9
	4	x/÷	1.02	1.16	1.27	x/÷	19.8	15.8	27.3
	5	x/÷	1.18	1.15	1.23	x/÷	18.0	14.7	23.5
	6	x/÷	1.17	1.14	1.21	x/÷	16.7	14.0	21.1
	12	x/÷	1.15	1.13	1.17	x/÷	14.7	13.0	17.1
	18	x/÷	1.16	1.15	1.18	x/÷	16.1	14.5	18.1
	24	x/÷	1.16	1.14	1.17	x/÷	15.5	14.2	17.2
	30	x/÷	1.14	1.13	1.16	x/÷	14.3	13.2	15.6
QM vGRF	3	x/÷	1.1	1.08	1.15	x/÷	10.0	7.8	15.0
	4	x/÷	1.11	1.08	1.14	x/÷	10.5	8.5	14.3
	5	x/÷	1.11	1.09	1.14	x/÷	10.6	8.7	13.7
	6	x/÷	1.1	1.08	1.12	x/÷	9.9	8.3	12.4
	12	x/÷	1.1	1.09	1.12	x/÷	10.1	8.9	11.7
	18	x/÷	1.09	1.08	1.1	x/÷	9.1	8.2	10.2
	24	x/÷	1.09	1.08	1.09	x/÷	8.6	7.9	9.5
	30	x/÷	1.08	1.08	1.09	x/÷	8.3	7.7	9.1
QM RFD	3	x/÷	1.55	1.41	1.9	x/÷	55.2	41.2	89.8
	4	x/÷	1.56	1.43	1.81	x/÷	55.6	43.3	80.7
	5	x/÷	1.6	1.48	1.82	x/÷	59.8	47.8	82.0
	6	x/÷	1.61	1.49	1.8	x/÷	60.7	49.4	79.9
	12	x/÷	1.49	1.43	1.58	x/÷	49.2	42.7	58.1
	18	x/÷	1.44	1.4	1.51	x/÷	44.3	39.5	50.5
	24	x/÷	1.41	1.37	1.46	x/÷	41.0	37.2	45.8
	30	x/÷	1.41	1.38	1.45	x/÷	41.1	37.7	45.4
SaA vGRF	3	x/÷	1.06	1.05	1.09	x/÷	6.3	4.9	9.4
	4	x/÷	1.06	1.05	1.08	x/÷	6.0	4.8	8.1
	5	x/÷	1.06	1.05	1.08	x/÷	6.4	5.3	8.2
	6	x/÷	1.06	1.05	1.08	x/÷	6.2	5.2	7.7
	12	x/÷	1.05	1.05	1.06	x/÷	5.5	4.8	6.3
SaA RFD	3	x/÷	1.26	1.20	1.40	x/÷	26.0	19.9	40.0
	4	x/÷	1.28	1.22	1.39	x/÷	28.2	22.4	39.4
	5	x/÷	1.24	1.20	1.32	x/÷	24.4	20.0	32.2
	6	x/÷	1.22	1.18	1.28	x/÷	22.1	18.4	28.0
	12	x/÷	1.16	1.14	1.18	x/÷	15.9	14.0	18.4
	18	x/÷	1.14	1.13	1.16	x/÷	14.3	12.9	16.1

Walk vGRF	3	x/÷	1.02	1.02	1.03	x/÷	1.9	1.5	2.9
	4	x/÷	1.02	1.02	1.03	x/÷	2.1	1.7	2.8
	5	x/÷	1.03	1.02	1.03	x/÷	2.5	2.1	3.3
	6	x/÷	1.03	1.02	1.03	x/÷	2.8	2.3	3.4
	12	x/÷	1.03	1.03	1.04	x/÷	3.1	2.4	3.3
	18	x/÷	1.03	1.03	1.03	x/÷	3.1	2.7	3.5
	24	x/÷	1.03	1.03	1.03	x/÷	3.1	2.7	3.4
	30	x/÷	1.03	1.03	1.03	x/÷	3.1	2.8	3.4
Walk RFD	3	x/÷	1.45	1.34	1.72	x/÷	45.2	34	72.2
	4	x/÷	1.5	1.39	1.71	x/÷	49.6	38.8	71.4
	5	x/÷	1.48	1.38	1.64	x/÷	47.6	38.3	64.4
	6	x/÷	1.49	1.4	1.64	x/÷	49.2	40.3	64.1
	12	x/÷	1.66	1.57	1.78	x/÷	65.7	56.6	78.3
	18	x/÷	1.59	1.53	1.68	x/÷	59.3	52.7	68.1
	24	x/÷	1.57	1.52	1.64	x/÷	57.4	51.8	64.5
	30	x/÷	1.55	1.51	1.61	x/÷	55.4	50.6	61.4
SaE vGRF	3	x/÷	1.06	1.05	1.09	x/÷	5.9	4.6	8.7
	4	x/÷	1.05	1.04	1.07	x/÷	5.4	4.4	7.3
	5	x/÷	1.06	1.05	1.07	x/÷	5.8	4.8	7.5
	6	x/÷	1.06	1.05	1.08	x/÷	6.1	5.1	7.6
	12	x/÷	1.07	1.06	1.08	x/÷	6.6	5.9	7.6
	18	x/÷	1.06	1.06	1.07	x/÷	6.4	5.8	7.1
SaE RFD	3	±	35.4	27.8	51.6	±	13.0	10.18	21.9
	4	±	31	25.2	41.5	±	10.9	8.05	17.4
	5	±	29	24.1	37	±	10.4	7.76	16.7
	6	±	28.7	24.3	35.5	±	10.5	7.39	15.9
	12	±	26.9	23.9	30.8	±	9.8	7.03	15.1
	18	±	25.7	23.4	28.7	±	9.2	6.52	14.0

Table 2: For the sake of brevity, a reduced number of trials were reported highlighting the initial changes in WS variation with the inclusion of additional single trials, and to highlight the extent of change in WS variation calculated from a greater number of trials. TE, typical error for *n* cycles; LCL, lower confidence limit; UCL, upper confidence limit; random error is represented in absolute form; ±, random error is represented in ratio form; x/÷. The vGRF and RFD foot-drill data found to obtain a SB are not presented in table 2, hence the variation in the total number of trials presented between foot-drills.

Test-retest reliability

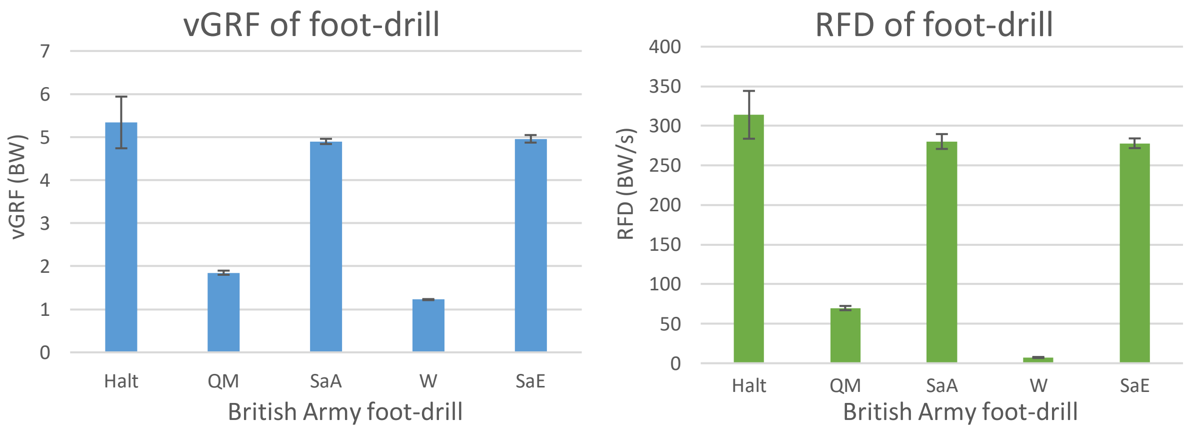
Table 3 illustrates the level of performance stability achieved for all foot-drills across the vGRF and vertical RFD variable. The maximum ICC value was recorded for the Walk vGRF condition (ICC = 0.92) with maximum ICC values ranging from 0.61 to 0.92. The number of trials required to achieve maximum ICC values ranged from 3 to 28 trials (mean ± SD = 12.9 ± 9.3 trials) across both predictor variables. With the exception of the vGRF SaE, vertical RFD SaA and Halt conditions, all remaining foot-drills achieved an ICC value ≥0.75 from 3 to 10 trials (mean ± SD = 4.0 ± 2.6). The vGRF variable illustrated greater levels of performance stability (mean ± SD, ICC = 0.835 ± 0.093) when compared with the vertical RFD variable (mean ± SD, ICC = 0.73 ± 0.79), suggesting that the vGRF variable could be defined as a more reliable measure with which to accurately determine changes in foot-drill performance. The maximum number of trials required to achieve an ICC of 0.80 from the remaining two testing sessions and the initial 8 trials from each session ranged from 3 to 16 trials (mean ± SD = 6.8 ± 5.5). Only the QM and Walk vGRF conditions achieved an ICC ≥0.85 from a total of 3 trials (mean±SD = 3.0 ± 0.0 trials).

Table 3 – vGRF and RFD foot-drill ICC results

Variable (Unit or Ratio)	ICC Maximum (*n* cycles)	ICC	ICC (95%LCL)	ICC (95% UCL)	ICC 0.75 (*n* cycles)	ICC 0.80 (*n* cycles)	ICC 0.85 (*n* cycles)
Halt vGRF	5	0.821	0.659	0.929	3	4	--
Halt RFD	15	0.673	0.503	0.843	--	--	--
QM vGRF	28	0.912	0.843	0.963	3	3	3
QM RFD	28	0.802	0.677	0.911	3	20	--
SaA vGRF	8	0.810	0.670	0.920	3	8	--
SaA RFD	16	0.621	0.446	0.810	--	--	--
Walk vGRF	3	0.924	0.818	0.972	3	3	3
Walk RFD	3	0.791	0.552	0.919	3	--	--
SaE vGRF	4	0.699	0.456	0.872	--	--	--
SaE RFD	19	0.764	0.622	0.892	10	--	--
Mean (SD)	12.9(9.3)				4.0(2.6)	7.6(7.2)	3.0(0.0)

Table 3: represents the maximum number of trials required to achieve poor, moderate and strong levels of test retest reliability; -- indicates that the ICC value was never achieved. The minimum number of trials required to achieve ICC levels of 0.75, 0.80 and 0.85 were also calculated. Only the Walk and QM vGRF condition illustrated an ICC <0.90.

Figure 3 – Ground reaction forces of foot-drill



Normalised vGRF (BW) and RFD (BW/s) generated by all participants during all five foot-drills. Values are means and bars are SD.

DISCUSSION

The present study is the first to report reliability measures of the kinetic variables of British Army foot-drill. The initial aim of the present study was to determine the existence and magnitude of between-session and within-session systematic bias. In addition, this study has quantified the impact loading forces and loading rates associated with British Army foot-drill within an untrained male civilian population. The statistically significant (P < 0.05) between-session mean differences in vGRF and vertical RFD for SaA and SaE indicate that a single familiarisation session is required before collecting reliable foot-drill force data; suggesting that the key performance markers of selective foot-drills (SaA and SaE) may require more time to learn when compared with other foot-drills. The requirement of a single familiarisation session can best be explained by the novelty and complexity of foot-drill for untrained males. Initial analysis of the whole data set revealed within-session (between-trial) differences of the vGRF SaA and SaE conditions. However, after the removal of the first session data no between-trial differences remained, suggesting that the systematic bias apparent in the vGRF data during the first testing session were large enough to influence the remainder of the data.

The second aim was to ascertain the magnitude of the within-subject variation in each of the variables. The levels of $\%CV_{te}$ reported for the vGRF and vertical RFD variables within the present study (figure 2a and 2b) are similar in magnitude to those reported by Floria *et al.,* [14] which examined the reliability of repeated trials (n = 3) of the GRF of two different countermovement jumps ($\%CV_{te}$ range: vGRF = 12.3% - 13.3%, range RFD = 74.6% - 77.4%). In addition, Copic *et al.,* [10] also revealed similar mean $\%CV_{te}$ values from repeated trials (n = 3) for GRF variables in vertical jump performance (mean $\%CV_{te}$: vGRF = 5.7%, RFD = 29.1%). As reported in previous reliability literature [8, 19], the $\%CV_{te}$ was found to reduce when the number of trials utilised to calculate the average score increased, with the greatest increases in reliability ($\%CV_{te}$) shown within the initial increase in the number of trials used to calculate the mean value.

Reductions in $\%CV_{te}$ (improved reliability) were apparent within the present study for the vGRF Halt, SaA, QM and vertical RFD SaE condition, with the greatest increases in reliability shown within the initial changes in the number of trials used to calculate the mean value. For example, an average $\%CV_{te}$ reduction of 0.97% was observed when using six trials compared with three trials, a further 0.35% average reduction by using seven trials compared with four trials, and an average reduction in $\%CV_{te}$ of 0.81% when using eight trials compared with five trials. Beyond eight trials, the use of additional trials of data to calculate the mean value across all foot-drills resulted in diminishing returns; for every additional trial utilised in the calculation of the mean values, the smaller the reduction in the $\%CV_{te}$ [8]. Similar average reductions in $\%CV_{te}$ were observed for the vertical RFD variable, however, these reductions did not show worthwhile improvements in levels of reliability across remaining foot-drills.

The final aim of this study was to determine the test-retest reliability of foot-drill force data to provide additional information to make decisions regarding the number of trials of data required to achieve stable levels of performance, and to accurately track changes in foot-drill performance over time. However, it should be noted that ICC values at which test-retest reliability are deemed poor (ICC ≤

0.75), moderate (ICC 0.75 – 0.85) and strong (ICC ≥ 0.85) are arbitrary values [25]. Nevertheless, the ICC is defined as more of an objective means of assessing the number of trials required to establish the stability of performance than other measures (i.e., sequential averaging), as it involves fewer arbitrary decisions when assessing performance stability [8, 20].

The initial interpretation of the ICC analyses shows that the vGRF Halt, QM, SaA and Walk condition achieved moderate to strong levels of test-retest reliability, with only SaE failing to achieve an ICC value ≥ 0.75. Maximum ICC values for the vertical RFD variable range from 0.62 for SaA, to 0.80 for QM, illustrating poor to strong levels of test-retest reliability. However, strong levels of test-retest reliability were only achieved in QM and Walk. The QM, SaE, and Walk vertical RFD values achieved moderate levels of test-retest reliability, with Halt (range = 0.36-0.67) and SaA (range = 0.24-0.62) failing to achieve an ICC value ≥ 0.75 [16]. This finding suggests that multiple trials of foot-drill force data (mean ± SD: vGRF =8.5 ± 6.7 trials, RFD =13.7 ± 12.9 trials) are required before maximum ICC values can be obtained.

It is recommended that ICC data should not be considered in isolation, rather, within-subject variability data should also be taken in to account when making decisions regarding the minimum number of trials required to accurately represent the GRF of foot-drill data as data can be adversely influenced by the homogeneity of the test sample, which will affect any interpretation of reliability [3, 8, 16, 19, 23]. Also, by considering the magnitude of the within-subject variation, the number of trials required to ensure a reliable assessment of each force variable can provide a measure of accuracy with which any future changes in vGRF and/or vertical RFD of foot-drill performance can be monitored [8].

This study has reported foot-drill mean peak vGRF and vertical RFD data similar to those reported in previous foot-drill research [5, 9] and are comparable with peak vGRF and vertical RFD apparent in high level plyometric drills [29]; demonstrating that foot-drill represents a substantial mechanical load placed on the MSK structures of the lower-extremities. The Halt foot-drill exhibited the greatest mean peak vGRF (5.3 ± 0.6) and vertical RFD (313.9 ± 30.2) when compared with the remaining foot-drills, with SaE and SaA exhibiting vGRF and vertical RFD in excess of 4.9BW and 278.1BW/s, respectively (figure 3). In addition, selective participants were found to produce vGRF and vertical RFD values relative to the Halt foot-drill of 6.9BW and 825.1BW/s, respectively.

Recently, QM has been show to exhibit comparable vGRF and vertical RFD values to running speeds of 3m/s (1.6BW) to 3.5m/s (1.3BW) [24]. In this study, QM was found to exhibit greater vGRF (1.8BW) and vertical RFD (69.3BW/s) values when compared with a normal walking gait (vGRF = 1.2BW, vertical RFD = 7.3BW/s). Previous (*in vivo*) research [22] has shown that high repetitive impact loading forces (≥ 3.0BW) may produce tensile, shear and compressive strain-rates that may initiate bone damage at a microstructural level, resulting in single or multiple lower-limb stress fractures. Thus, the magnitude of forces and repetitive skeletal loading of foot-drill may significantly contribute to the high incidence rates of lower-limb MSK overuse injuries sustained by untrained male recruits, and significantly increase the risk of sustaining one or more lower-limb bone stress fractures during the initial weeks of BMT.

One limitation of the current investigation is the all-male sample. Previous biomechanical studies have demonstrated that recreationally active females exhibit distinct loading mechanics and lower-limb kinematics when compared with their male counterparts [5, 29]. Thus, it is unlikely that these results can be generalizable to a recreationally active female population. In addition, study participants performed foot-drill in a training shoe, whereas, foot-drill is usually performed in the combat boot. Due to a lack of CB readily available for this study, the kinetic variables of foot-drill reported may not truly reflect those experienced when wearing the CB. Nevertheless, the peak vGRF and vertical RFD of foot-drill are similar in magnitude to those reported previously in untrained samples [5, 9].

PRACTICAL APPLICATIONS

A pragmatic approach is recommended when deciding on the number of trials used to represent foot-drill force data [8, 19] considering the requirement of high test-retest reliability and acceptable levels of within-subject variation concurrently with the economic, practical and logistical concerns of collecting repeated trials/sessions of foot-drill data. As previously mentioned, the greatest increases in stability and reliability are shown within the initial changes in the number of trials used to calculate the mean ICC and $\%CV_{te}$ value; with diminishing returns in reductions in $\%CV_{te}$ data observed beyond eight-trials, with the achievement of a moderate level of test-retest reliability for each foot-drill of the vGRF variable, excluding SaE. Each one of the foot-drills (excluding SaE) relative to the vGRF variable demonstrated acceptable levels of reliability. However, in accordance with previous reliability literature [3, 8, 19] the magnitude of a variable's stability and reproducibility depends on its intended use, and subsequently, the researcher must determine whether it is sufficiently reliable to measure the smallest worthwhile change in an individual's performance.

The findings of the present study support the inclusion of a single familiarisation session specific to the SaA and SaE foot-drills. It was determined that the vertical RFD variables exhibited poor levels of reliability across foot-drills. Similar levels of reliability of the vertical RFD variable have been reported in previous literature [10, 14]. Nevertheless, it was determined that an average of eight-trials is required to achieve moderate to strong levels of reliability of foot-drill GRF data. The reliability of the vGRF and vertical RFD variable differed notably. However, in the majority of foot-drills there was a consistent trend for reliability to marginally improve when the average score of multiple trials was used as the measurement of interest.

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Appendix 3b: The Effects of Standard Issue British Army Footwear on the Vertical Ground Reaction Forces of British Army Foot-drill. Accepted. DOI:10.1519/JSC.0000000000002139

Abstract

High rates of occupational training-related lower-limb musculoskeletal [MSK] overuse injuries are reported for British Army recruits during basic training. Foot-drill is a repetitive impact loading occupational activity and involves striking the ground violently with an extended-knee [straight-leg] landing. Foot-drill produces vertical ground reaction forces [vGRF] equal to and/or greater than those reported for high-level plyometric exercises/activities. Shock absorbing footwear aid in the attenuation of the magnitude of vGRF, resulting in a reduced risk of lower-limb MSK overuse injury when running. The potential shock absorbing characteristics of standard issue British Army footwear on the magnitude of vGRF and temporal parameters of foot-drill are scant. Therefore, this study sought to determine the magnitude and examine changes in vGRF and temporal parameters of foot-drill across three types of British Army footwear. Sampled at 1000hz, the mean of eight-trials from fifteen recreationally active males were collected from four foot-drills; stand-at-ease [SaE], stand-at-attention [SaA], quick-march [QM] and halt. Analysis of a normal walk was included to act as a comparison with quick-march. Significant main effects [$P<0.05$] were observed between footwear and foot-drill. The training shoe demonstrated significantly greater shock absorbing capabilities when compared with the combat boot and ammunition boot. Foot-drill produced peak vGRF and peak vertical rate of force development in excess of 5bw, and 350bw/sec, respectively. Time to peak vGRF ranged from 0.016-0.036ms across foot-drills, indicating that passive vGRF may not be under neuromuscular control. The marginal reductions in the magnitude of vGRF and temporal parameters in foot-drill associated with the training shoe may act to reduce the accumulative impact shock experienced by recruits, subsequently minimising the severity and rates of lower-limb MSK overuse injuries and recruit medical discharges during basic training.

Keywords;
recruits, force plate, basic military training

Introduction

British Army personnel are required to maintain a state of physical readiness enabling them to perform effectively in any training and/or operational environment. Due to the rigorous physical demands of warfighting and physical training, basic military training [BMT] is a critical feature in the physical development of the entry-level recruit. However, high rates of occupational training-related lower-limb musculoskeletal [MSK] overuse injuries are reported for recruit populations during BMT, significantly impacting on their tactical and operational readiness[22]. The etiology of occupational training-related injuries sustained during BMT are multi-factorial and diverse. Therefore, efforts to minimise the injury incidence during recruit physical training is of primary focus for military organisations worldwide[25].

British Army foot-drill, most notably, stand-at-attention [SaA], stand-at-ease [SaE], halt, and quick-march [QM], is a fundamental military occupational activity that is learned by recruits during the initial weeks of BMT and practiced throughout their military career. Foot-drills are characterised by their own unique key performance markers[3]. QM involves marching at two paces per second whilst impacting the ground with an exaggerated heel strike. SaA, SaE (left-leg) and Halt (right-leg) require soldiers to raise the active limb to 90° hip flexion and forcefully stamp the heel onto the ground with an extended-knee (straight-leg) landing. Foot-drill is performed in standard issue military footwear, namely, the combat boot [CB], and ammunition boot [AB]. The CB is issued to entry-level recruits on induction to BMT, and worn with uniforms on a daily basis, and by military units on parade in full dress uniform[7]. The AB [or similar] is commonly worn by British military personnel in dress uniform or during ceremonial and/or drill duties[17] [figure 1].

Measurement of GRF and temporal parameters such as vertical ground reaction force [vGRF], vertical rate of force development [vertical RFD], and time to peak vertical force [TTP] have been utilised as non-invasive measures of lower-limb bone loading as a means of quantifying the potential development of MSK overuse injuries, most notably, bone microdamage and subsequent stress fracture of the foot and/or shank[4, 27]. Furthermore, these specific vGRF and temporal parameters have been utilised to indirectly assess the shock absorbing functionality of specific footwear, during a variety of lower-limb tasks[12, 13, 27]. For example, previous footwear research has demonstrated that the CB, when compared with other military and commercially available footwear, produces significantly greater impact loading forces when running and marching at velocities of 4m-s^{1} and 1.5m-s^{1}, respectively[12, 27]. In addition, the CB has also been shown to significantly increase the risk of metatarsal stress fracture when running at 3.6m-s^{1} [19].

The magnitude of specific vGRF parameters representative of foot-drill, irrespective of the type of footwear worn, may be a contributing risk factor in the development of lower-limb MSK overuse injuries within recruit populations[4, 24]. To date, only three studies have investigated the impact loading forces of foot-drill whilst wearing training shoes[6, 24] and defender combat boots[4]; reporting peak vGRF [range = 1.3 – 5.1 bodyweights] [BWs] and peak vertical RFD [range = 67.6 – 536 bodyweights/second] [BWs/s] values similar to, and in some cases greater than those observed for high level plyometric exercises[2, 29]. The primary objective of these studies was to quantify vGRF parameters of foot-drill, and did not directly consider the potential influential factors associated with standard issue footwear on impact loading forces of foot-drill.

Factors that mitigate the magnitude and rate of force transmitted to the MSK structures of the lower-limbs can be achieved via the use of footwear with shock absorbing capabilities[14], thereby potentially reducing the risk of developing such MSK injuries as lower-limb stress fractures. Recently, military footwear has undergone considerable scrutiny regarding its functionality and capacity to provide military personnel with the necessary shock absorbing properties required to withstand the demands of military training-related activities. For example, Nunns[19] and Sinclair and Taylor[27] demonstrated that the CB increased the magnitude of several biomechanical risk factors associated with third metatarsal stress fractures during marching, and was inferior in minimising the instantaneous and average loading rates of running when compared with training shoes. Previous footwear research[13, 33] has demonstrated that the CB produced significantly greater peak decelerations, shorter times to deceleration, higher peak-plantar pressures, and greater vGRF forces at the heel and forefoot when compared with hiking boots and training shoes. From these studies, it can be suggested that the CB may not achieve the necessary shock absorbing capacity required to effectively attenuate the cyclic high impact loading forces during running, marching or drop landings. Therefore, in agreement with previous research[19, 12, 33] the CB and its use during cyclic high impact loading activities, may potentially be a contributing mechanism responsible, in part, for the high rates of lower-limb MSK overuse injuries sustained by recruits during BMT. Nevertheless, it remains unclear as to how the vGRF and temporal parameters of foot-drill are influenced by the CB and other types of British Army footwear within a recruit population. Limited empirical research exists regarding the magnitude of loading during foot-drill within a recruit population, with no research investigating the influence of current standard issue footwear on specific vGRF and temporal parameters of foot-drill.

Knowledge of the biomechanical loading forces of these regimented movements is an essential component of understanding the dynamics of foot-drill as a potential training-related lower-limb MSK overuse injury risk factor. Furthermore, these data can provide a greater understanding of whether the use of a shock absorbing footwear is effective in the attenuation of the impact loading forces of foot-drill experienced by a British Army recruit population. Therefore, the aim of the present study was to compare the magnitude of the vGRF and temporal parameters of each foot-drill, namely, peak vGRF, peak vertical RFD, and TTP across three different types of standard issue British Army footwear, namely the CB, AB and Hi-Tech Silver Shadow training shoe [TR]. This study tests the hypothesis that foot-drill, when compared with the loading patterns of a normal gait, would produce greater peak vGRF, peak vertical RFD, and shorter TTP values; and that the TR would significantly attenuate peak vGRF, peak vertical RFD, and produce longer TTP values when compared with the CB and AB for all foot-drills.

Methods

Fifteen recreationally active healthy males [mean ± SD; age 24.4 ± 2.1years; height 175 ± 8.3cm; weight 86 ± 5.7kg] with no pathological lower-limb, hip or spinal conditions volunteered to participate in the present study. All participants at the time of testing were taking part in moderate physical activity [gym training] and/or sport [soccer, rugby, badminton] a minimum of two-to-three times per week for approximately 1-2 hours over the previous three years. Forty-eight hours prior to testing participants refrained from high intensity activity as to eliminate potential fatigue effects on performance data. Ethical approval for the present study was gained from the local ethics committee and written informed consent was obtained from each participant prior to data collection. Study participants were defined as "untrained" as they had no prior experience of British Army foot-drill preceding data collection. Nevertheless, the study participants obtained similar anthropometric characteristics and training histories when compared with male entry-level recruit populations[22].

A within-participant repeated-measures study design was employed to assess the vGRF dependent variables of five British Army foot-drills involving; stand-at-attention [SaA], stand-at-ease [SaE], quick-march [QM], halt, and a normal walking gait. Eight trials of a normal walk were collected to act as a comparison with the vGRF and temporal data of QM based on similarities in biomechanical movement patterns. The vGRF and temporal parameters of each foot-drill were assessed across three different types of standard issue British Army footwear. The allocation of footwear was counterbalanced for each day of testing. A Kistler force plate [Kistler Instruments AG, 9281CA, Switzerland] flush with the lab floor [Force plate dimensions: 600mm x 400mm x 100mm] situated in a 10-m walkway was used to measure and record peak vGRF, peak vertical RFD, and TTP. Study participants attended the lab on three non-consecutive days with 24-hours separating each test day. Each testing session was conducted at the same time of day and performed under the instruction and guidance of the same researcher.

Each participant performed a standardised 10-min warm up consisting of dynamic lower-limb bodyweight exercises, namely, variations of the lunge and bilateral squat. Preceding the collection of foot-drill vGRF and temporal data, a single familiarisation session was conducted on the first day of testing, whereby each participant performed ten trials of each foot-drill[24]. Post familiarisation and a 15min recovery period, a total of eight trials per foot-drill were collected, as it has been demonstrated that a minimum of eight-trials is required to produce accurate and stable levels of foot-drill vGRF data [CV_{te}% <10%, ICC > 0.75][24]. The force plate was interfaced with BioWare 3.2.5 software and set at a sampling frequency [fs] of 1000Hz, with each foot-drill recorded for a maximum of 3-sec. The foot-drill vGRF and temporal data were collected using an eight channel 16-bit analog to digital converter [Qualisys, 8128, Sweden]. A 90-sec recovery period between each trial and a 15-min recovery between foot-drills was employed. All footwear used for analysis in the present study was unworn prior to data collection, eliminating the influence of retrospective wear on foot-drill data. Trials were discarded and repeated if targeting[5] and/or adjustments in key performance markers of foot-drill were observed.

Figure 1 – British Army Standard Issue Footwear

Figure 1 – Depicts the three different types of standard issue British Army Footwear used in the present study. From left to right - Combat boot [CB], Ammo Boot [AB], and Hi-Tech Silver Shadow™ training shoe [TR].

A comprehensive description of each foot-drill analysed within the present study can be found in the British Army Drill Instructor Manual[3]. The foot that struck the force plate during each of the foot-drills was referred to as the active limb with the opposite limb referred to as the support limb [figure 2]. Study participants were instructed to walk at their preferred walking speed. Speed [m/s] was measured via timing gates [Fusion sport, SmartSpeed, Australia] situated at 0-m, 5-m and 10-m along the 10-m walkway, and monitored across each test session, with a maximum deviation of +/- 5% allowed from each participant's predetermined walking velocity[27].

Figure 2. Representation of a typical British Army Stand-at-Attention foot-drill wearing the CB

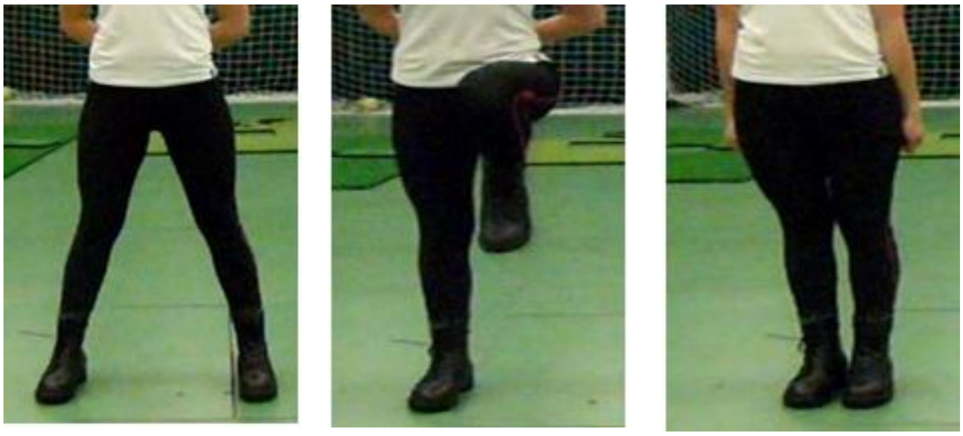

Figure 2. Illustrates a typical SaA British Army foot-drill whilst wearing the CB. From left to right, the SaA is performed from the SaE position. On command, the participant flexes at the hip to 90° followed by an exaggerated stamping of the foot onto the surface of the force plate, landing with the knee in an extended position.

The foot-drill vGRF and temporal data were exported via BioWare 3.2.5 system. Based on previous power spectrum analysis, ensuring that 95% of the signal content was retained, data were filtered with a low pass 4th order zero-lag [single bi-directional] Butterworth filter with a cut off frequency ranging between 50hz (walk, QM) and 150Hz (SaA, SaE, Halt). As a means of comparing between participants the vGRF and RFD foot-drill data were normalised to BW, computed as;

$$BW_{Norm} = \frac{\mathrm{Fz}_{peak}}{BW} \qquad [1]$$

where, BW_{Norm} is the normalized vGRF expressed in BW, Fz*peak* is the peak vGRF measured in Newtons [N], and BW is the participant's bodyweight determined via the force plate and expressed in N. The vertical RFD variable was computed as;

$$RFD = \frac{\Delta F}{\Delta T} \qquad [2]$$

where, *RFD* is the vertical rate of force development measured in N per second [N/s], *ΔF* represents the change in force measured in N and, *ΔT* represents the change in time measured in sec. vRFD was normalised relative to the participant's BW computed as;

$$NormRFD = \frac{RFD}{BW} \quad [3]$$

where, *NormRFD* is the RFD normalised to the participant's bodyweight, measured in N. *Time to* Fz*peak* is defined as the time to reach Fzpeak expressed in milliseconds [ms] computed as;

$$Time\ to\ Fz_{peak} = t_{max} - t_{min} \quad [4]$$

where, t*min* represents the time point of the initial onset of vGRF and t*max* represents the time point of Fz*peak,* measured in sec. The initial onset of vGRF was defined as when the vGRF component exceeded a threshold of 20N.

Prior to statistically analysing the vGRF dependent variables of foot-drill and walk data between footwear; peak vGRF, peak vertical RFD, and TTP were examined for heteroscedascity[9]. The vGRF and vertical RFD data illustrated a significant violation in the assumption of normality. Therefore, these data were log transformed in SPSS using natural logarithm of the observed value[1]. The time to peak force [TTP] data illustrated no significant violation from a normal distribution. Therefore, the raw TTP data were utilised in the analysis. A series of one-way repeated-measures analysis of variance [RM ANOVA] with Bonferroni adjusted multiple comparisons were conducted for each of the vGRF dependent variables [vGRF, vertical RFD, and TTP] for each of the foot-drills and walk across each footwear. A paired samples t-test was conducted to quantify potential significant differences in mean peak vGRF and vertical RFD between the QM and walk foot-drill across footwear. Alpha was set at 0.05 and data were statistically analysed via IBM SPSS™ 20.

Results

The mean walking speed for all participants was 1.6±0.6m/s. Although a metronome was used to standardise QM pacing across participants, the mean speed for QM was 2.02±0.01m/s. Significant differences in force-time characteristics between the QM and walk foot-drill were determined. As illustrated in figure 6, the QM foot-drill demonstrates a distinct impact peak in comparison to the walk, with QM showing a steeper initial slope from initial contact to peak vGRF; characterising the magnitude of the vertical RFD of the initial portion of the vGRF component.

Figure 3. A representative force-time profile of the QM and walk across all footwear types

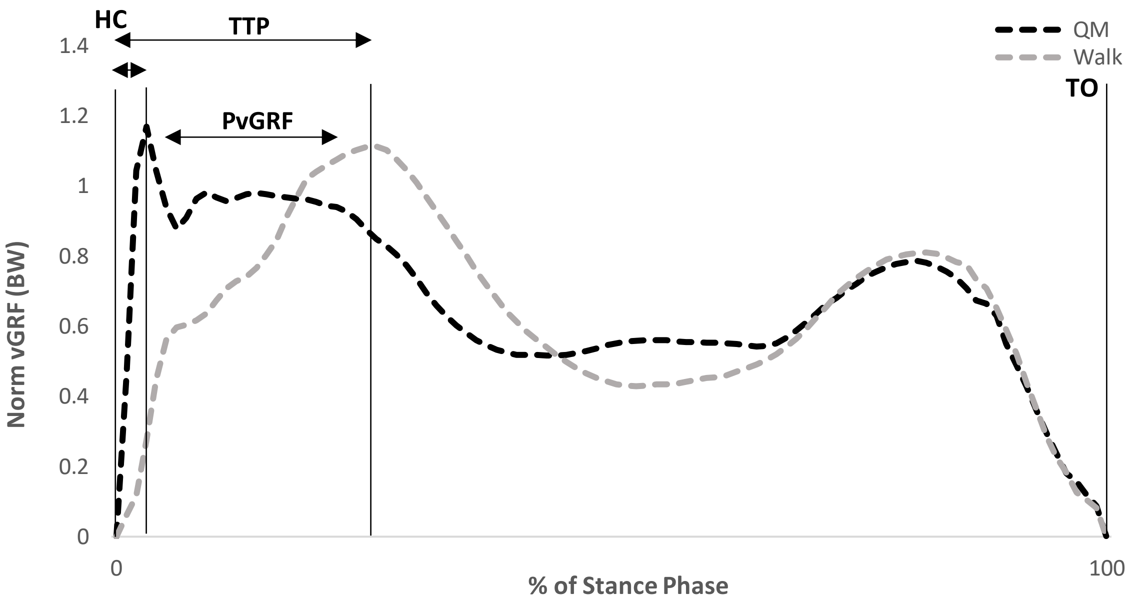

Figure 3. An exemplar of a typical QM and Walk (right foot) gait cycle of a single participant whilst wearing the CB. These data were time normalised in Visual 3D to 100 data points representing 0% to 100% of the stance phase from heel contact to toe off. HC = Heel contact for both QM and Walk, TO = toe off for both QM and Walk, TTP = time to peak vertical force, PvGRF = peak vertical ground reaction force.

Statistically significant main effects were found for peak vGRF in SaA, SaE, and Halt foot-drill. Pairwise comparisons indicated significant differences between footwear conditions, with the TR exhibiting significantly lower magnitudes of vGRF in SaA [3.9±0.3bw], SaE [3.8±0.3bw], and Halt [4.2±0.3bw] when compared to the CB and AB [p<.05] [figure 4]. No significant differences were observed for walk [F = 0.028, P = .973, Np^2 = .003] or QM [F = 2.518, P = 0.106, Np^2 = 0.201].

Figure 4. The vGRF as a function of footwear across British Army foot-drill.

Figure 4. The mean peak vGRF of each foot-drill across each footwear, showing significant differences [*p*<0.05] between footwear across foot-drill with vGRF data normalised to bodyweight [BW]. * = illustrates a significant difference. Values are means; bars are SD.

Statistically significant main effects were observed for the peak vertical RFD in SaA, SaE, QM, and Halt foot-drill [*p*<.05]. Pairwise comparisons indicated significant differences between footwear conditions with the TR exhibiting significantly lower magnitudes of vertical RFD in SaA [226±24bw/s], QM [36±8.9bw/s], SaE [217±19.4bw/s] and Halt [249±18.6bw/s] when compared to CB and AB [*p*<.05] [figure 5]. No significant differences were observed for walk [F = 2.673, P = .094, Np^2 = .211] between footwear conditions.

Figure 5. The mean peak vertical RFD as a function of footwear across British Army foot-drill

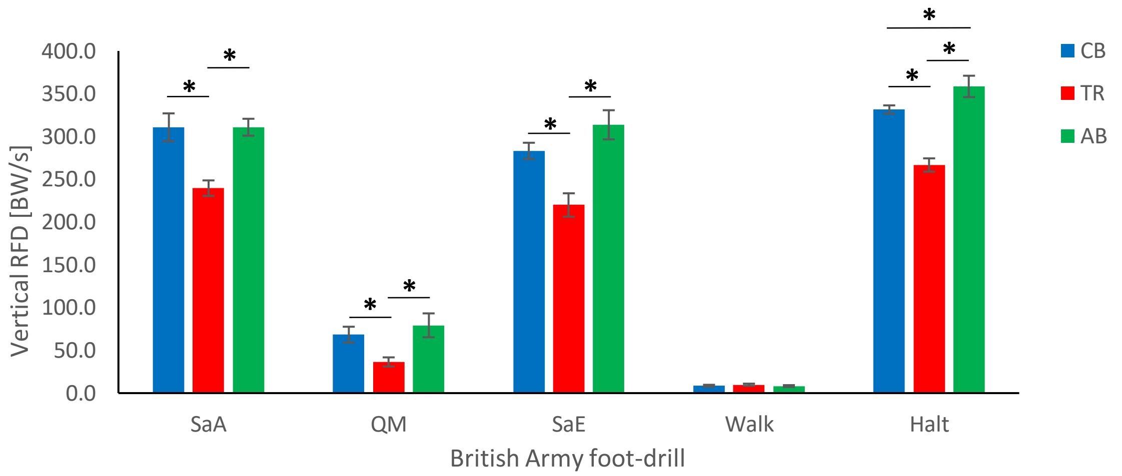

Figure 5. The mean peak vertical RFD of each foot-drill across the three types of footwear, showing significant differences [*p*<0.05] between footwear across foot-drill with vertical RFD data normalised to bodyweight/second [BW/s]. * = illustrates a significant difference. Values are means; bars are SD.

Statistically significant differences were observed in the mean peak vGRF and vertical RFD values between the QM and walk foot-drill across footwear conditions [*p*<.001], with QM exhibiting significantly greater mean vGRF [1.6±0.2bw] and vertical RFD [62.2±22.8bw/s] across footwear conditions [figure 6].

Figure 6. The vGRF and vertical RFD as a function of footwear across the QM and Walk foot-drill

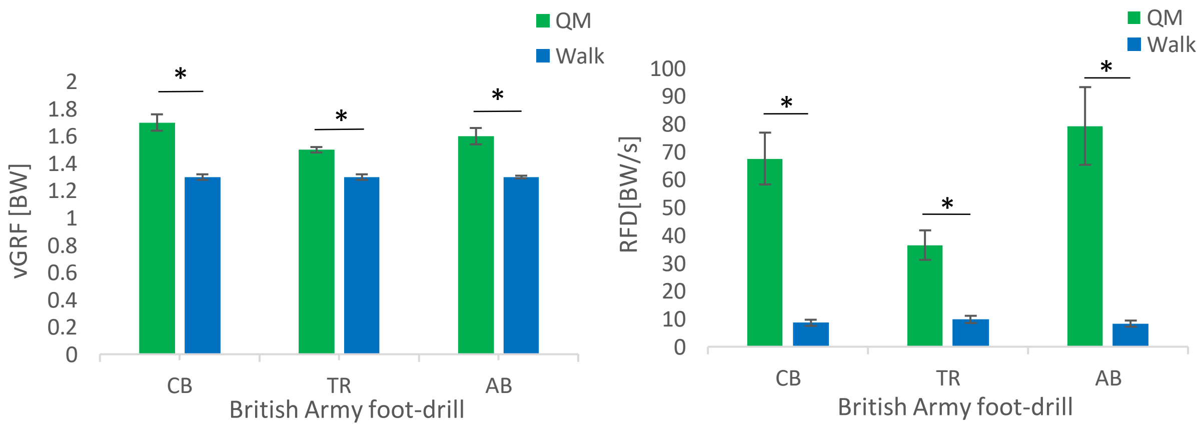

Figure 6. Significant differences [*p*<0.05] between the QM and Walk foot-drill across footwear, with vGRF normalised to [BW], and vertical RFD data normalised to BW/s. * = illustrates a significant difference. Values are means; bars are SD.

Statistically significant main effects were observed for TTP across footwear in SaA, SaE, QM, and Halt. Pairwise comparisons indicated significant differences between footwear conditions with the TR demonstrating significantly greater TTP in SaA [17±.01ms], SaE [18±.01ms] and Halt [16±.01ms] when compared to the AB, with significantly greater TTP values observed for TR in QM [71±.02ms] when compared to the CB and AB [p<.05] [table 1]. No significant differences were observed in walk across footwear conditions [F = 1.991, P = .166, Np^2 = .181].

Table 1. The TTP as a function of footwear across each British Army Foot-drill.

Foot-drill	**British Army Footwear**			**Δ [%]**		
	CB	**TR**	**AB**	**CB vs AB**	**TR vs AB**	**CB vs TR**
SaA	0.016 [0.002]	0.017 [0.003]	0.015* [0.001]	6.3%	11.8%	5.9%
SaE	0.017 [0.001]	0.018 [0.002]	0.015* [0.002]	11.8%	16.7%	5.6%
Halt	0.017 [0.012]	0.016 [0.002]	0.014* [0.002]	17.6%	12.5%	5.9%
QM	0.036* [0.032]	0.071 [0.037]	0.026* [0.077]	27.8%	63.4%	49.3%
Walk	0.229 [0.167]	0.196 [0.169]	0.275 [0.190]	16.7%	28.7%	14.4%
Mean [SD]	-	-	-	16% [8]	27% [22]	16% [0.19]

Table 1. The mean [SD] time to peak vGRF [TTP] [sec] of each foot-drill across footwear, showing percentage differences [Δ] between footwear and foot-drill, with TTP expressed in seconds [sec]. * = indicates the specific foot-drill and footwear type that exhibited significantly shorter TTP values. CB=Combat boot, TR=Training shoe, AB=Ammunition boot. Δ [%] = indicates percentage difference. Alpha p<0.05.

Discussion

Knowledge of the biomechanical loading forces of British Army foot-drill is an essential component of better understanding the dynamics of foot-drill as a potential occupational training-related lower-limb MSK injury risk factor. The present study sought to determine and compare the magnitude of the vGRF and temporal parameters of British Army foot-drill across three different types of standard issue British Army footwear. These results confirm the hypothesis, indicating that when performing British Army foot-drill in footwear with greater shock absorbing capabilities, namely the TR, significant reductions in peak vGRF and peak vertical RFD are achieved when compared to CB and AB. Given the structural and mechanical properties of the AB outsole, it was anticipated that the AB would provide less shock absorbency resulting in greater peak vGRF and vertical RFD when compared with the CB. However, similar magnitudes of peak vGRF and vertical RFD to that of the CB were observed. These results mirror those of others[9], whereby little to no significant differences in the magnitude of impact forces between hard and moderately hard midsole footwear were observed. Apart from QM, the AB demonstrated significantly shorter TTP values when compared to CB and TR. However, regardless of footwear, all foot-drills demonstrated TTP values ≤50ms. It is suggested that the capacity of any active force [under neuromuscular control] generated by the lower-limb neuromuscular system at ground contact may have been reduced by the exaggerated heel strike of QM, and the extended straight-leg landing of SaA, SaE, and Halt. Nevertheless, shorter TTP values were expected for foot-drill when compared to other landing activities, namely, drop jumps[11], as recruits are taught to actively reduce the magnitude of knee and hip flexion at ground contact, thus reducing the ability of the quadriceps and hamstring co-contraction forces to absorb and attenuate the high impact loading forces of British Army foot-drill.

The CB and AB exhibited mean peak vGRF and vertical RFD in excess of 5.1BW and 358.6BW/s for SaA, SaE, and Halt. Two participants wearing the CB and AB demonstrated peak vGRF and peak vertical RFD in excess of 6.6BW and 514BW/s for SaA, SaE, and Halt. The magnitude of impact loading forces of foot-drill are similar to those reported by Carden[4], whereby untrained [recruits] exhibited mean peak vGRF and vertical RFD in excess of 4.6BW and 536BW/s whilst wearing the Defender Combat Boot [DCB], respectively. The DCB has been standard issue within the British Army since 2012; specifically designed to minimise the risk of lower-limb MSK injury in the dismounted soldier via the integration of an inbuilt shock absorbing mid-layer[16]. However, based on the vGRF and temporal parameters of foot-drill, the direct comparison from the present study, and an indirect comparison of the data from Carden[4] would suggest that the DCB may not provide greater shock absorbing capabilities when compared with the CB. However, like the CB, the DCB was not solely designed to reduce the impact loading forces of foot-drill, rather to accommodate dismounted troops during high-level activity roles in temperate climates. Thus, based on the results of the present study and those of others[4,27], it is recommended that recruits wear a form of shock absorbing footwear similar to that of the TR, as to reduce the cyclic high impact loading forces of foot-drill, that may contribute to an increased risk of lower-limb MSK injury.

In comparison to CB and AB, the TR demonstrated significantly smaller magnitudes of peak vGRF and vertical RFD across the majority of foot-drills. These results are comparable to others[27], whereby training shoes [running and cross trainer] demonstrated superior shock absorbing capabilities when compared with military boots. However, the TR demonstrated peak vGRF and peak vertical RFD in excess of 4bw and 260.7bw/s, respectively, with two participants producing values in excess of 5.8bw and 420bw/s for Halt. Although the TR displayed significant reductions in impact force, the mean peak vGRF of SaA, SaE, and Halt whilst wearing the TR are similar to those reported for 30cm, 60cm, and 90cm drop landings in adolescent Division 1 collegiate gymnasts[26]. In addition, the peak vertical RFD observed for the TR during foot-drill far exceed those exhibited during running speeds of 6.7m/s whilst wearing a hard-soled spike running shoe[14]. Despite the significant reductions in peak vGRF and vertical RFD of foot-drill associated with the TR, the magnitude of these GRF components similar to those reported in previous empirical studies[14,26], may be a contributing lower-limb MSK injury risk factor. Nevertheless, based on the present study's results, it can be suggested that lower levels of MSK injury risk are associated with the shock absorbing capabilities of the TR in comparison to the CB and AB.

The unique landing techniques of foot-drill combined with the lack of shock absorbing capabilities of standard issue footwear, namely the CB and AB, typically present high vertical RFD. The magnitude of peak vertical RFD of SaA, SaE, and Halt [range: 286.3 - 514BW/s] are considerably higher than those reported for countermovement jumps and box step offs [mean range: 185.9 – 303.7BW/s][1], and moderately higher than those reported for 61cm drop landings [472BW/s][2]. The large disparity in the magnitude of vertical RFD between foot-drill and other high impact activities is that individuals will attempt to actively mitigate the impact loading forces by increasing the duration of loading via greater hip and knee flexion and ankle plantarflexion, whereas during foot-drill they will not, as recruits are instructed to land with the heel in an extended-knee landing[4]. All biological MSK structures are viscoelastic in nature, whose material properties are rate dependent[11]. Therefore, when considering the relative safety of high impact loading activities, it is important to determine the vertical RFD as it is generally accepted that greater magnitudes of vertical RFD are more associated with risk of injury; as MSK structures are generally stiffer under high velocity movements[11]. Although the experimental evidence to support these claims is scant, it is likely that the high mean vertical RFD of foot-drill [$\bar{x}$ range: 8.3 – 358BW/s] could place recruits at greater risk of lower-limb MSK overuse injury[8].

Results of the present study are similar to those reported previously[4, 7, 24] demonstrating similarities in the magnitudes of the impact loading forces of QM within trained and untrained men and women. The QM foot-drill, regardless of the type of footwear worn, exhibited significantly greater magnitudes of peak vGRF [$\bar{x}\Delta$: 18.4%], peak vertical RFD [$\bar{x}\Delta$: 85.4%], and shorter TTP [$\bar{x}\Delta$: 80.7%] when compared to walk. These significant differences observed between QM and walk may be associated with the greater mean speeds observed in QM [0.39m/s, $\bar{x}\Delta$:19.2%] when compared to walk. Further observations indicated that QM demonstrated a distinct impact peak across all footwear types when compared to the walk, with a steeper initial slope from initial contact to peak vGRF [figure 2].

The greater forces and shorter TTP of QM have been linked to the effective mass of the stamping [active] limb travelling at a higher velocity prior to ground contact[4]. It was reported that untrained [recruits] men produced mean peak tibial impact accelerations of 38 ± 16m/s^{-2} when marching[4]. suggesting that the exaggerated heel strike of QM is likely a factor associated with an increased risk of calcaneus stress fractures, plantar fasciitis, Achilles tendinopathy, and muscle strains of the soleus and gastrocnemius. Despite these data being extracted during the impact phase, whereby footwear and specific neuromuscular mechanisms are likely to have influenced the magnitude of accelerations, these data provide an indirect approximation of the peak tibial impact accelerations of British Army foot-drill in an untrained military sample.

In accordance with previous research[26], an inverse relationship generally exists between the magnitude of peak vGRF and TTP. During cyclic high impact loading activities, the MSK system is exposed to forces that contain passive components; forces that peak within the initial 10ms, and active components; forces that peak over a longer period and represent the role of the muscles in force attentuation[15]. The mean TTP relative to Halt, SaA, and SaE ranged between 18–14ms, which is considerably lower than the threshold range [50-70ms] for muscle to actively respond to the landing/contact stimulus[8]. In accordance with previous research[8], it is reasonable to suggest that the peak vGRF of SaA, SaE and Halt are passive forces, and when achieved, may not be under neuromuscular control, potentially causing the corresponding high deflection in the vertical direction to exceed the threshold stress (maximum tolerable stress)[15], potentially increasing the risk of bone-on-bone contact and subsequent depression of the tibial and femoral cartilage and meniscus[15].

Unlike traditional athletic landing techniques, whereby athletes are encouraged to land with greater degrees of knee and ankle flexion as a means of attenuating and dispersing the impact loading forces at ground contact, foot-drill necessitates an extended-knee landing, whereby both male and female recruits are taught to forcefully impact the ground with minimal to no hip, knee and/or ankle joint flexion [figure 2]. The stiffer landing patterns/strategies of foot-drill may predispose recruits to bone strains within [400-1500με] and above [10,000με] the single-load failure threshold, typically resulting in bone micro-damage and subsequent stress fracture[30].

A strategically more robust shock absorbing outsole design worn during foot-drill training could potentially contribute to a marginal reduction in the relative magnitude and accumulative impact loading forces of foot-drill, subsequently contributing to a potential reduction in the high incidence rates of lower-limb MSK overuse injuries and medical discharges of British Army recruit populations. Understanding the functionality and utility of different military footwear and their implications with respect to injury potential [and its mitigation] in recruits during BMT, is essential for maintaining effective operational and tactical performance, and could provide important information regarding injury prevention and performance optimisation strategies for commanders. Furthermore, reducing the critical stress distributions and potential bone-on-bone contact of the knee and ankle joint during the exaggerated heel strike of QM, and the extended-knee landing of SaA, SaE, and Halt, we recommend that the movement/landing patterns of these regimented manoeuvres be modified and/or strategically managed by commanders and physical training instructors [PTIs] in accordance with other maximal and submaximal loading activities.

Practical Implications

The foot-drill movement performed with the TR resulted in a total reduction in the magnitude of peak vGRF and peak vertical RFD of 17.9% and 16.8% when compared to the CB, and 25.5% and 32.3% when compared to the AB, respectively. These data provide commanders and PTIs with important information concerning the shock absorption interactions of specific standard issue footwear during foot-drill and the potential for impact-related lower-limb MSK overuse injury. Furthermore, commanders and PTIs are able to make better-informed decisions on the specific type of footwear most effective at marginally reducing the accumulative high impact loading forces of foot-drill during the initial phases of BMT.

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