Lower Limb Injury Prevention in the New Zealand Army

A thesis presented in partial fulfilment of the
requirements for the degree of

Doctor of Philosophy (PhD)
in Sport and Exercise

at Massey University, Wellington, New Zealand

Jacques Jean Rousseau
(Student ID: 01351982)

2019

Declaration

I certify that this thesis is the result of my own investigations, except where otherwise stated. All other sources of information have been acknowledged, both in text and in reference sections. Moreover, this work has not previously been accepted for any degree and is not being submitted in candidature for any degree.

Name: Jacques Jean Rousseau (candidate)

Signed:

Date: 31/05/2019

Contents

i. List of Figures

ii. List of Tables

iii. List of Abbreviations

Abbreviation	Term
AEP	Accredited Employer Provider
A-P	Anterior-posterior
CAP	Circumferential applied pressure
CFL	Calcaneofibular ligament
COP	Centre of pressure
EMG	Electromyography
FTCL	Fibulotalocalcaneal ligament
GAS-L	Gastrocnemius lateral
GAS-M	Gastrocnemius medial
M-L	Medial-lateral
MSK	Musculoskeletal
MTSS	Medial tibial stress syndrome
Nm	Newton meters
NZA	New Zealand Army
NZDF	New Zealand Defence Force
P-D	Plantar-dorsiflexion
PTFL	Posterior talofibular ligament
PTTC	Anterior tibiotalar ligament
RNZAF	Royal New Zealand Air Force
RNZN	Royal New Zealand Navy
ROM	Range of Motion
STTC	Superficial posterior tibiotalar ligament
TA	Tibialis anterior
TCL	Tibiocalcaneal ligament
TNL	Tibionavicular ligament
TSL	Tibiospring ligament
US	United States
WF	Work fatigue

iv. Abstract

Background

The mobility of the New Zealand Defence Force (NZDF) and its ability to deploy personnel at short notice is compromised by the high number of musculoskeletal injuries, particularly to the lower limbs. Literature searches indicated footwear may be the issue. The aim of this research is to examine the extent of the problem, which injuries and anatomical structures are most affected, the aetiology involved, and finally, the effects of a possible remedial intervention.

Methodology

Information from 11 years of NZDF injury records were examined. Chi square analysis was used to determine most affected joint(s), injury type and activities (sporting or military). The ankle joint appeared most vulnerable to injury, particularly during sporting or military activities involving running. Traumatic ankle sprains and strains were the most prolific injuries and this occurred when not wearing the military boot. This information was used to determine the subsequent investigations of the biomechanical and neurological aetiology underlying habitual boot-wear that might give rise to these injuries.

Ankle range of motion (ROM), endurance strength, power and fatigue were measured using an isokinetic dynamometer (Biodex) in new recruits and repeated after one year of military boot-wear. Muscle activation of *tibialis anterior* and both the medial and lateral *gastrocnemius* were also measured during quiet standing on a force platform to measure postural sway.

The same measures of aetiology were conducted on 65 habitual boot wearing regular force military male personnel pre and post-introduction of a low-cut flexible shoe. These 65 personnel all had served greater than two years in the NZDF. At 10 weeks, the effects of pre- and post- flexible shoe wear were measured to determine if the effects of habitual boot-wear could be reversed.

Results

After 12 months of habitual military boot-wear, ankle ROM was decreased in all planes of movement, endurance strength and power were significantly reduced and fatigue onset increased after one year of boot-wear. Muscle activation was increased in tibialis anterior and both the medial and lateral gastrocnemius, which coincided with significantly increased sway patterns indicating poor postural stability.

After 10 weeks of transitioning from habitual military boot-wear to a flexible shoe, ankle ROM, and strength significantly increased, while fatigue, muscle activation and postural sway decreased.

Conclusion

Chronic military boot-wear causes mal-adaptations and is associated with the high number of ankle injuries in the NZDF, however the effects can be reversed. It was advised that when not on military manoeuvres that personnel wear a low-cut flexible garrison shoe.

v. Acknowledgements

The commitment to complete a PhD study as a part-time student while working full-time and attempting to balance family life cannot be underestimated. Completing this thesis has required the utmost amounts of dedication, patience and drive on a personal level.

This project would not have been made possible without my principal supervisor Dr Sally Lark whose support, assistance, guidance and friendship were invaluable. Her encouraging words on bad days and her enthusiasm on good days motivated me to finish this project. Thank you for all the opportunities you gave me and your trust in me. Our discussions were always very instructive and inspiring for me. You saw things from different perspectives and taught me to question everything. Thank you for your insightful suggestions. Thanks also to my co-supervisor Associate Professor Wyatt Page for his wisdom and guidance and through the "technicalities" of the project. His scientific and critical view on the biomechanical aspects of this project were inimitable. Many thanks also to Associate Professor Hugh Morton for his guidance with the initial statistical analysis. Thanks also to my military supervisors Lieutenant Colonel Andrew Dunn and Wing Commander Paul Nealis for their support and assistance. I wish to express my heartfelt thanks to my PhD colleague Mostafa Yaghoubi for his support and assistance with the sometimes laborious processing of the EMG data analysis.

Additionally, this project would not have been possible without the support from the New Zealand Defence Force; the New Zealand Army and the Directorate of Defence Health. There are far too many individual members of the New Zealand Defence force to individually thank, however I would particularly like to thank Brigadier Andrew Grey for his support and interest in the project, Major-General Dave Gawn for his vision and

enthusiasm, Colonel Andrew Fox and Lieutenant Colonel Tony Downey for their participation and allowing access to recruits and regular force staff. I would also like to thank Lieutenant Colonel Peter Cosgrove for being the “instigator” of the project becoming a PhD. To Lieutenant Colonel Michelle Williams who has been with me on this journey since day one, thank you for your support and encouragement. Many thanks go to Warrant Officer John Irving for his friendship, constant support and motivation to see the project through.

This project could not have existed without the voluntary assistance from members of the New Zealand Army Physical Training Corps, in particular Corporal Ele Lilo and Staff Sergeant Davey Forbes for their patience and technical assistance with the data collection equipment. I would also like to thank Captain David Edgar and Lieutenant Pete Whalley for their assistance, enthusiasm and support of the project. I am grateful to all the servicemen and women of the New Zealand Army who so generously gave their time to the project.

To my family and friends. Although you were not physically involved in this project, I thank you for your encouragement, support and for simply listening, especially when the going was tough! I would especially like to thank my parents, without your love, trust, care, support and encouragement I would never have been able to complete this PhD. To my son Giscarde and his partner Quinn, my son Matthieu and my daughter-in-law Alecia Jane (AJ) and my grandson Hadleigh, your love support and encouragement has been priceless throughout this journey.

And ‘last but not least’, I would like to thank my wife Rita, the love of my life. Thank you for your love, your patience, your friendship and for the everlasting support in which ever choice I made.

Soli Deo Gloria

This PhD is dedicated to my father, Nicolaas Rousseau

(10 September 1933 - 19 October 2011)

who always told me that “*knowledge is power*”

vi. Preface

The New Zealand Defence Force approached me as they thought there was a problem with the high number of injuries that was affecting the number of people available for deployment. I then discussed this with Dr Sally Lark, as I thought the problem may lie with the footwear as the injuries appeared to be mostly lower limb and to be happening during sports when not wearing the military boot. Together Dr Lark and I designed the experimental procedure as a progressive series of investigations, starting with the epidemiology, and then the mechanisms and reasons why there might be so many lower limb injuries. Once we had established the factors causing these injuries and aetiology, we designed an intervention to see if the effects could be reversed.

I was fully involved in all aspects of the experimental design, did all the recruitment and data collection. I learnt how to use several new pieces of equipment such as the force-plate and EMG system. I also learnt how to process the data files and analyse them using the bespoke software. I measured over 200 military personnel for this work, which generated an extraordinary amount of data to be analysed. I did have some help in processing the hundreds of EMG data files.

I was instructed initially on how to do some of the statistical analyses such as Chi-Square test, but also learnt other new statistical tests such as effect sizes, paired t-tests and bivariate correlations used on the analyses of the data. I discussed the implications of the results with my supervisory team and applied the physiology underpinning these.

I have presented each stage of this work to various military groups both nationally and internationally, and it has received some unprecedented interest from international military organisations such as the UK, Australia, Canada and the USA. More importantly, this work has provided the evidence required to institute a ‘Shoe Policy’ in the NZ Defence Force, whereby a garrison shoe has been introduced to minimise the time spent wearing a military boot.

This work is being reviewed for publication in scientific journals and therefore the thesis is set out as a series of individual publication chapters, each with their own reference list.

I have enjoyed the PhD journey immensely, and have become very passionate about the work, the research process, and most of all the impact it has had on improving the lives of service men and women of the NZDF.

Jacques Rousseau

Chapter 1: Introduction

1.1 Background

Similar to defence forces globally (Havenetidis et al., 2011; Kaufman et al., 2000; Knapik et al., 2001), New Zealand Defence Force personnel are also subject to a high number of lower limb injuries (Davidson ey al., 2008).

According to the Reid Classification System (Chisholm, 1990) used by the New Zealand Defence Force the lower limb is usually defined as the area from the hip downwards. As a result of the findings in the literature regarding lower limb injuries and identifying the ankle being one of the most commonly injured anatomical sights (Andersen et al., 2016; Havenetidis et al., 2011; Neves et al., 2017; Schwartz et al., 2018), this study was confined around the lower part of the lower limb, i.e. from the knee downwards.

Much of the literature regarding lower limb injuries focussed on lifestyle factors (e.g. gender, weight, fitness levels) as risks and causative factors (Almeida et al., 1999; Billings, 2004; Scott et al., 2015). Physical activities such as military and physical training (PT) are also listed as possible causes of lower limb injuries (Cameron et al., 2010; Lauder et al., 2000). Foot wear was highlighted in research as a possible factor for lower limb injuries (Andersen et al., 2016; Heir, 1998), however most research regarding foot-wear focussed on the use of foot-wear as an injury prevention and structural support mechanism to particularly prevent lateral ankle sprains (Chander et al., 2014; Chander et al., 2015; Garner et al., 2013). This is very much in line with original thinking that the boot must provide stability hence the stiff structure, particularly the shaft, of military boots.

Literature indicates that most injuries occur during sport and physical training. However, military boots are not usually worn during physical training or sport. This led to the thought that there may be a connection between the action and function of the boot having a destabilising influence on the ankle that is apparent when the boot is not being worn. Therefore, the assumption was made that the boot was a factor for causing ankle injuries and the foot may be relying on the boot for inherent stability.

In order to address this assumption, and indeed lower limb injury problem within the New Zealand Defence Force, a study was designed in three phases to investigate the scope of the problem, causes, and possible intervention to decrease the high incidences of lower limb injuries in the New Zealand Army. The three phases are:

- Phase 1: Epidemiology
- Phase 2: Aetiology (biomechanical and neural)
- Phase 3: Intervention

1.2 Phase 1 Epidemiology (Chapter 2)

Phase 1 investigated 11 years of injury data extracted from the New Zealand Defence Force (NZDF) Accredited Employer Programme (AEP), which is affiliated to the New Zealand Government Accident Compensation Corporation Act (ACC) 2001. The AEP allows an employer to act on behalf of the ACC, managing workplace injuries for their employees and providing entitlements under the 2001 Act for work-related personal injuries and illnesses. All injuries are legally required under the Act to be recorded through the AEP process.

Examination of the AEP data found there has been no decline in lower limb injuries despite some interventions. To further analyse the injury data, the narratives were examined using word recognition search to determine the specific activities when injury occurred. Chi-square cross tabulation analysis was used to test the relationships between the injuries and activities participated in when injured. The most common activities when injured were found to be military training and sport.

It was found that the ankle joint was the most injured joint, and the highest number of injuries occurred during running activities, more so during individual running. This was very interesting as running as an individual activity is normally done without wearing military boots and usually over longer distances on reasonably even surfaces. This was further evidence in the assumption that the boot may be a factor for causing ankle injuries.

1.3 Phase 2 Aetiology (Chapters 3 and 4)

Phase 2 attempts to identify of the aetiology or deficits for lower limb injury mechanisms caused by boot-wear. The biomechanical aspects and muscle activation were investigated.

In order to identify whether boots were the cause of lower limb injury, newly enlisted recruits who had not previously habitually worn a military boot before were recruited. They were tested before they were issued with their military boots and retested after 12 months of habitual boot-wear.

The cohort was made up of 122 male recruits with the average age of 22. Male recruits were chosen as only 12% of all recruits are female. Female recruits are also known to have a higher attrition rate than males. 122 recruits were used as there was no sample size to base calculations on. Previous boot and orthotic studies on military personnel were one-off investigations, and only had 13 - 20 participants and no differences in results were reported. A sample of convenience based on the New Zealand Army maximum recruit intake was used in my studies.

The cohort was a very homogenous group;

- they all lived in barracks
- ate at the same mess
- participated in the same training (both physical and military)
- wore the same uniform
- did not play sport during this time
- they were all medically screened
- were injury free
- had to pass an entry level fitness test (they had a base-line fitness level)
- when retested they were injury free and reported having no injuries.

As a result of this homogeneity it was decided to use paired pre-post analysis as this would be a robust method of analysing this group.

The following biomechanical factors (see chapter 4) were tested to identify changes in fundamental movement and strength function. These were measured using a Biodex isokinetic chair and bubble inclinometer:

- Range of Movement (ROM) (passive inversion and eversion and active plantar- and dorsi-flexion) and

- Strength (ankle dorsiflexor and plantar flexor muscles).

The pre-post analysis revealed a significant decrease in strength and ROM and a subsequent increase in fatigue. This is noteworthy as a decreased ROM was identified as a risk for ankle injury in a study by Willems et al. (2005). The implication of these results is the protective effect of the boot is causing mechanical restrictions which in turn are having a mal-adaptative effect on the ankle range of movement.

The decrease ROM leads to a loss of plantarflexion force which has implications for the loss of forward movement propulsion, simultaneously the loss of inversion and eversion ROM has an effect on medial-lateral stability, meaning there is less movement range before failure when turning or twisting the ankle.

The neural effects (see chapter 5) of habitual military boot wearing were examined via the level of muscle activation and variance of activity using surface electromyography during quiet standing on a force plate. Results from these tests revealed an increase in muscle activation of the Tibialis Anterior, Medial and Lateral Gastrocnemius, and an increase in movement distance around the Centre of Pressure (95% ellipse area of Centre of Pressure (CoP)). This indicates an overall decrease in stability and an increase in medial-lateral and anterior-posterior movement. These increases in muscle activation correlated with the large sway patterns for CoP which appears to indicate that these muscles are working harder to maintain static balance after one year of military boot-wear.

It was concluded from the results of Phase 2 that wearing a military boot for 12 months leads to physiological and biomechanical maladaptations and is causing the ankle joint to become unstable. The boot is causing the problem and not correcting the problem.

This is a paradigm shift in thinking that the boot is protective wherein fact it is destabilising the ankle. Ordinarily wearing a high shaft boot was thought to stabilise the ankle joint by limiting movement to reduce ankle injury, however the results in phase 2 show that boot wearing was a probable leading cause of injury. This is noteworthy as the boot is an external stabilisation for the ankle joint. The change in thinking is that this external support over a period of time (1-year) is making the ankle joint inherently unstable.

1.4 Phase 3 Intervention (Chapter 5)

Phase 3 attempts to reverse or resolve the problem of the loss of ankle function and physiological maladaptation. As a result of the findings of phase 2 it was decided that one of the simplest ways to resolve the problem would be to replace the military boot with a shoe. The shoe had to free the foot and ankle, notably the absence of the high shaft. The shoe construction materials were much more flexible and allowed full range of movement at the ankle and metatarsals. A shoe was sourced that met the criterion of not having a high shaft, having a low heel drop and a flexible material upper, therefore the Salomon Sensa Mantra 3 was chosen.

For the shoe trial, soldiers who had been in the military for more than 24 months were recruited to participate in the study. This was to ensure the maladaptations seen in Phase 2 were evident and again a homogenous group:

- they were all from the same unit
- wore the same boot and uniform
- all participated in unit PT

- did the same military tasks
- all had to pass their 6 monthly required fitness tests
- they all wore the shoe for 10 weeks
- none of these participants had current musculoskeletal injuries.

There was no control group per say as the intervention was 10-weeks and the results from phase 2 were known. When examining the post-1-year boot-wear results (of phase 2) with the pre-shoe group results (of this phase) it showed they were very similar. The exact same tests and methodological protocols were used as in phase 2, and analysed in the same manner for this shoe-wearing group.

Results:

- increase in ROM
- increase in strength
- decrease in activation
- decrease in movement around CoP
- decrease in medial-lateral and anterior-posterior movements.

All results were seen to be opposite to those who wore boots for 12 months, i.e. stronger lower limb, better balance and a larger range of movement to produce strength. The implication of these results is that the adaptations to the ankle joint can be reversed by a simple intervention such as 10-weeks of flexible shoe wearing.

The increase in ROM and strength enhanced postural stability probably by augmented proprioceptive feedback. The decreased reliance on muscles for stability means a decrease in muscle fatigue. These factors may reduce the incidence of ankle injuries long term in the Defence Force.

1.5 References

Almeida, S. A., Williams, K. M., Shaffer, R. A., & Brodine, S. K. (1999). Epidemiological patterns of musculoskeletal injuries and physical training. *Med Sci Sports Exerc, 31*. doi:10.1097/00005768-199908000-00015

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Billings, C. E. (2004). Epidemiology of injuries and illnesses during the United States Air Force Academy 2002 Basic Cadet Training program: documenting the need for prevention. *Military Medicine, 169*(8), 664-670.

Cameron, K. L., Owens, B. D., & DeBerardino, T. M. (2010). Incidence of Ankle Sprains Among Active-Duty Members of the United States Armed Services From 1998 Through 2006. *Journal of athletic training, 45*(1), 29-38. doi:10.4085/1062-6050-45.1.29

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science, 6*(1), 59-66. doi:10.1080/19424280.2013.834979

Chander, H., Wade, C., & Garner, J. C. (2015). The influence of occupational footwear on dynamic balance perturbations. *Footwear Science, 7*(2), 115-126.

Chisholm, J. (1990). The read classification. *British Medical Journal, 300*(6372), 1092.

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

Garner, J. C., Wade, C., Garten, R., Chander, H., & Acevedo, E. (2013). The influence of firefighter boot type on balance. *International Journal of Industrial Ergonomics, 43*(1), 77-81. doi:https://doi.org/10.1016/j.ergon.2012.11.002

Havenetidis, K., Kardaris, D., & Paxinos, T. (2011). Profiles of musculoskeletal injuries among Greek Army officer cadets during basic combat training. *Mil Med, 176*(3), 297-303.

Heir, T. (1998). Musculoskeletal injuries in officer training: one year follow-up. *Military Medicine, 163*(4), 229-233.

Kaufman, K. R., Brodine, S., & Shaffer, R. (2000). Military training-related injuries: surveillance, research, and prevention. *Am J Prev Med, 18*. doi:10.1016/s0749-3797(00)00114-8

Knapik, J. J., Sharp, M. A., Canham-Chervak, M., Hauret, K., Patton, J. F., & Jones, B. H. (2001). Risk factors for training-related injuries among men and women in basic combat training. *Med Sci Sports Exerc, 33*. doi:10.1097/00005768-200106000-00014

Lauder, T. D., Baker, S. P., Smith, G. S., & Lincoln, A. E. (2000). Sports and physical training injury hospitalizations in the army. *American Journal of Preventive Medicine, 18*(3), 118-128.

Neves, E. B., Eraso, N. M., Narváez, Y. S., Rairan, F. S. G., & Garcia, R. C. F. (2017). Musculoskeletal Injuries in sergeants training courses from Brazil and Colombia. *Journal of Science and Medicine in Sport, 20*, S117.

Schwartz, O., Kanevsky, B., Kutikov, M. A. J. S., Olsen, C. H., & Dudkiewicz, I. (2018). Medical Attrition from Commanders Training in the Israeli Defense Forces (IDF): A Cross-sectional Study on 23,841 Soldiers. *Military Medicine*. doi:10.1093/milmed/usy004

Scott, S. A., Simon, J. E., Van Der Pol, B., & Docherty, C. L. (2015). Risk factors for sustaining a lower extremity injury in an Army reserve officer training corps cadet population. *Military Medicine, 180*(8), 910-916.

Willems, T. M., Witvrouw, E., Delbaere, K., Mahieu, N., Bourdeaudhuij, L. D., & Clercq, D. D. (2005). Intrinsic Risk Factors for Inversion Ankle Sprains in Male Subjects: A Prospective Study. *The American Journal of Sports Medicine, 33*(3), 415-423. doi:10.1177/0363546504268137

Chapter 2: Literature Review

2.1 General injury rates in military populations

2.1.1 Introduction

The nature of military training and tasks requires military personnel to attain and maintain a level of fitness, which is much higher than usually found in civilian populations. It is therefore not surprising that many military occupations require a higher level of physical exertion and fitness than most civilian occupations (Cowan et al., 2003). Soldiers are required to maintain a state of physical readiness that allows them to meet the demands of military duty in any training and operational environment, accordingly regular physical training forms an integral part of military life (Cowan et al., 2003).

Operational readiness and success in the profession of arms depends heavily on high levels of physical fitness and physical training, together with the obligatory traits of mental and physical toughness (Garrison et al., 2016). It is therefore not surprising that military physical training is not without risk, and injuries to soldiers are common (Blacker et al., 2008; Knapik et al., 2007; Knapik et al., 2001; Schneider et al., 2000; Tomlinson et al., 1987). This is worth noting as injuries are recognised as a leading health problem in the military and injury-related musculoskeletal conditions are common in this active population group (Hauret at al., 2010; Lovalekar et al., 2016). This can also be confirmed by many uniformed service personnel expressing frustrations and concerns that musculoskeletal injuries interfere with military tasks and the effect these injuries have on their military readiness (Jennings et al., 2008).

2.1.2 Musculoskeletal Injuries

Musculoskeletal (MSK) injuries are by far the leading cause of attrition of military personnel numbers during initial military combat training (Schwartz et al., 2014). They are the most prevalent factor for not achieving physical readiness (Andersen et al., 2016) and are the most common cause for discontinuing military service (Frilander et al., 2012). These injuries are the leading cause of discontinuing military training due to medical reasons (Kaufman et al., 2000). In the U.S. Army, musculoskeletal injuries have a greater impact on the health and readiness of military personnel than any other category of medical complaint, and training related injuries treated on an outpatient basis may have the biggest single impact on military readiness (Cowan et al., 2003).

Musculoskeletal injuries are viewed as being endemic in military population groups (Owens & Cameron, 2016), and were highlighted as a 'hidden epidemic' in an article on injuries in the military by Peake (2000). To pursue the 'epidemic' in order to make changes to minimise injuries, lost duty time and lost careers of service, a scientific basis and vital command attention was needed (Peake, 2000). Many of these injuries involved physical damage caused by acute trauma such as sprains, strains and ruptures or cumulative micro-trauma (overtraining) in physical training, sports, recreation, and work performance (Hauret et al., 2010). High injury rates occur as a result of physical training (Kaufman et al., 2000) and in a survey of exercise and sports related injuries among US military service members Hauret et al. (2015) found 52% of all injuries were exercise and sport related and can be categorised as musculoskeletal injuries (Hauret et al., 2010). When reporting on sports and exercise-related injuries in the military Garrison et al. (2016) found these to be the leading cause of outpatient medical visits in the US military.

It is worth noting the inclusion of injuries as a result of sport participation in the military; sports participation is not only a standard method for military members to sustain and enhance physical fitness, but also serves to improve morale and is considered an essential tool in developing mental and physical toughness for the military environment (Garrison et al., 2016).

Secondary Military Training and Deployment

There is an increasing wealth of research in relation to musculoskeletal injuries (Table 2.1) during initial military training (basic combat or recruit training) (Blacker et al., 2008; Knapik et al., 2006; Molloy et al., 2012; Psaila & Ranson, 2017; Schwartz et al., 2014). Hhowever, the analysis of injuries during military training after the completion of basic training (e.g., corps training, course related training which consists of courses that qualify non-commissioned junior commanders and officers for infantry and non-infantry combat units and military exercises) is limited (Schwartz et al., 2018). Basic trainees do not meet the requirements for assignment to operational units and conclusions drawn from recruit studies may not apply to seasoned, operational soldiers as these soldiers are likely to have higher fitness levels than those of new recruits (Smith & Cashman, 2002).

Table 2.1. Studies indicating musculoskeletal injuries in military personnel

Author	Year	Country	Stage of Military Training	Study	Observation period	Injury rates
Amako et al.	2018	Japan	Regular force soldiers	Longitudinal cohort study	2008 – 2012	26 837 MSK injuries reported
Andersen et al.	2016	Australia	Active duty ADF personnel	Narrative review	Data from 10 years reviewed.	31.7% sustained an injury during military training
Belmont et al.	2016	USA	Deployed soldiers in Afghanistan and Iraq	Descriptive epidemiology	2003 – 2011	48% medically evacuated as a result of noncombat MSK injury
Blacker et al.	2008	Britain	Recruit/basic training	Retrospective analysis of training and medical records	1 January 2003 – 1 March 2005	Over 8% discharged from military as a result of MSK
Davidson et al.	2008	New Zealand	Active duty NZDF personnel	Descriptive epidemiology	Injuries from an 11-month period	26.7% sustained a MSK injury
Frilander et al.	2012	Finland	Recruits/conscripts	Survey	Survey carried out over 1 year	Total of 58% of conscripts sought medical consultation as a result of MSK
Halvarsson et al.	2018	Sweden	Deployed soldiers	Cross-sectional survey	6 months	47% reported a MSK injury
Havenetidis et al.	2011	Greece	Officer cadet training	Cohort study	7 weeks	28.3% sustained a MSK injury
Heir	1998	Norway	Officer cadet training	Cohort study	1 year	60% sustained a MSK injury

Author	Year	Country	Stage of Military Training	Study	Observation period	Injury rates
Heir and Glomsaker	1996	Norway	Recruit/basic training	Cohort study	6 – 10 weeks	61.9% sustained a MSK injury
Jones et al.	1993	USA	Recruits	Cohort study	12 weeks	31% sustained a MSK injury
Kaufman et al.	2000	USA	Recruits and active duty US Army personnel and Navy Special Warfare candidates	Review	Training periods between 8 – 25 weeks	32% sustained a MSK injury during recruit training 11% sustained a MSK injury during active duty training 42% sustained a MSK injury during special warfare trainees 8% of officer cadets sustained a MSK injury
Larsson et al.	2009	Sweden	Recruit/basic training	Cohort study	7 – 10 months	32% attrition due to MSK
Neves et al.	2017	Brazil and Columbia	Sergeants training course	Cohort questionnaire	12 months	113 out of 499 sustained a MSK injury
Pope et al.	1999	Australia	Recruit/basic training	Cohort study	12 weeks	21% sustained a MSK injury
Psaila and Ranson	2017	Malta	Recruit/basic training	Cohort study	135 days	26% sustained a MSK injury
Reynolds et al.	2009	USA	Infantry, Artillery, Construction Engineers and Special Forces soldiers on deployment	Two-year prospective study	2 years	70% of Infantry, Artillery and Construction Engineers sustained a MSK injury, and 50% of Special Forces soldiers were injured.

Author	Year	Country	Stage of Military Training	Study	Observation period	Injury rates
Schram et al.	2019	Australia	Active duty and part-time personnel	Retrospective cohort study	Injury data collected 1 July 2012 – 30 June 2014	1385 reported injuries out of 6082 active duty and part-time personnel
Schwartz et al.	2018	Israel	Commanders training	Cross-sectional study	2012 – 2015	43% attrition due to MSK
Sharma et al.	2015	Britain	Recruit/basic training	Prospective descriptive study	Injury data collected over 26 weeks	48.65% sustained a MSK injury
Taanila et al.	2009	Finland	Recruit/basic training	Cohort study	6 months	33% sustained a MSK injury
Wilkinson et al.	2011	Britain	Infantry pre-deployment training	Cohort study	1 year	58% sustained a MSK injury

ADF – Australian Defence Force; NZDF – New Zealand Defence Force; MSK – musculoskeletal; USA – United States of America

In a study examining the incidence of musculoskeletal injuries during a one year officer cadet training course in the Norwegian Defence Force (Heir, 1998), 60% of the cadets sustained an injury during the course which demonstrated similar rates of injuries when compared to basic combat training. Similarly, musculoskeletal injuries were examined during a sergeants training course of 499 military students with more than one year's military experience from the Brazilian and Columbian Defence Forces, in this study 113 musculoskeletal injuries were reported (Neves et al., 2017). Likewise, a study examining musculoskeletal injuries among British army infantry soldiers during predeployment training over a one year period (Wilkinson et al., 2011) found a cumulative injury incidence of 58% amongst these soldiers.

When investigating musculoskeletal injuries in uniformed military personnel in the Australian Defence Force, a 62-month retrospective study (Gruhn et al., 1999) of 4,993 personnel members' physiotherapy admission records determining injury epidemiology associated with military training and sport revealed 96.2% of males (4,803/4993) and 3.8% of females (190/4993) were referred for physiotherapy treatment as a result of musculoskeletal injury. A further retrospective cohort study examining injury rates and trends among full-time and part-time Australian Army personnel during a two year period Schram et al., (2019) found 1385 reported injuries out of 6082 full-time and part-time personnel. In a similar study investigating epidemiological patterns of musculoskeletal injuries from 2008 – 2012 in the Japanese Military 26,837 musculoskeletal injuries were obtained from patient review sheets from those referred to Japan Self Defence Force Hospitals (Amako et al., 2018).

As outlined above, musculoskeletal injuries are not only problematic for militaries during initial military training on home soil, during secondary training and during military exercises, but are also endemic during overseas operational deployment (Roy et al., 2015). When determining injuries in trained units' operational and fitness activities Reynolds et al. (2009) found 70% of Infantry, Artillery and Construction Engineers sustained an injury, and 50% of Special Forces soldiers were injured. During the Afghanistan and Iraq conflicts, noncombat musculoskeletal injuries occurred at a rate of more than three times that of combat casualties with forty-eight percent of all musculoskeletal casualties in a US Army Brigade being medically evacuated from the combat theatre as a result of noncombat musculoskeletal trauma (Belmont et al., 2016). A study by Roy et al. (2015) reported that musculoskeletal injuries are the most common cause of ambulatory visits in the deployed setting. Halvarsson et al., (2018) found forty-seven percent of Swedish soldiers serving in Afghanistan reported musculoskeletal injuries.

2.1.3 International Injury Statistics

Recruit Training

As a result of mandatory training and fitness activities of the military, lost training time, disabilities, and health care costs are a major factor resulting from musculoskeletal injuries (Reynolds et al., 2009). Additionally, the leading cause of the loss of training days in the United States army are musculoskeletal injuries and their financial cost is estimated to be as high as US$2 billion dollars per year (Cloeren & Mallon, 2004). However, musculoskeletal injuries are not unique to the US Army and are a significant problem across military establishments worldwide (Andersen et al., 2016; Davidson et al., 2008; Kaufman et al., 2000; Sharma et al., 2015).

During British Army recruit infantry training, almost half of the recruits (48.65%) sustained at least one musculoskeletal injury during the 26 weeks of training (Sharma et al., 2015). In a similar study identifying the risk factors for training injuries among British Army recruits Blacker et al. (2008) found the discharge rate due to musculoskeletal injuries reached over 8%. In a study investigating attrition in basic military training in the Australian Army, Pope et al., (1999) found 276 out of 1317 recruits suffered a lower limb (musculoskeletal) injury, they also reported that recruits who sustained an injury during training were ten times more likely to fail to complete basic military training than those recruits not sustaining an injury. Attrition rates during combat training due to orthopaedic reasons in the Israel Defence Force were found to be 43% of overall attrition, making orthopaedic injuries the leading cause of leaving the military (Schwartz et al., 2018). Similarly, Larsson et al., (2009) found units in the Swedish Defence Force reporting a 32% rate of discharge from military service as a result of musculoskeletal injuries. Premature discharge from basic military training was also linked to musculoskeletal injuries in a study identifying risk factors for lower limb injuries in the Maltese Armed Forces, in this study Psaila and Ranson (2017) reported 26% of recruits cited musculoskeletal injury as the reason for withdrawal from military training.

Likewise, in a study investigating untimely discharge from military service in the Finland Defence Force, Taanila et al. (2009) found MSK injuries to represent the second largest justification for discharge. During their 12-month study period they found 33% of conscripts sustained one or more MSK injuries during their 6-month period of military service. Interestingly, in the same study it was reported that that over a period of 10 years the overall trend for musculoskeletal injuries in the Finland Defence Force was increasing. This is worth noting as a later study surveying the medical records of 2296 servicemen who had completed their 6 to 12-month military service in the Finland Defence Force, Frilander et al. (2012) found the most common reason for discharging from military service to be musculoskeletal injury. Of the 2296 service men surveyed in the study by Frilander et al. (2012), more than half sought medical care because of musculoskeletal injuries.

Further studies determining the incidence of musculoskeletal injuries in military recruit training include a study by Heir and Glomsaker (1996) revealing 61.9% of conscripts suffered an injury during basic military training in all three services (Army, Air Force and Navy) of the Norwegian Defence Force, and Havenetidis et al., (2011), who found 28.3% of Greek Army Officer recruits were injured at least once during a 7-week basic combat course.

2.1.4 Musculoskeletal Injuries in the New Zealand Defence Force

The New Zealand Defence Force is a relatively small and specialised military; however, the epidemiology of musculoskeletal injuries is comparable to that of other defence forces (Davidson et al., 2008). Of the three military services making up the New Zealand Defence Force (NZDF), the Royal New Zealand Navy (RNZN); the New Zealand Army (NZA); and the Royal New Zealand Air Force (RNZAF), the NZA is the service having the highest proportion of musculoskeletal injuries (Davidson et al., 2008). This is comparable to the United States where the rates for injury hospitalisation highest for the US Army followed by the US Navy and US Air Force (Smith et al., 2000). Higher injury rates for Army personnel are likely due to the nature of Army training and work-related activities such as field training and pack marching (Smith et al., 2000). In the NZDF, musculoskeletal injuries result in approximately 20% of the total number of NZA Regular Force personnel not able to be deployed at any given time (Annual Report on the Health of the New Zealand Army 2013, unpublished). Being a small Defence Force and a small Army, each and every soldier must count, New Zealand certainly cannot afford an Army plagued with injury. Additionally, musculoskeletal injuries are the most common cause of discontinuing military service (Frilander et al., 2012). Data extracted from the NZDF's Accredited Employer Programme (AEP) indicates that minor (Grade 1) to moderate (Grade 2) musculoskeletal injuries, such as a sprain or strain, are estimated to cost the NZA between $1 – 1.5M per annum (Annual Report on the Health of the New Zealand Army 2013, unpublished).

2.2 Injury Type

Injuries are grouped by 'type' into overuse, traumatic and other injuries. Overuse injuries are diagnosed as due or related to long-term, repetitive energy exchanges resulting in cumulative microtrauma and include stress fractures, tendonitis, bursitis, fasciitis and overuse syndromes (Knapik et al., 2007). Traumatic injuries are diagnosed as due to sudden energy exchanges resulting in abrupt overload with tissue trauma and these include sprains, strains, dislocations and fractures (Knapik et al., 2007). Other injury diagnoses included cold and heat injuries, bites/stings, neurological conditions and burns (Wilkinson et al., 2011).

In a study examining injury risk factors among British army infantry soldiers during predeployment training, Wilkinson et al. (2011) found that 83% of all injuries to soldiers in both recruit basic training and regular military training were classified as traumatic injuries. When comparing injuries/risk factors in infantry soldiers, military construction engineers, combat artillery, and Special Forces during their operational and fitness activities, injuries were found to be predominantly strains, sprains, tendonitis, and bursitis (Reynolds et al., 2009). A high proportion of sprains and strains are reported in Finnish Defence Force (Taanila et al., 2009), and similarly the Greek Army were reported to have strains and sprains as the most common types of injury, with the majority of strains occurring at the ankle (Havenetidis et al., 2011). Studies examining injuries in defence forces of other nations have reported similar results (Kaufman et al., 2000).

2.3 Injury Site

2.3.1 Lower Limb

Although injury to the ankle joint is prevalent in studies relating to musculoskeletal injuries in military populations, many studies agree that the majority of injuries occur in the lower limb (Andersen et al., 2016) with studies reporting that injuries as a result of military training are most commonly at or below the knee (Kaufman et al., 2000; Knapik et al., 2001). A report by the US Army Public Health Centre (USAPHC. Health of the Force, 2016) documents the number of musculoskeletal injuries in US Army soldiers with more than half of all injuries being lower extremity injuries.

Kaufman et al. (2000) stated that the majority of musculoskeletal injuries in military populations occur below the knee. Halvarsson et al. (2018) found forty-seven percent of Swedish soldiers serving in Afghanistan reported musculoskeletal injuries, the foot and knee being amongst the common anatomical sites injured. During basic military training in the Maltese armed forces, 20% of recruits withdrew from military training due to a lower limb injury (Psaila & Ranson, 2017), where the most common injuries were medial tibial stress syndrome, ankle lateral ligament injury, and heel fat pad contusion.

A retrospective study of musculoskeletal injuries in British Army recruits by Heagerty et al., (2017) found the most prevalent injury site to be the knee followed by the ankle. Sherrard et al., (2004) also found the knee and ankle joint as the predominant injury site in the Australian Defence Force. A study with the Japanese Defence Force (Amako et al., 2018) found the knee to be the most common body location of injury followed by the hand/finger and the ankle.

There is differing information regarding injuries to military Special Forces operators. Lovalekar et al. (2016) reported the shoulder joint having the highest injury rate (38.1% of injuries) followed by the ankle joint (34.9% of injuries), whereas Abt et al. (2014) reported the most common injury site for special forces operators as the lower extremity (knee and ankle) followed by the upper extremity (shoulder). Similar results were found by Peterson at al. (2005) when investigating the epidemiology of surgical management of injuries in Naval Special Warfare personnel. Peterson et al. (2005) found the most frequent injuries in this group were to the back/neck, knee and shoulder in order of decreasing frequency. However, when it came to surgical management of injuries to Special Forces soldiers, the knee was the highest followed by the shoulder, ankle and foot. It is interesting to note when investigating the probability of lower extremity musculoskeletal injury, ankle strength was identified as a significant risk for incurring injury to the lower limb (Wohleber et al., 2017).

Differences in reported injury type could be attributed to differences in health care provider referral patterns or consistency of documentation in medical records (Smith & Cashman, 2002). It is also worth noting that military units vary from location to location by the type of unit, operational tempo, and training cycle. There may be a time during the year when a military unit is training at a high operational pace in preparation for an upcoming deployment, prolonged field training exercise, or skills validation assessment (Garrison et al., 2016). Therefore, differences in injury type and anatomical site may be related to these differences in training intensity, frequency, duration, or terrain (Smith & Cashman, 2002).

Table 2.2. Studies indicating musculoskeletal injury site in military personnel

Study	Population	Study design	Participants (n)	Injury Site	Percentage Injured
Amako et al. 2018	Japan Self-Defence Force	Longitudinal cohort study of musculoskeletal injuries in Japanese Self-Defence Force Hospitals	22 340	Knee Hand/finger Ankle Shoulder	15.5 14.1 12.8 8.9
Billings 2004	US Air Force Academy Cadets	Retrospective observational study	1210	Ankle Hip Thigh	17.4 14.4 7.2
Davidson et al 2008	New Zealand Defence Force regular service personnel	Descriptive epidemiology. Analysis of lower limb AEP injury data	2 575 AEP data entries	Ankle Knee Upper leg Lower leg	37.1 21.7 17.7 15.9
Halvarsson et al. 2018	Swedish soldiers serving in Afghanistan	Cross-sectional survey of soldiers serving in Afghanistan	325	Knee Lower back	8 5
Hauret et al. 2009)	Active duty non-deployed US Military service members	Systematic review of musculoskeletal injuries in combined US Military services	9 605 (Musculoskeletal hospitalisations)	Knee Ankle Pelvis	22.4 13.0 3.7
Havenetidis et al. 2011	Greek Army Officer Cadets	Cohort study monitoring musculoskeletal injuries during basic combat training	233	Ankle (most prolific)	45.9
Lovalekar et al. 2016	US Armed Forces Naval special warfare sea, air, and land operators	Review of musculoskeletal injury data extracted from medical charts	210	Shoulder Lumbopelvic Ankle Knee Thigh Lower Leg	23.8 12.7 9.5 7.9 7.9 4.8

Study	Population	Study design	Participants (n)	Injury Site	Percentage Injured
Neves et al. 2017	Sergeants Training Course	Cohort study using self-reporting questionnaire during sergeants training course	318 (Brazilian Soldiers) 181 (Columbian Soldiers)	Ankle (most prolific) Ankle (most prolific)	21.7 42.8
Psiala et al. 2015	Maltese military recruits	Cohort study identifying risk factors for lower leg, ankle and foot injuries in Maltese military recruits	127	Foot Lower leg Ankle	13.4 12.6 9.4
Roy et al. 2015	US Military Infantry and Support battalion personnel deployed in Afghanistan	Retrospective cohort study of soldiers' musculoskeletal injuries during 12-month deployment to Afghanistan	536	Lower back Ankle and foot Head and neck Upper back Knee Shoulder Hand/wrist Elbow Hip	32 19 12 10 8 8 7 3 1
Schram et al. 2019	Australian Defence Force Regular Force and Reserves	Retrospective cohort study determining rates and patterns of injuries during basic training	6 082 (1 385 injuries)	Knee (minor injuries) Ankle and lower leg	27.6 21.8
Schwartz et al. 2018	Israeli Defence Force Commanders Training	Cross-sectional study of soldiers participating in commanders training	2 3842	Ankle (and calf) Knee Lower back Foot Wrist and hand Shoulder Pelvis	34 21 21 8 7 7 2

Study	Population	Study design	Participants (n)	Injury Site	Percentage Injured
Wilkinson et al. 2011	British Army infantry soldiers	Cohort study using questionnaire and training records during pre-deployment training	660	Knee Ankle Lower back	19 15 14

US – United States

2.3.2 Ankle

In a study by Neves et al. (2017) investigating musculoskeletal injuries in Brazilian and Columbian military students, the ankle joint was the anatomical site with the highest incidence of injury. Similarly, Schwartz et al. (2018) found the most frequent injury site in the Israeli Defence Force’s Commanders Training, to be the ankle joint. Havenetidis et al. (2011) reported 75.9% of musculoskeletal injuries among Greek Army Officer Cadets were to the lower extremities with the ankle and foot having the highest prevalence of injury. A snapshot of New Zealand Defence Force lower limb injuries from 2002-2003 Davidson et al. (2008) reported the largest number of lower limb injuries were at the ankle (37.1%), with the NZA having the highest number of ankle injuries.

Additional research has also highlighted that the ankle joint is one of the most common injury sites in military populations (Table 1.2) as reported by Andersen et al. (2016), Frilander et al. (2012) and Sammito et al. (2016). These authors attribute these injuries to challenging training programmes and other physical activities of military training and operations. Almeida et al. (1999) found the most frequent site of injury in US Marine Corps recruit training was the ankle/foot region (34.3% of injuries), followed by the knee (28.1%), and interestingly the most commonly diagnosed injury was ankle sprains. Similarly, Billings (2004) found the ankle joint to be the site most commonly injured during the US Air Force Academy basic cadet training programme. A study by Roy et al. (2015) reported that musculoskeletal injuries are the most common cause of ambulatory visits in the deployed setting, with the foot and ankle being one of the most common injury sites.

2.4 Causes of Musculoskeletal Injuries

2.4.1 Physical Training

When investigating ankle injuries, ankle sprains are most common within military Populations (Davidson et al., 2008; Lauder et al., 2000; Milgrom et al., 1991; Strowbridge & Burgess, 2002). Furthermore, according to earlier studies (Davidson et al., 2008; Lauder et al., 2000; Strowbridge & Burgess, 2002), most ankle sprains reported within military personnel were a result of participation in organized and recreational sports, exercise, and physical training. A high rate of sport, exercise, and physical training related ankle sprains among US Armed Services were documented by Cameron et al., (2010) with similar causes of high rates of ankle sprains found in the British Army (Strowbridge & Burgess, 2002) and New Zealand Defence Force (Davidson et al., 2008) populations.

Lauder et al. (2000) found that ankle sprains specifically, were second only to knee injuries among hospital admissions for sport and physical training related injuries between 1989 and 1994 in the US Army. Ankle sprains were noted as the most prevalent injury related to physical training among men in the US Army, accounting for 35% of all lower extremity injuries, and the third most prevalent injury (of all injuries) during Basic Combat Training (Jones et al., 1993). Similarly, Almeida et al. (1999) studied musculoskeletal injury rates among men and women during US Marine recruit training which includes training to improve aerobic fitness, muscle endurance and strength through running, resistance training, battle training and loaded marches, and discovered that ankle sprain was the second most commonly reported injury. Even during combat operations whereby soldiers are required to work, shoot and rapidly move, often in extreme environments in undulating terrain, physical training and sport related injuries were found to be the leading causes of medical evacuations from the theatres of operations (Hauret et al., 2010).

2.4.2 Running

As reported above, and by Lauder et al. (2000), when investigating acute musculoskeletal injury hospitalizations, many of these injuries occur during physical training and sports. In particular, running appears to be a high-risk associated activity. Lovalekar et al. (2016) found when examining data about injury cause and activity in an US Army Air Assault Division, that the most frequent cause of injury was running, and the most frequent activity that subjects were participating in when injury occurred was physical training. In a survey of exercise and sports-related injuries in the military Hauret et al. (2015) found military servicemembers made almost two million medical visits for injuries in one year. Half of those injuries were lower extremity overuse injuries such as those commonly resulting from running and other weightbearing physical activities. They reported running to be the leading injury related activity accounting for 45% of all sport and exercise related injuries. When comparing injuries and risk factors in infantry, artillery, construction engineers and Special Forces soldiers, Reynolds et al. (2009) found over half of the injuries were associated with running.

Davidson et al. (2008) found the most common individual activity associated with ankle injury in the New Zealand Army was cross-country jogging/running. Similarly, when describing the epidemiology of musculoskeletal injuries among soldiers of the USA 101st Airborne Division, Lovalekar et al. (2016) found running and physical training to be a common cause for ankle sprains. In the Israel Defence Forces' combat training units, approximately half of all injuries occurred during or as a result of running (Schwartz et al., 2018). When investigating the incidence of injury in US Army Light Infantry Soldiers, Smith and Cashman (2002) found 60% of all lower limb injuries occurred during physical training and 30% of those were linked to running.

2.4.3 Boots

Footwear can lead to injury as it may have a significant effect on gait and task performance (Andersen et al., 2016) and the military boot has been blamed for overuse injuries in military populations (Heir, 1998). Andersen et al. (2016) suggested that the shaft of the military boots being worn and the running shoes used during physical training may not be providing sufficient support to the ankle (Figure 2.1).

The military boot is designed to protect the ankle and foot. Characteristics of military boots include stiffness and thickness of the boot sole (Cikajlo & Matjačić, 2007), a boot shaft height and stiffness (Bohm & Hosl, 2010). These provide protection to the foot and ankle and include control of medio-lateral foot motion (Hamill & Bensel, 1992; Hamill & Bensel, 1996). A specific protective mechanism of the military boot shaft height and stiffness is to improve the acute effects on balance performance when being worn (Chander et al., 2014; Chander et al., 2015). These properties are important for military personnel as they provide protection from environmental hazards such as uneven surfaces and sharp penetrating objects and for sustaining human performance by providing support and stability to the ankle (Garner et al., 2013). However, the boot shaft has two competing design limitations, it must be rigid enough to support the ankle joint, at the same time being flexible enough to allow adequate range of motion to achieve sufficient propulsion (Bohm & Hosl, 2010). Small changes in ankle range of movement such as ankle dorsiflexion can have a significant effect on Achilles tendon strain and therefore lead to injury occurrence (Dixon et al., 2003). Furthermore, the boot characteristics also affect the neuromuscular activation of the lower extremity (Hill et al., 2017) and similarly Fu et al., (2014) found support above the ankle joint decreases ankle muscle activation when performing landing tasks.

The military boot has been blamed for overuse injuries (Jones, 1983) and in a study investigating the epidemiology of musculoskeletal injuries among Norwegian conscripts undergoing basic military training, most injuries were associated with ordinary military activities wearing military boots (Heir & Glomsaker, 1996). Soldiers traditionally wear high-top military boots to provide stability to the ankle joint while performing high-risk training activities (Milgrom et al., 1991). Military boots are designed to protect the foot and ankle (Kaufman et al., 2000). However, footwear such as the military boot can have a significant influence on gait by restriction the range of motion of the foot and ankle joint (Bohm & Hosl, 2010; Hamill & Bensel, 1996). This restriction of movement can lead to an increase in loading of the ankle, knee and hip (Arndt et al., 2003; Bohm & Hosl, 2010). In a review regarding musculoskeletal lower limb injury risk in army populations, Andersen et al. (2016) state that footwear can have a significant effect on gait and performance tasks which can lead to injury.

Figure 2.1. Diagram of a military boot

2.5 Interventions

2.5.1 Bracing

External ergonomic aids, including braces and orthotics, have been used as a means to reduce musculoskeletal injuries (Knapik et al., 2008; Verhagen et al., 2001). The purpose of bracing and taping is to support the ankle joint by providing external mechanical restriction to large range of movements that would result in ankle sprain, and possibly by increasing the activation of the supporting joint muscles, which would reduce the stress on the ligaments keeping the joint together (Hume & Gerrard, 1998). When investigating the use of orthotic devices in the treatment of ankle sprains, Scheuffelen et al. (1993) found an external ankle support should protect against extreme inversion amplitudes if the risk of injury is to be reduced. A variety of ankle braces exist as a means to protect ankle joints from injury by restricting range of movement. These include soft braces, semi-rigid braces and rigid braces, with each having a different effect on the ankle joint (Maeda et al., 2016).

Based on systematic reviews regarding injury prevention in the military, Bullock et al. (2010) recommended the use of semi-rigid ankle braces during high-risk activities and ankle bracing was determined to be an effective intervention of reducing ankle sprain, fracture and injury incidence during military parachuting by Knapik et al. (2008). Janssen et al., (2014) studied male and female athletes who had suffered a recent lateral ankle sprain and found bracing to be more effective than neuromuscular conditioning exercises for preventing recurrent ankle injuries. Although the precise mechanism of ankle braces is yet to be determined, studies have found a reduced incidence of ankle sprains by using an ankle brace (Surve et al., 1994; Tropp et al., 1985). These findings suggest that wearing ankle braces for high-risk activities such as parachuting and/or following ankle injury can protect against sustaining new or recurrent ankle injuries (Wardle, 2017). However, in a review of the effectiveness of external ankle supports Dizon and Reyes (2010) concluded that wearing an ankle brace or using prophylactic ankle taping appeared to be beneficial for previously injured recreational and elite adolescent and adult athletes from various sports, but <u>not</u> effective for non-injured players. In a review of the effectiveness of external ankle support, Hume and Gerrard (1998) concluded that there was either no effect, or a decrease in the performance of a variety of movement tasks with the use of some types of external supports. They also reported little information was available on how external support worked to reduce injury. Interestingly, when investigating the effect of ankle bracing on athletic performance, Bot and Van Mechelen (1999) found ankle braces may influence ankle musculature and ligament function when used over long periods and consequently influence athletic performance in a negative way.

2.5.2 Orthotics

Orthotics inserted into footwear are frequently used as an intervention strategy in the military to reduce risk of injury (Baxter et al., 2012). Pathologies such as plantar fasciitis, shin splints and non-specific knee pain may result from abnormal mechanics of the foot and ankle, and are frequently treated with foot orthoses (Hume et al., 2008). Foot orthoses are considered a biomechanical treatment modality for prevention and/or rehabilitation of foot and ankle injuries to re-establish the normal biomechanics of the foot and ankle (Duddy et al., 1989). Foot orthoses are also used in the military setting to protect the foot from direct impacts and unpredictable ground conditions by manipulating the cushioning and support provided by the boot by the addition of an insole or a supportive orthotic device (Dixon, 2007; Milgrom et al., 1992).

In a study by Franklyn-Miller et al. (2011) investigating the use of foot orthoses during military training, newly enlisted officer cadets were randomized to receive or not receive customized orthoses according to gait related and biomechanical risk as assessed by means of pressure plate recording of their contact foot pressures during walking. This study revealed some preliminary evidence as a result of the prescription of orthoses based on the biomechanical assessments of gait which had an effect in reducing lower limb overuse injuries in male and female Naval Officers. In terms of injury prevention, there has been much discussion over the use of shock-absorbing insoles. Withnall et al., (2006) performed a large randomized controlled trial comparing various types of insoles to injury over initial military training and found no difference in injury rate among any of the cohorts. This finding was similar to earlier work comparing orthotic prescription with simple insoles in the prevention of stress fractures (Finestone et al., 1999), and results suggested that non-custom insoles have little role in injury prevention. In a review of the use of foot orthoses in lower limb overuse conditions, Richter et al. (2011) supported the use of foot orthoses to prevent a first occurrence of lower limb overuse conditions. However, evidence was insufficient to recommend foot orthoses for the treatment of lower limb overuse conditions. The literature does not support the custom casting for orthoses in injury treatment or prevention, finding little difference in prefabricated and custom-modelled orthoses (Finestone et al., 2004; Pfeffer et al., 1999). Baxter et al. (2012) determined no strong conclusions can be made on the use of orthotics as a preventive measure for overuse injury in the military. This is supported by a study investigating the effectiveness of foot orthoses for treatment and prevention of lower limb injuries by Hume et al. (2008), who stated further research with randomized controlled trials is needed to establish the clinical use of particular types of foot orthoses (i.e. rigid, semi-rigid, soft) for treatment and prevention of various lower limb injuries.

2.5.3 Training Strategies

Training strategies such as neuromuscular warm-up, which incorporate stretching, strengthening and balance exercises, sports-specific agility drills and landing techniques, have been proposed to provide the greatest potential for reduced lower limb injury rates and should be completed for a duration of longer than three consecutive months (Herman et al., 2012). Training programs that improve muscle control around the ankle joint should allow more effective responses to perturbations, thus reducing ligament loading and the likelihood of injury. These training programs, which Davidson et al. (2009) termed "stability training", include unipedal balancing exercises and exercises conducted while standing on an unstable base. This intervention was recommended by Davidson et al. (2009) for a military setting, however they did acknowledge that logistic and effectiveness issues such as the duration of training programmes, extreme levels of activity and a range of climate and terrain conditions, needed to be resolved before adoption by military forces. A study by Peck et al. (2017) demonstrated that preventive training programs can decrease injury rates in military recruits. They also acknowledged that the logistics of implementing these programs outside of the research setting can be challenging. Peck et al. (2017) implemented a 10 to 12-minute lower extremity preventive training programme in a controlled, structured environment with highly motivated individuals and program leadership. The interventions were scheduled at regular intervals and the military setting ensured compliance. The results of the study showed that a 10 to 12-minute lower extremity preventive training program can be implemented in a large-scale military setting without having an adverse effect on fitness measures. However, they did acknowledge that in the military setting, it is sometimes hard to achieve buy-in from commanders and other decision makers.

Recent studies have provided evidence that preventive interventions involving balance and agility training are effective in decreasing injuries to the lower limb, and particularly to the knee and ankle, in specific sports (Bahr et al., 997; Caraffa et al., 1996; Verhagen et al., 2004). The consensus from these studies is that balance and agility training improves motor control by refining muscle synergy, meaning improved co-activation of muscles recruited and thus improving the accuracy of lower limb movement prior to and during dynamic activity (Goodall et al., 2013). Goodall et al. (2013) stated that the specific balance or agility training interventions used by researchers varied, but generally included various balance activities and sport specific agility sequences. However, based on an earlier comprehensive literature review, Hrysomallis (2007) cautioned that, although there is evidence that balance training can reduce the risk of ankle and knee ligament injury, it has sometimes increased the risk of overuse and other significant knee injuries and it is more effective in preventing recurring of ankle injuries than in primary prevention of injuries. This can be illustrated by a randomised controlled trial of where 1020 soldiers underwent a concurrent 12-week training programme (Brushoj et al., 2008). The programme was not effective in reducing the incidence of overall injury incidence in soldiers undergoing an increase in activity level, the possibility is that that the simultaneous start of the intervention combined with the rapid increase in the expected load of military training could be a reason why the intervention did not succeed in the prevention of injuries.

When considering training interventions in an attempt to prevent knee, ankle or other lower limb injuries for military populations it is suggested that caution should be applied when adding balance and agility training to already intensive training programmes (Goodall et al., 2013). This was illustrated by a cluster-randomised controlled trial investigating a structured balance and agility training programme added to normal recruit physical training which did not significantly reduce lower limb, knee and ankle, or knee and ankle ligament injury rates (Goodall et al., 2013). Attention to the overall duration of military training programmes is critical if balance and agility training is to be added.

2.5.4 Footwear

Footwear has been identified as having an effect on lower limb injuries in military populations (Andersen et al., 2016). Most of the interventions regarding military boots have focused on poor shock absorption of the boot sole and the role thereof in injury prevention (Dixon et al., 2003; Hamill & Bensel, 1992; Hamill & Bensel, 1996; Kaufman et al., 2000; Williams, 1997). However, a study by Harman (1999) found no evidence of a lack of shock absorption when inspecting ground reaction forces in military boots. Shock absorption is only one factor to consider, military footwear should provide good support to minimize ankle sprains while also providing good shock absorption to minimize overuse injuries (Kaufman et al., 2000). Other considerations of ankle injury prevention such as additional support provided by the height and stiffness of the military boot shaft have been discussed in section 2.4.3.

2.6 Ankle Joint Function

2.6.1 Introduction

The ankle joint and its complementing structures allow it and the foot to sustain large weight-bearing stresses and enable these to be transmitted up the long-bones of the leg under a variety of surfaces and activities that maximise stability and motion. The ankle joint forms the kinetic linkage allowing the lower limb to interact with the ground, a key requirement for gait and other activities of daily living (Brockett & Chapman, 2016). The ankle and foot must meet the stability demands of providing a stable base of support for the body in a variety of weight-bearing postures without excessive muscular activity and energy expenditure, and act as a rigid lever for active push-off during gait (Levangie, 2005). The stability requirements can be contrasted to the mobility demands of reducing rotations imposed by the more proximal joints of the lower limbs, being flexible enough to absorb the shock of the overlaid body weight as the foot hits the ground, and permitting the foot to conform to a wide range of changing and varied terrain (Morris, 1977). The three major contributors to the stability of the ankle joints are (1) the congruity of the articular surfaces when the joints are loaded, (2) the static ligamentous restraints, and (3) the musculotendinous units, which allow for dynamic stabilization of the joints (Hertel, 2002).

2.6.2 Articulation

The ankle joint is formed from three articulations (Figure 2.2): the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis. These three joints work together to permit coordinated movement of the rear foot. Rear foot motion is usually outlined as occurring within the cardinal planes as follows: sagittal-plane motion (plantar flexion-dorsiflexion), frontal-plane motion (inversion-eversion), and transverse-plane motion (internal rotation-external rotation) (Huson, 1987). Rear foot motion, however, does not occur in isolation within the individual planes; instead, coordinated movement of the three joints permits the rear foot to manoeuvre as a unit around an axis of rotation oblique to the long axis of the lower leg. Rear foot motion does not occur strictly within the cardinal planes because of the talocrural and subtalar joints each having oblique axes of rotation. Coupled rear foot motion is best characterized as pronation and supination (Hertel, 2002). Within the open kinetic chain, pronation consists of dorsiflexion, eversion, and external rotation, whereas supination consists of plantar flexion, inversion, and internal rotation (Rockar Jr, 1995). Within the closed kinetic chain, pronation consists of plantar flexion, eversion, and external rotation, while supination consists of dorsiflexion, inversion, and internal rotation (Rockar Jr, 1995).

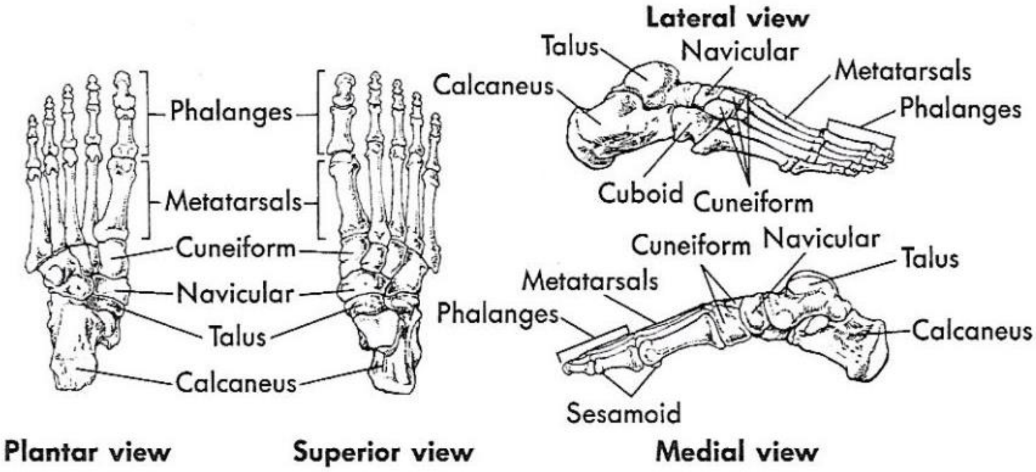


Figure 2.2. Articulating bones of the ankle joint (Source Hall, 1999. Reproduced with permission from McGraw Hill)

The talocrural, or tibiotalar joint is made up by the articulation of the dome of the talus, the medial malleolus, the tibial plafond, and the lateral malleolus. The form of the talocrural joint permits force to be transmitted from the lower leg (internal and external rotation) to the foot (pronation and supination) throughout weight bearing. This joint is usually referred to as the ‘‘mortise’’ joint and, in isolation, could also be thought of as a hinge joint that enables the motions of plantar flexion and dorsiflexion (Hertel, 2002). The axis of rotation of the talocrural joint passes through the medial and lateral malleoli. It is slightly anterior to the frontal plane since it passes through the tibia and somewhat posteriorly to the frontal plane as it passes through fibula. Isolated movement of the talocrural joint is primarily in the sagittal plane; however, small amounts of transverse- and frontal plane motion additionally occurs about the oblique axis of rotation (Lundberg et al., 1989).

The articulations between the talus and the calcaneus create the subtalar joint and, like the talocrural joint, it converts torque between the lower leg (internal and external rotation) and also the foot (pronation and supination). The subtalar joint permits pronation and supination movement and consists of an intricate structure with two separate joint cavities. The posterior subtalar joint is formed between the inferior posterior facet of the talus and the superior posterior facet of the calcaneus (Rockar Jr, 1995). The anterior subtalar joint is formed from the head of the talus, the anterior-superior facets, the sustentaculum tali of the calcaneus, and the concave proximal surface of the tarsal navicular (Hertel, 2002). This articulation is similar to a ball-and-socket joint, with the talar head being the ball and the anterior calcaneal and proximal navicular surfaces forming the socket in conjunction with the calcaneus and plantar calcaneonavicular ligament (spring ligament) (Perry, 1983). Considerable individual variation in the architecture of the anterior subtalar joint has been reported (Viladot et al., 1984).

2.6.3 Ligaments

The talocrural joint receives ligamentous support from a joint capsule and several ligaments (Figure 2.3), including the anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL), calcaneofibular ligament (CFL), and deltoid ligament. The ATFL, PTFL, and CFL support the lateral aspect of the ankle, while the deltoid ligament provides medial support (Hertel, 2002).

The ligaments of the subtalar joint include the CFL and lateral talocalcaneal (LTCL) and fibulotalocalcaneal (FTCL) ligaments. The CFL is essential in preventing excessive inversion and internal rotation of the calcaneus relative to the talus (Hølmer et al., 1994; Stephens & Sammarco, 1992). Though the CFL does not usually connect the calcaneus to the talus, various attachments of the anterior aspect of the CFL to the talus have been reported (Harper, 1991).

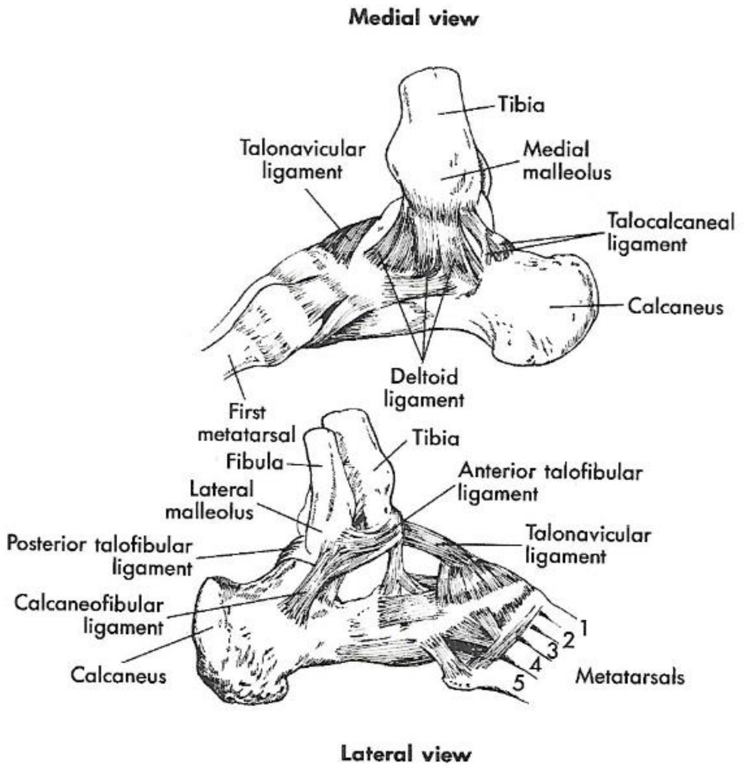


Figure 2.3. Ligaments of the ankle joint (Source Hall, 1999. Reproduced with permission from McGraw Hill)

The distal articulation between the tibia and fibula forms the third joint of the ankle complex. This joint is a syndesmosis that permits limited movement between the two bones; however, accessory gliding at this joint is crucial to standard mechanics throughout the entire ankle complex (Mulligan, 1995). The joint is stabilized by a thick interosseous membrane and the anterior and posterior inferior tibiofibular ligaments. The structural integrity of the syndesmosis is essential to form the stable roof for the mortise of the talocrural joint (Hertel, 2002). The anterior inferior tibiofibular ligament is frequently injured in combination with eversion injuries, and damage results in the so-called high ankle sprain rather than the more common lateral ankle sprain (Miller et al., 1995).

The medial ankle ligament includes four superficial components, the tibiospring (TSL), tibionavicular (TNL), superficial posterior tibiotalar (STTL), and tibiocalcaneal ligament (TCL), of these only the TSL and the TNL are constant i.e., they do not form components of other ankle ligament structures (Milner & Soames, 1998). Two deep ligament components exist, these are a deep posterior tibiotalar ligament (PTTL) and a deep anterior tibiotalar ligament (ATTL), of which only the PTTL is constant (Milner & Soames, 1998). The medial ankle ligaments are important stabilizers not only against valgus forces but also against rotational forces and their insufficiency may lead to degenerative joint disease in the ankle (Boss & Hintermann, 2002).

The LTCL runs parallel and anterior to the CFL but only crosses the posterior subtalar joint (Hertel, 2002). While the LTCL is weaker and smaller than the CFL, it helps prevent excessive supination of the subtalar joint (Burks & Morgan, 1994; Stephens & Sammarco, 1992). Several shapes of the LTCL have been described, and occasionally its fibers are continuous with those of the CFL (Burks & Morgan, 1994; Harper, 1991). The FTCL runs from the posterior surface of the lateral malleolus to the posterolateral surface of the talus and then to the posterolateral calcaneus, it assists in resisting excessive supination and lies distinctly posterior to the CFL (Hertel, 2002).

In summary: the axis of rotation at the ankle joint is essentially frontal, and motion at the joint occurs primarily in the sagittal plane and functions as a hinge joint during the stance phase of gait (Hall, 1999). There are three movements at the ankle joint, plantarflexion/dorsiflexion, inversion/eversion, and abduction/adduction, with the primary movements of the ankle joint being dorsiflexion and plantarflexion (Levangie, 2005). Pronation and supination occur in the foot and are terms used to describe movement about an axis resulting from “coupled” movements e.g., pronation is movement about an axis resulting from coupled movements of dorsiflexion, eversion, and abduction. Supination is a movement about an axis resulting from coupled movements of plantarflexion, inversion, and adduction (Levangie, 2005).

2.6.4 Ankle Ligament Injuries

In most cases of ankle injury, there is an order of ligament injury, the anterior talofibular (ATFL) is injured first as a result of its positioning at the instant of loading in inversion and its inherent weakness (Siegler et al., 1988). When the ankle assumes a plantar flexed position, the ATFL aligns with the fibula and functions as a collateral ligament, this alignment with the ATFL’s relative weakness, predisposes it to injury (Whiting, 2008). In terms of order of injury, the calcaneofibular (CFL) is injured next (Hertel, 2002; Whiting, 2008), followed by injury to the posterior talofibular ligament (PTFL) (Whiting, 2008). The PTFL is usually only injured in severe ankle sprains where the both the ATFL and CFL have been ruptured prior to tearing of the PTFL as the injury continues around the lateral aspect of the ankle (Renström and Lynch, 1998). PTFL injury is frequently accompanied by fractures or dislocations or both (Hertel, 2002). Simultaneous damage to the talocrural joint capsule and the ligamentous stabilizers of the subtalar joint is also common with lateral ankle sprains (Hertel, 2002).

2.6.5 Neuromuscular Function

The majority of movement produced by the foot and ankle is brought about by the twelve extrinsic muscles originating within the leg and insert in the foot (Figure 2.4). These muscles are contained in four compartments; the anterior compartment, the lateral compartment, the posterior compartment and the deep posterior compartment

(Brockett & Chapman, 2016). The tibialis anterior, the extensor digitorum longus, the extensor hallucis longus, and the peroneus tertius form part of the anterior compartment. Dorsiflexion and inversion of the foot are produced by the tibialis anterior and the extensor hallucis longus, whereas dorsiflexion and eversion of the foot are produced by the peroneus tertius. The extensor digitorum longus only produces dorsiflexion of the foot. The peroneus longus and the peroneus brevis are the two muscles of the lateral compartment and they produce plantarflexion and eversion of the foot. Three muscles make up the posterior compartment, they are the gastrocnemius, the soleus, and the plantaris. These three muscles contribute to plantarflexion of the foot. The deep posterior compartment is composed of three muscles: the tibialis posterior, the flexor digitorum longus, and the flexor hallucis longus, which produce plantarflexion and inversion of the foot (Procter & Paul, 1982).

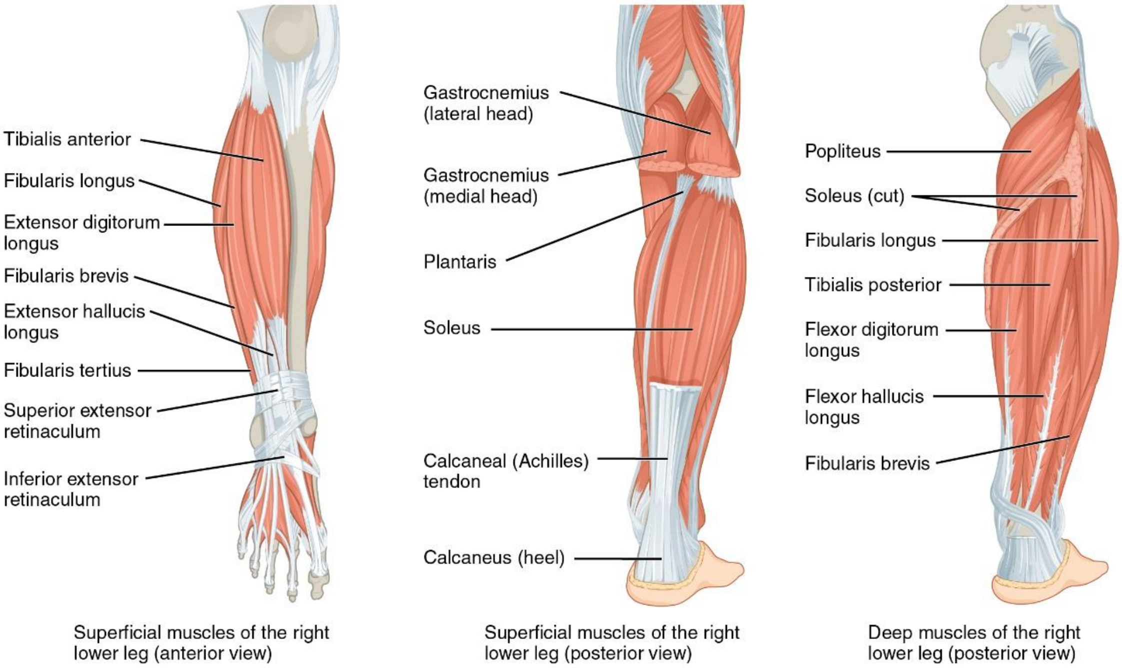


Figure 2.4. Muscles of the lower leg (Source Shutterstock, 2019)

The motor and sensory supplies to the ankle complex stem from the lumbar and sacral plexes whereas the motor supply to the muscles comes from the tibial, deep peroneal, and superficial peroneal nerves (Hertel, 2002). These three mixed nerves and two sensory nerves, the sural and saphenous nerves, are responsible for sensory supply. Mechanoreceptors that contribute to proprioception have been shown to extensively innervate the lateral ligaments and joint capsule of the talocrural and subtalar joints (Michelson & Hutchins, 1995). The sensory output from ligaments aids in controlling muscle stiffness and co-ordination around a joint, thereby increasing stability. It may well be that mechanoreceptor-mediated joint proprioception acts by influencing muscle length or tension or by both these mechanisms (Michelson & Hutchins, 1995). Khin-Myo-Hla et al., (1999) suggested that ankle stability is dependent on an intact reflex mechanism modulated by sensory afferents. The reaction time of the peroneal muscles is also thought to involve the stretch reflex of these muscles (Khin-Myo-Hla et al., 1999). The mechanism of the stretch reflex is that stimulation of stretch receptors, called muscle spindles, is carried through afferent fibres directly to the alpha motor neurons in the spinal cord, then returns to the muscle through the efferent motor nerve and contracts the muscle (Khin-Myo-Hla et al., 1999). Excitation of gamma motor neurons in the spinal cord contracts the muscle spindles. These contractions bring down the threshold of stretch receptors, and the receptors become more alert. The mechanism is called the gamma-muscle-spindle system (Khin-Myo-Hla et al., 1999). Hertel (2002) describes the muscle spindles of the peroneal muscles as being of major importance to proprioception about the ankle complex.

Neuromuscular control is an important factor of joint stability and a contributing aspect is the strength of the muscles acting on the joint (Blackburn et al., 2000). Additionally, eccentric strength augments joint stability by providing antagonistic resistance to joint translation, and therefore a stronger muscle or muscle group has a heightened ability to promote joint stability (Blackburn et al., 2000). Consequently, proprioception and muscular strength play crucial roles in modifying balance by way of neuromuscular control (Blackburn et al., 2000). This is worth noting as Bok et al. (2013) suggested that static balance may be related to plantarflexor strength, more than dorsiflexor strength, when examining the effects of changes in ankle strength and range of motion on balance. They further found it was not only strength of muscles, but also joint movement that influenced maintenance of balance. Similarly, Horak et al. (1997) reported that when the body is first exposed to gravity or external forces, ankle strength and flexibility are required. Interestingly, when investigating the effects of ankle immobilisation on plantarflexion strength, balance and walking Caplan et al. (2015) found plantarflexor strength was reduced and subsequently balance performance was impaired immediately after the removal of a cast immobilising the ankle joint. Furthermore, they found plantarfexion torque was reduced by almost one-quarter after only seven days of immobilisation as a result of a shortening of the plantarflexor muscle fibres in series, which would reduce the stretch-reflex involvement in muscle activity normally seen during the walking gait cycle and could contribute to a possible reduction in muscle-spindle excitability.

2.6.6 Range of Motion

Motion of the ankle joint occurs mainly in the sagittal plane, with plantar- and dorsiflexion occurring largely at the tibiotalar joint (Brockett & Chapman, 2016). Studies by Grimston et al. (1993) and Stauffer et al. (1977) indicate a total range of motion (ROM) in the sagittal plane of between 65˚ and 75˚, moving from 10˚ to 20˚ of dorsiflexion through to 40˚ to 55˚ of plantarflexion. In the frontal plane the total range of motion is approximately 35˚ (23˚ inversion and 12˚ eversion) (Stauffer et al., 1977). When investigating a kinematic model of the ankle joint, Dul and Johnson (1985) defined movement of the ankle joint as primarily plantarflexion/dorsiflexion with the maximum range of motion being 45˚, more or less equally divided between plantarflexion and dorsiflexion. This differs from an earlier study examining the normal range motion of joints in male subjects completed by Boone and Azen (1979), where average plantarflexion was found to be 54.3˚ and dorsiflexion 12.2˚ in males above the age of 19. Similar results were reported in a study of range of motion measurements in healthy individuals by Soucie et al. (2011), where ankle plantarflexion was found to be 54.6˚ and dorsiflexion 12.7˚ in male subjects aged 20 – 44. A study by McKay et al. (2017) to establish reference values for flexibility of joint movements in healthy male and female population groups found similar measurements of 56˚ for plantarflexion in male subjects aged 20 – 59 years, however they found dorsiflexion to be 32˚ in this age group. The American College of Sports Medicine's (ACSM) (*ACSM's Resource Manual for Guidelines for Exercise Testing and Prescription*, 2013) normative range of plantarflexion is 45˚ and dorsiflexion is 15˚. When considering the variation in ranges of plantarflexion and dorsiflexion presented above it would be in agreement with Levangie (2005) who reported normal ankle joint ranges of movement to be 10˚ to 20˚ for dorsiflexion and 20˚ to 50˚ for plantarflexion.

The subtalar joint contributes to inversion/eversion (Rodgers, 1995) with Brukner and Khan (2009) reporting the amount of inversion being approximately 20˚ and eversion approximately 10˚. However, in a review of dynamic foot biomechanics Rodgers (1995) reported a range of 5˚ to 50˚ for inversion and 5˚ to 26˚ for eversion. Dul and Johnson (1985) were more specific and reported the average range of inversion to be 20˚ to 25˚ and eversion to be 5˚, while Boone and Azen (1979) reported the normal range of inversion and eversion in males between 25 and 59 years old to be 36˚ and 19˚ respectively. The American College of Sports Medicine (ACSM) report similar normative values for inversion, 30˚ to 35˚ and 15˚ to 20˚ for eversion (*ACSM's Resource Manual for Guidelines for Exercise Testing and Prescription*, 2013). When describing the distribution variables of ankle complex motion in uninjured ankles in order to establish normative reference values for use, Schwarz et al. (2011) found inversion to be 20.5˚ and eversion 13.6˚ for males ranging from 19 to 25 years old. A reason for the variations in normative values for inversion and eversion could be due to sample size, range of subject age and inconsistent methodology in measuring joint range of motion (Soucie et al., 2011). According to Levangie (2005), there are large variations in degrees of ankle movement due to differences in measurement techniques, subject populations and which joints are included in measurements, for example, if the foot is included in the ankle joint.

Excessive supination of the rear foot about an externally rotated lower leg soon after initial contact of the rear foot, also described as forced plantar-flexion and inversion as the body’s centre of mass moves over the joint during gait or landing from a jump, are the most common causes of lateral ankle sprains (Bahr & Krosshaug, 2005; Davidson et al., 2008). Excessive inversion and internal rotation of the rear foot, coupled with external rotation of the lower leg, results in strain to the lateral ankle ligaments. If the strain in any of the ligaments exceeds the tensile strength of the tissues, ligamentous damage occurs (Hertel, 2002). Increased plantar flexion at initial contact appears to increase the likelihood of suffering a lateral ankle sprain (Wright et al., 2000), and lateral ankle sprains (also referred to as inversion sprains) in particular, have been acknowledged as one of the most common injuries in military populations (Milgrom et al., 1991).

The structural response of connective tissues, the viscoelastic properties of ligaments and nerves, plus the level of proprioception and strength, all possibly affect the stability of joints and their susceptibility to injury. It is the proportion of these individual components that will determine the range of motion of a joint, while the degree of resistance of ligaments and muscle to force will determine if an ankle sprain will occur (Hume et al., 2008). Joints are in part predisposed to injury due to the degree of flexibility and strength of muscles surrounding it. The joint function is controlled by the central and peripheral nervous systems which includes the muscle stretch reflex, which is a joint protective mechanism to prevent excessive range of motion (Hume et al., 2008). Pre-activation of muscle pairs about the joint (coactivation) is also a protective mechanism of the ankle joint. Without muscle pre-activation, sudden inversion relies on the strength of the ligaments and the anatomical alignment, as the muscle reflex time is too long to prevent excessive inversion (Hume et al., 2008). Ligaments surrounding the ankle joint have a restrictive function on the allowable range of motion directions of the joint, and when forced to limit abnormal motion occurring around a joint, the ligaments do not function well (Hume et al., 2008).

Decreased range of motion has been identified as a significant intrinsic risk factor for ankle sprain (de Noronha et al., 2006; Hadzic et al., 2009; Pope et al., 1998; Willems et al., 2005). Intrinsic risk factors are those related to the individual characteristics of a person such as age, height, gender, flexibility, strength, postural stability, etc. (Waterman et al., 2010; Willems et al., 2005), whereas extrinsic risk factors relate to environmental factors such as physical activity, footwear, playing field conditions, amount of training and more (Waterman et al., 2010; Willems et al., 2005).

When investigating the effects of ankle range of motion on injury risk in army recruits, Pope et al. (1998) found ankle dorsiflexion range of motion to be a significant predictor of the risk of suffering an ankle sprain. They found poor flexibility in the ankle joint was associated with 2.5 times the risk of injury associated with average flexibility. This calls to attention further research that also indicates a decreased range of ankle dorsiflexion to be a predictive factor of ankle sprain (de Noronha et al., 2006; Hadzic et al., 2009; Willems et al., 2005). Hadzic et al. (2009) suggested the decrease in range of motion was possibly due to a shortening of the gastrocnemius placing the foot in a position of greater plantarflexion in different physical activity tasks and consequently increasing the risk of inversion injury. A decrease in subtalar eversion range was also reported to be a predicter of injury risk by Baumhauer et al. (1995), however the importance of this outcome remains unclear as the strength of the association was not investigated. Nevertheless, Arakawa et al. (2013) found that when restricting ankle joint movement, a significant reduction in maximum power and work was noted, and a decrease in the maximum ankle flexion angles resulted in a significantly restricted mechanical output at the ankle. These results are reflected in an earlier statement by Ferguson (1973) that muscles lose strength because they are limited in the ranges that they can work.

Plantar flexion range of movement effects the ability of the plantarflexor muscle group to generate power during push-off (Cikajlo & Matjačić, 2007), which is a significant source of propulsion during gait on level surfaces in healthy human individuals (Requiao et al., 2005). This can be explained by the stretch shortening cycle where stretching of an activated muscle prior to its shortening enhances its performance during the concentric contraction. This was demonstrated by Bosco et al. (1982) when examining the series elastic elements of muscle during the stretch shortening cycle. Subjects performed maximal vertical jumps on a force platform from two different starting positions: maximal plantar flexion from a static position (pure concentric contraction), and a toe-standing position with preliminary counter-movement. In this condition, the calf muscles were actively stretched before concentric work. The results of the examination indicated that the utilization of the stretch-shortening cycle enhanced performance (Bosco et al., 1982). In a study investigating the stretch-shortening cycle during vertical jumps, Kopper et al. (2014) found increased range of ankle motion affects the magnitude and time of muscle stretch prior to shortening, and resulted in large muscle activation levels at the beginning of muscle shortening. This phenomenon has been interpreted to be primarily due to the utilisation of elastic energy stored in the series elastic elements of the muscle during the stretch (Bosco et al., 1982). The use of elastic energy can enhance muscle performance in the concentric phase if prior to shortening muscle stretch occurs (Kopper et al., 2014).

2.6.7 The Gait Cycle

The gait cycle is the period of time measured from initial contact of one foot to the next initial contact of the same foot (Rodgers, 1988). The gait cycle consists of two phases: the swing phase, which begins with toe-off and ends with heel strike, and the support phase, which begins with heel-strike and ends with toe-off (Hamilton et al., 2012). The swing phase provides for forward momentum of the leg as well as preparing and aligning the foot for heel strike and ensures that the swinging foot clears the floor (Rodgers, 1988). The propulsive period begins at the end of midstance when the heel leaves the ground and ends with toe off at the end of the stance phase (Kawalec, 2017). Stance comprises about 60% of the total gait cycle at freely chosen speeds and functions to allow weight-bearing and provide body stability. Five distinct events occur during the stance phase, which are described by Rodgers (1988) as: heel-strike, foot flat, mid-stance, heel rise, and toe-off.

The tibialis anterior muscle's major activity is at the end of swing to keep the foot in a dorsiflexed position (Rodgers, 1988). The tibialis anterior muscle peaks directly after heel-strike, and generates forces to lower the foot to the ground in opposition to the ground reaction forces effect on plantarflexion. At toe-off, a second burst of activity begins which results in dorsiflexion in order to clear the foot during mid-swing (Rodgers, 1988). According to Rodgers (1988), the extensor digitorum longus muscle has almost identical activity to the tibialis anterior muscle in its function to lower the foot after heel-strike and to dorsiflex the foot and toes for clearance during swing phase.

One major long-duration phase of activity is seen by the gastrocnemius and soleus muscles throughout the single-limb support period. This starts just before heel-strike and increases during stance, peaking just before mid-push-off (Rodgers, 1988). Peak activity in the plantarflexors is reached from heel-off to toe-off (Hamilton et al., 2012) as the calf muscles contract to actively plantar flex the foot and to generate an explosive push-off (Rodgers, 1988). The gait cycle is illustrated in Figure 2.5.

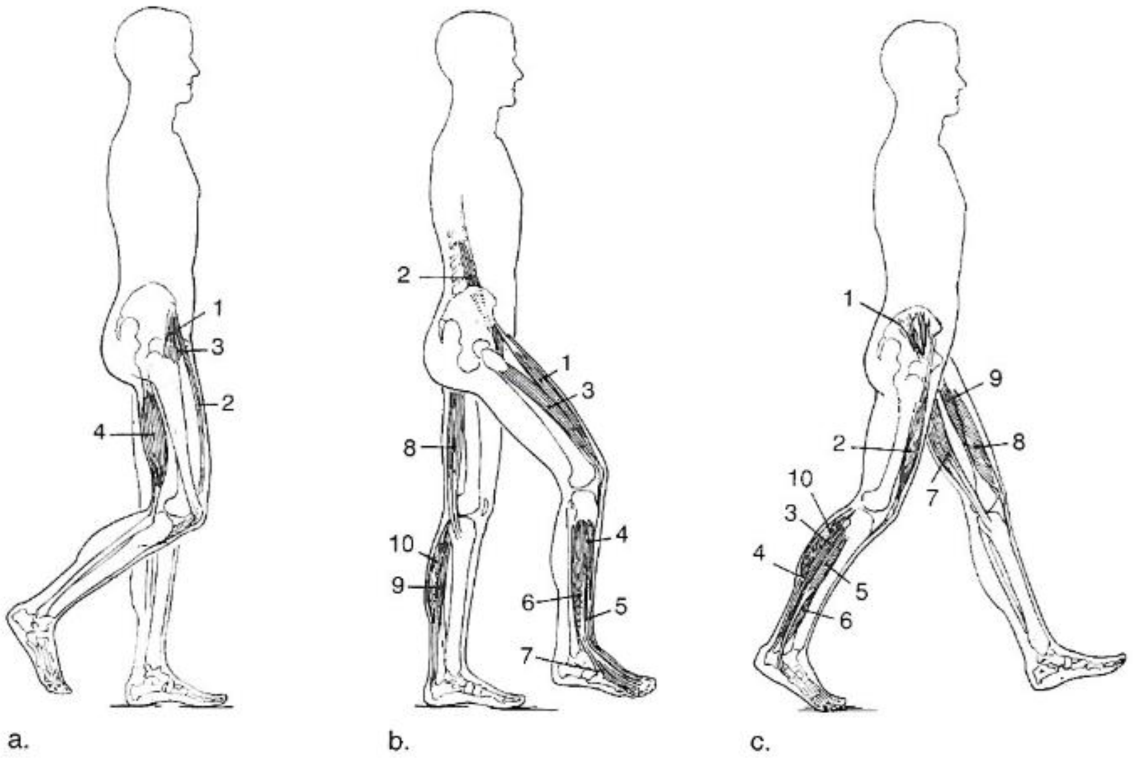


Figure 2.5. The muscles of the lower extremity used during gait. Key: a (start of swing phase):1. tensor fasciae latae; 2. sartorius; 3. pectineus; 4. biceps femoris. b (support phase and end of swing phase): 1. rectus femoris; 2. iliopsoas; 3. vastus lateralis (medius and intermedius are not shown); 4. tibialis anterior; 5. extensor hallucis longus; 6. extensor digitorum longus; 7. peroneus tertius; 8. semitendinosus and semimembranosus; 9. soleus; 10. gastrocnemius. c (toe off and heel strike): 1. gluteus medius; 2. rectus femoris; 3. soleus; 4. tibilis posterior (underneath); 5. peroneus longus; 6. peroneus brevis; 7. semitendinosus and semimembranosus; 8. vastus medialis and intermedius (lateralis not shown); 9. adductor longus; 10. gastrocnemius. (Source Hamilton et al., 2012. Reproduced with permission from McGraw Hill)

When investigating EMG during walking, Winter and Yack (1987) found muscle activity quickly drops until toe-off where low-level gastrocnemius activity continues into swing, this probably indicated the gastrocnemius acting as a knee flexor to cause adequate knee flexion before swing-through. They also found that the peroneus longus muscle has a small burst of activity during weight acceptance, appearing to stabilise the ankle (possibly as a co-contraction to the tibialis anterior muscle). A higher activity during push-off indicates the peroneus longus muscle functioning as a plantar flexor (Winter & Yack, 1987). During early swing, a low-level peroneus longus muscle activation is likely a co-contraction with the tibialis anterior muscle to control foot dorsiflexion and supination range of motion (Winter & Yack, 1987).

2.6.8 Balance

Balance is the process of maintaining the position of the body's centre of gravity vertically over the base of support and relies on rapid, continuous feedback from visual, vestibular and somatosensory structures and then executing smooth and coordinated neuromuscular actions (Nashner, 2014). Balance movements also involve motions of the ankle, knee, and hip joints, which are controlled by coordinated actions along the kinetic chain (Nashner, 2014).

An isolated muscle acts like a spring, inclined to resist attempts to stretch it beyond its resting length, the degree to which a muscle will resist the amount of stretch is called muscle stiffness (Nashner, 2014). The strength of the activation of the muscle will determine its resting length and stiffness, an inactivated muscle will have an extended rest length and will offer little resistance to stretching. The rest length of a highly active muscle is shorter, and the muscle vigorously resists stretching (Nashner, 2014).

When pairs of opposing muscles combine to exert forces about a joint the effect is to resist rotation of the joint relative to its resting position, the amount of resistance to rotation is called joint stiffness (Lark et al., 2003). The resting position and the stiffness of the joint are each changed independently by altering the activation levels of one or both muscles. According to Nashner (2014), joint resting position and joint stiffness are by themselves an inadequate basis for controlling postural movements. The reason given by Nashner (2014) was a result of the stiffness properties of muscle being highly nonlinear. When reviewing the regulation of stiffness in the skeletal system, Houk (1979) stated that resistance to small displacements during rest can be strong, however unless activation levels are increased resistance to larger displacements will break down.

The ability to maintain a base of support with minimal movement is known as static balance, whereas dynamic balance is the ability to perform a task while maintaining or regaining a stable position (Winter et al., 1990) or the ability to maintain or regain balance on an unstable surface (Paillard & Noé, 2006) with minimal non-essential motion (Hrysomallis, 2011). A number of different tests to assess static and dynamic balance and to examine the relationship between balance ability and physical performance are used. The predominant laboratory test for static balance is assessing the centre of pressure (COP) motion as a subject attempts to stand as quietly as possible on a force platform, unipedal or bipedal and with eyes open or closed for a specified period of time (Aalto et al., 1990; Asseman et al., 2008; Paillard et al., 2002). In Winter's *ABC (anatomy, biomechanics and control) of Balance during Standing and Walking* (1995), it is acknowledged that COP motion is not identical to centre of gravity motion, however, minimal COP motion indicates good balance (Hrysomallis, 2011) and COP measured from a force platform is usually considered the gold standard measure of balance (Clark et al., 2010). Counting the number of floor contacts in 30 seconds while performing a unipedal stance on a wobble board (Hrysomallis, 2011) and the Star Excursion Balance Test (SEBT) (Firth, 2016; Kanko, 2017), which involves stable unipedal stance with maximal targeted reach distance of the free limb in a number of directions, are examples of field tests of dynamic balance.

Balance is an important aspect of the postural control system (Guskiewicz & Perrin, 1996). The postural control system operates as a feedback control circuit between the brain and the musculoskeletal system. Muscles and tendons contain specialised sensory receptors sensitive to stretch, tension, and pressure (McArdle et al., 2015). These end organs known as proprioceptors, almost instantaneously relay information regarding muscular dynamics and limb movement to conscious and subconscious portions of the central nervous system (McArdle et al., 2015). Feedback is obtained from the vestibular, visual, and proprioceptive sensors and commands are relayed to the muscles of the extremities, which then generate an appropriate contraction to maintain postural stability (Guskiewicz & Perrin, 1996; Nashner, 1982; Shumway-Cook & Horak, 1986). The proprioceptive system functions via the mechanoreceptive senses of touch, pressure, vibration, and tickle. These are all generally referred to as the tactile senses, and the sense of position, which determines the rates of movement and the relative positions of parts of the body (Vander, 1991).

The nervous system is provided with continuous feedback regarding the status of each muscle by means of the muscle spindles and Golgi tendon sensory receptors (proprioceptors). These play a vital role in the nervous system's control of posture (Guskiewicz & Perrin, 1996). Stretch receptors consisting of afferent nerve fibre endings that are wrapped around modified muscle fibres, are embedded within the muscle enabling muscle length and changes in length to be monitored (Guskiewicz & Perrin, 1996). Several of these are enclosed in a connective tissue capsule, the entire structure is called a muscle spindle (Vander, 1991). Information about either the muscle length or its rate of change in length is sent to the nervous system by the muscle spindles, afferent fibres from the muscle spindle enter the central nervous system and divide into branches that can take several different paths (Guskiewicz & Perrin, 1996). During standing balance one path directly stimulates motor neurons going back to the muscle that was stretched, thereby completing a reflex arc known as the stretch reflex or myotatic reflex (Guskiewicz & Perrin, 1996). In response to a muscle being stretched, a reflex reaction causes the muscle to contract (Vander, 1991).

Golgi tendon organs are located in the tendons near their junction with the muscles, they detect differences in the tension generated by active muscle rather than muscle length (McArdle et al., 2015), serving as a second type of afferent receptor (proprioceptor) (Guskiewicz & Perrin, 1996). They are responsible for sending information about the rate of change of tension or the tension of the muscle (Vander, 1991). The afferent neuron's firing activity supplies the motor control systems, both locally and in the brain, with continuous information about muscle tension (Guskiewicz & Perrin, 1996). The Golgi tendon organs assist as a protective mechanism to relax a muscle that is being overstretched. They sense tension within a muscle, transmit the information to the central nervous system, and through polysynaptic reflexes inhibit the motor neurons of the contracting muscle (Vander, 1991).

The muscle spindle detects, responds to and modulates changes in the length of the extrafusal muscle fibres. This provides an important regulatory function for movement and maintenance of posture (McArdle et al., 2015). Postural muscles continuously receive neural input to sustain their readiness to respond to voluntary movements, these muscles require continual subconscious activity to adjust to the pull of gravity in upright posture (McArdle et al., 2015). This can be illustrated when the ankle is rotated causing a stimulus of the functional stretch reflex (myotatic) that occurs in many persons (Guskiewicz & Perrin, 1996). After a change in erect posture, it appears to be the first useful phase of activity in the leg muscles (L. Nashner, 1976). The myotatic reflex can be seen when perturbations of gait or posture automatically induce functionally directed responses in the leg muscles to compensate for imbalance or increased postural sway (Dietz et al., 1989; Nashner, 1976). Muscle spindles respond to stretching of the agonist muscles, thus sending the sensory impulse along its afferent nerve fibres to the spinal cord (McArdle et al., 2015). From there the information is transferred to alpha and gamma motor neurons that carry information back to the muscle fibres and muscle spindle, respectively, and contract the muscle to prevent or control additional postural sway (Dietz et al., 1989).

In order to achieve the highest competitive level, yet avoid lower limb injuries in many sports, superior balance ability is necessary (Hrysomallis, 2007, 2011; Kiers et al., 2013). The central nervous system (CNS) integrates visual, vestibular, and proprioceptive information to produce motor commands that coordinate the activation patterns of muscles in order to control balance (Han et al., 2015; Shumway-Cook, 2013). Proprioception has been defined as the body’s ability to integrate sensory signals from various mechanoreceptors enabling the determination of body position and movements in space (Han et al., 2015b), and this plays a critical role in balance control (Han et al., 2015b).

To successfully perform the complex motor tasks required in elite sport (and military training), ankle proprioception is essential to provide vital information enabling the ankle to adjust to different positions and to movements of the upper body (Di Giulio et al., 2009; Sasagawa et al., 2009). Ankle proprioception may be an important component contributing to balance control in sport, as during most sports activities, the ankle-foot complex is the only part of the body contacting the ground (Han et al., 2015). A systematic review by Hrysomallis (2011) regarding the ability to balance and athletic performance found that static balance ability of rifle shooters and archers was associated with their shooting accuracy. Similarly Aalto et al. (1990) found trained competitive shooters (non-military) had significantly better stability than untrained shooters. Of interest to military population is that in shooting, the importance of stability is much higher than other sport events (Aalto et al., 1990). A further study investigating influences of balance, speed and power on agility performance by Sekulic et al. (2013), found agility performance was significantly correlated to balance ability in male soccer, handball, basketball, and volleyball athletes. Moreover, Blackburn et al. (2000) found balance deficits may result in increased injury rates for athletes when determining whether proprioception or muscular strength is the dominant factor in balance and joint stability. This suggests that balance control is essential to sports performance (Han et al., 2015) and is most likely to be important for military training and tasks.

2.6.9 The Ankle Joint and Military Personnel

Soldiers are often required to carry heavy loads while on tactical operations and on deployment for long distances and over uneven terrain (Knapik ey al., 1996; Knapik, 2012). When studying load carriage injuries in military personnel, Birrell and Hooper (2007) suggested that carrying loads over long durations may be the cause of injuries to the foot and ankle. Sell et al. (2013) further suggested carrying unaccustomed loads during deployment increased ankle and knee injuries. It has been demonstrated that altered or diminished postural stability is a risk factor for lower leg injuries (McGuine et al., 2000; Trojian & McKeag, 2006; Wang et al., 2006; Willems et al., 2005). The additional weight worn and carried by military personnel is for both tactical and protective purposes, but this additional weight reduces dynamic postural stability (Sell et al., 2013). Further studies by Schiffman et al. (2006) and Birrell and Hooper (2007) found load carriage to increase body sway and therefore resulted in less stability. In a study examining the addition of body armour to military personnel, Sell et al. (2013) found increases in medial-lateral and anterior-posterior sway with the addition of ~12.5 kg body armour. Similarly, when studying the effects of load weight carried by soldiers, Schiffman et al. (2006) found body sway, as quantified by traditional COP measures, increased linearly with increases in the external load on the body. These increases in medial-lateral and anterior-posterior sway may have important considerations for ankle sprains, more so the increase in medial-lateral sway (Hertel, 2002).

It is a requirement of all military personnel to attain and maintain a level of fitness much higher than usually found among civilians of the same age (Cowan et al., 2003). Generally, the training during initial (recruit) military training is oriented toward rapidly increasing the physical strength and endurance of those personnel entering military service, while training after recruit training in military units is oriented toward maintaining the level of fitness appropriate for the task required of specific units (Cowan et al., 2003). Military training includes many activities such as loaded running, walking, climbing and marching, often performed at high intensity levels (Davidson et al., 2008). Considerably more rigorous training is required in specialist units such as Special Forces operators, commandos and navy divers. These units will often train already physically fit military personnel at levels similar to those of elite athletes (Cowan et al., 2003). These high intensity workloads military personnel are exposed to are often the cause of neuromuscular fatigue causing postural and balance discrepancies (Nardone et al., 1997). Gribble and Hertel (2004) found that localised muscular fatigue diminished the ability of the muscle proprioceptors to relay joint position of the limbs to the central nervous system. Similarly, previous research reported that when muscles become fatigued the threshold for proprioceptive activation increases which decreases neural transmission of a reflex to respond to environmental perturbations (Gimmon et al., 2011; Gribble & Hertel, 2004) which would increase instability.

During training and occupational activities military personnel are exposed to intense physiological workloads resulting in fatigue (Grenier et al., 2012; Hollander & Bell, 2010; Kaufman et al., 2000) which has been found to decrease balance performance (Fox et al., 2008; Paillard, 2012). It is speculated that the stiff, high-shaft boot adds to the muscular fatigue, postural instability increases as the duration of exposure in work boots increases (Garner et al., 2013). Long workload duration, load carriage, surface inclination, increased gait velocity are some of the variables typical of military training/tasks which are of a significant intensity to cause increased COP excursion

(DeBusk et al., 2018). Extended duration of exposure in boots may elicit alterations in neuromuscular adaptations.

This decreased ability to maintain balance is an important musculoskeletal injury risk factor for military personnel, as revealed in the 2008 US Army Annual Injury Epidemiology report, which states 18.4% of all causes of injury were attributed to falls/near falls, slips and trips (Dada-Laseinde et al., 2009). Similarly, 19% of all musculoskeletal injuries in the New Zealand Army were attributed to trips, slips and falls (Davidson et al., 2008).

2.7 Footwear

Heir and Glomsaker (1996) made an interesting observation when studying musculoskeletal injuries among Norwegian conscripts undergoing basic military training. They found that the largest number of acute injuries, such as sprains and strains, occurred during physical training in sports clothes, which included the wearing of running shoes and not boots. The usage of military boots and running shoes during physical training varies between countries and services (Andersen et al., 2016). However, most militaries have dress regulations for physical training, and these regulations state: when performing physical training running (or gymnasium) shoes are to be worn (Australian Army Dress Manual, Chapter 5 Orders of Dress, US Army Regulation (AR) 670-1: Headquarters, Department of the Army, Washington, DC., Chapter 12 Physical Fitness Uniform, NZ Army Orders for Dress, NZ P23, Part 2, Chapter 2, Section 2, Issue 17, June 17).

A common approach to prevention of ankle eversion/inversion injuries in sport and military occupations is to brace the ankle with high-lacing boots to limit the overall possible movement, as seen in basketball. Changes in foot movement characteristics are the result of specialised footwear, particularly in the kinetic behaviour under load (Li et al., 2013). Limitation of ankle inversion angle and rate of angular displacement is achieved by higher shaft footwear with supportive lacing (Ricard et al., 2000) and can be effective at preventing sprains or mitigating sprain severity (Fu et al., 2014). However, footwear can have a significant effect on the musculoskeletal system, where muscle function is particularly affected (Goonetilleke, 2012).

When examining the influence of footwear on stride length and range of motion of ankle, knee and hip joints, Schulze et al. (2014) found that combat boots significantly limited the range of movement in the ankle joint during normal gait, particularly during plantar flexion. In a study examining the effect of shoe collar height on sagittal ankle range of motion, kinetics and power output during single-leg and double-leg jumps, Li et al. (2013) found wearing high-top shoes decreased the dorsiflexion ankle joint torque and power output during the push-off phase in single-leg jump. A reason cited for this is that rigid footwear extending above the ankle joint reduces flexibility of the joint and plantar flexion is restricted more than other movement directions (Schulze et al., 2014). The high-top footwear approach may not be ideal as evidence suggests that high-top footwear to prevent ankle injuries reduces the strength of the surrounding muscles and induces ankle instability (Fu et al., 2014). In a study of female basketballers, eversion torque in players wearing high-top footwear was significantly reduced compared to identical trials of eversion torque while unshod (Yentes et al., 2014). Low eversion torque has been linked to a higher likelihood of injury (Wang et al., 2006), which decreases proprioception ability (Payne et al., 1997) and may increase the chance of further ankle injuries (Mohammadi & Roozdar, 2010). Ashton-Miller et al. (1996) determined that stronger ankle evertor muscles were a superior preventer of inversion injuries to high footwear or strapping, citing a six-fold greater moment at full muscle activity in a 15-degree inversion than a three-quarter shoe, and a three-fold greater moment than strapping tape or an orthosis. It has been shown that boot-shaft stiffness considerably influences the kinematics and kinetics of the ankle joint and that softer footwear enables a larger range of motion and power generation in the ankle joint during push-off (Cikajlo & Matjačić, 2007). This would be quite significant in military boot-wear as ankle power generation is an important contributor in limb advancement in gait (Requiao et al., 2005).

The sole of the foot has a large number of mechanoreceptors that recognise dynamic changes, this makes it one of the most sensitive parts of the body. These mechanoreceptors transform deformation information in static or dynamic conditions, balance and distortions into nerve-transmitted signals (Khin-Myo-Hla et al., 1999). A review on the effect of footwear on instability, excessive impact, and ankle spraining by Steven Robbins and Waked (1997), directed attention to these adapting mechanoreceptors having myelinated afferents (SAII mechanoreceptor), as these are responsible for sensing plantar load and for precise foot position awareness. Even though incapable of accurate spatial localisation as a result of overlapping and indistinct sensory fields, individual afferent fibres of SAII mechanoreceptors do respond in direct relation to changes to the plantar surface and to shear stress, thereby adapting both vertical and horizontal load. This makes individuals capable of sensing amplitude load and foot position awareness (Robbins & Waked, 1997). When the unshod foot contacts support surfaces, the result is deformation to the plantar surface, and the shear pressure is adequate stimuli for plantar tactile SAII mechanoreceptors. This information enables humans to walk, run, and jump with high stability, safe levels of impact, and adequate ankle support (Robbins & Waked, 1997).

Interestingly, when Robbins et al. (1992) observed the influence of shoe sole thickness on balance in older men, they found that thick, soft midsoles reduced sensory feedback and negatively affected balance. Similarly, when studying the effect of footwear on balance in healthy subjects, Rose et al. (2011) found anterior-posterior stability, medial-lateral stability, vertical stability, and dynamic postural stability all significantly improved when subjects were in bare feet than when wearing standard running shoes. The reason given by Rose et al. (2011) was that it is likely due to the increasing filtering of sensory input that results from additional material between the foot and the ground, therefore filtering or masking of sensory input by footwear, which can affect dynamic postural stability. Robbins and Waked (1997) found footwear filters stimuli for plantar tactile receptors humans use in making precise judgements of plantar load and position and orientation of plantar surface with respect to the leg (i.e., foot position awareness). When wearing shoes humans are less stable, prone to ankle sprains, and overuse injuries resulting from chronic unwarranted impact during locomotion (Robbins & Waked, 1997).

Brenton-Rule et al. (2011) found a significant increase in postural sway in the anterior-posterior (AP) direction when comparing wearing shoes versus bare feet when investigating the effects of walking shoes on postural stability in healthy older adults. They further stated this effect could be accounted for by the effects of the footwear on the somatosensory system. Additionally, this study found postural sway was significantly increased in the AP direction in the eyes closed condition, compared to eyes open condition. This indicates greater sensory deprivation in comparison to barefoot as a result of there being no visual input, along with reduced sensory input due to the lack of direct contact between the feet and floor (Brenton-Rule et al., 2011). The soles of footwear have been shown to absorb and disperse sensory information from the ground surface when compared to bare feet, this contributes to increases in postural response latencies (Hosoda et al., 1997).

A study by Chander et al. (2015) examining the impact on balance while walking in occupational footwear, found the barefoot condition demonstrated significantly faster reaction latencies when compared to tactical boots (16.5 cm boot shaft height) and work boots (18.5 cm boot shaft height). Furthermore, significantly less lower extremity muscle activity was displayed by the tactical boot during backward and forward perturbations when compared to bare feet and a work boot. This was demonstrated by a significantly lower mean and percentage maximum voluntary contraction (%MVC) of lower leg muscle activity. Chander et al. (2015) suggested that only minimal muscle activation is required to maintain balance while wearing the tactical boot indicating high boot shafts seem to benefit balance performance during static balance. In this case the boot may have an inverted pendulum effect which is inherently unstable. It may only require a small force to correct balance but applying the right amount of force at the right time is compromised. Similarly Fu et al. (2014) found that the effect of high-top shoes on ankle inversion kinematics and muscle activation was to provide a smaller muscular effort and changed proprioceptive feedback. However, they stated this might be detrimental to establishing and maintaining functional ankle joint stability in ankle strain situations due to a delayed pre-activation timing and decreased amplitude of evertor muscle activity while wearing a high-top laced boot. Interestingly, Yang et al., (2015) found that muscle fatigue in the lower extremities was induced by walking in high shaft rain boots, which affected the joints and the postural control muscles. The motion of the distal joints was affected more than the proximal joints by the length of the shoe shaft, which caused an impaired ability to balance (Yang et al., 2015). Consequently, the ability to balance was affected by muscle fatigue induced by the shoe soles and the shaft height of the shoes.

2.7.1 Military Boots

Gait and performance of tasks in military populations is significantly affected by footwear, which in turn has an important influence on injury mechanics (Dixon et al., 2003; Lieberman et al., 2010). Robbins and Waked (1998) further stated that foot proprioception was precise when barefoot, but becomes distorted when wearing shoes. This is worth noting as impaired proprioception is a cause of ankle sprains due to inadequate use of anticipatory muscle movement under dynamic conditions, such as an increased time to respond to acute muscle loading. This is highlighted by Kynsburg et al. (2010), who stated that temporary or permanent failure of the proprioceptive function plays a main role in the development of acute ligament injuries in the ankle.

Schulze et al. (2011) observed increased neuromuscular activity in the tibialis anterior and rectus femoris muscles when wearing combat boots. They also stated that increased muscle activity in these specific muscle groups may influence the occurrence of certain strain related disorders such as medial tibia stress syndrome (shin splints) and patella-femoral pain. Furthermore, a study done by Cikajlo and Matjačić (2007) suggested the major influence of boots on the kinematics and kinetics of the leg appeared to be limited to the muscles of the ankle joint.

When walking long distances wearing boots, foot kinematics change as a result of fatiguing muscles which could be the cause of injury, this is accentuated during pack marching (Piasis et al., 2008). Pohl et al. (2010) found a significant increase in rear foot eversion movement as a result of a decrease in tibialis posterior strength as a result of fatigue caused by walking. It may be that chronic fatiguing of the tibialis posterior leads to deficiencies which are associated with greater forefoot abduction and dorsiflexion. Once fatigue of the tibialis posterior occurs then compensation of other muscles takes place, which then leads to the possibility of muscular imbalances which may in-turn lead to injuries. Harkins et al. (2005) reported that when the larger ankle muscles, the plantar flexors and dorsiflexors, become fatigued the possibility exists that other muscles are used to compensate. They further stated that instead of relying on the ankle muscles for stability, corrective action of the proximal joints, the knee and hip is increased which may lead to injuries in these joints. When postural stability is compromised as a result of ankle fatigue the soldier may be susceptible to further injury. It should also be noted that Ness et al. (2008) reported that flat arched individuals activate the tibialis posterior far more than those with normal arches and the army boots do not come with inbuilt arch support.

An important factor reported by Robbins and Waked (1998) is that the intrinsic foot muscles become lazy when wearing boots (particularly rigid boots). They reported that footwear distorts the sense of foot position which accounts for ankle sprains. Moreover, Warburton (2001) stated that the natural structures of the foot are weakened by long-term footwear which leads to the reliance of footwear to support the foot which is not the same as the support provided by a well-functioning foot.

2.8 References

Aalto, H., Pyykkö, I., Ilmarinen, R., Kähkönen, E., & Starck, J. (1990). Postural stability in shooters. *Orl, 52*(4), 232-238.

Abt, J. P., Sell, T. C., Lovalekar, M. T., Keenan, K. A., Bozich, A. J., Morgan, J. S., . . . Lephart, S. M. (2014). Injury Epidemiology of U.S. Army Special Operations Forces. *Military Medicine, 179*(10), 1106-1112. doi:10.7205/MILMED-D-14-00078

ACSM's Resource Manual for Guidelines for Exercise Testing and Prescription. (2013). (D. P. Swain, & Brawner, C. A. Ed. 9 ed.). Philadelphia: Lippincott Williams and Wilkins.

Almeida, S. A., Williams, K. M., Shaffer, R. A., & Brodine, S. K. (1999). Epidemiological patterns of musculoskeletal injuries and physical training. *Med Sci Sports Exerc, 31*. doi:10.1097/00005768-199908000-00015

Amako, M., Yato, Y., Yoshihara, Y., Arino, H., Sasao, H., Nemoto, O., . . . Nemoto, K. (2018). Epidemiological patterns of traumatic musculoskeletal injuries and non-traumatic disorders in Japan Self-Defense Forces. *Injury Epidemiology, 5*(1), 19. doi:10.1186/s40621-018-0150-2

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Arakawa, H., Nagano, A., Hay, D. C., & Kanehisa, H. (2013). The Effects of Ankle Restriction on the Multijoint Coordination of Vertical Jumping. *Journal of Applied Biomechanics, 29*(4), 468-473. doi:10.1123/jab.29.4.468

Arndt, A., Westblad, P., Ekenman, I., & Lundberg, A. (2003). A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait Posture., 18*. doi:10.1016/s0966-6362(02)00191-1

Ashton-Miller, J. A., Ottaviani, R. A., Hutchinson, C., & Wojtys, E. M. (1996). What best protects the inverted weightbearing ankle against further inversion? Evertor muscle strength compares favorably with shoe height, athletic tape, and three orthoses. *The American Journal of Sports Medicine, 24*(6), 800-809.

Asseman, F. B., Caron, O., & Crémieux, J. (2008). Are there specific conditions for which expertise in gymnastics could have an effect on postural control and performance? *Gait & Posture, 27*(1), 76-81.

Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med, 39*(6), 324-329. doi:10.1136/bjsm.2005.018341

Bahr, R., Lian, Ø., & Bahr, I. (1997). A twofold reduction in the incidence of acute ankle sprains in volleyball after the introduction of an injury prevention program: a prospective cohort study. *Scandinavian journal of medicine & science in sports, 7*(3), 172-177.

Baumhauer, J. F., Alosa, D. M., Renström, P. A., Trevino, S., & Beynnon, B. (1995). A prospective study of ankle injury risk factors. *The American Journal of Sports Medicine, 23*(5), 564-570.

Baxter, M. L., Ribeiro, D. C., & Milosavljevic, S. (2012). Do orthotics work as an injury prevention strategy for the military? *Physical Therapy Reviews, 17*(4), 241-251. doi:10.1179/1743288X12Y.0000000013

Belmont, P. J., Owens, B. D., & Schoenfeld, A. J. (2016). Musculoskeletal Injuries in Iraq and Afghanistan: Epidemiology and Outcomes Following a Decade of War. *JAAOS - Journal of the American Academy of Orthopaedic Surgeons, 24*(6), 341-348. doi:10.5435/jaaos-d-15-00123

Billings, C. E. (2004). Epidemiology of injuries and illnesses during the United States Air Force Academy 2002 Basic Cadet Training program: documenting the need for prevention. *Military Medicine, 169*(8), 664-670.

Birrell, S. A., & Hooper, R. H. (2007). Initial subjective load carriage injury data collected with interviews and questionnaires. *Military Medicine, 172*(3), 306-311.

Blackburn, T., Guskiewicz, K. M., Petschauer, M. A., & Prentice, W. E. (2000). Balance and Joint Stability: The Relative Contributions of Proprioception and Muscular Strength. *Journal of Sport Rehabilitation, 9*(4), 315-328. doi:10.1123/jsr.9.4.315

Blacker, S. D., Wilkinson, D. M., Bilzon, J. L., & Rayson, M. P. (2008). Risk factors for training injuries among British Army recruits. *Mil Med, 173*. doi:10.7205/milmed.173.3.278

Bohm, H., & Hosl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *J Biomech, 43*. doi:10.1016/j.jbiomech.2010.05.029

Bok, S.-K., Lee, T. H., & Lee, S. S. (2013). The Effects of Changes of Ankle Strength and Range of Motion According to Aging on Balance. *Ann Rehabil Med, 37*(1), 10-16. doi:10.5535/arm.2013.37.1.10

Boone, D. C., & Azen, S. P. (1979). Normal range of motion of joints in male subjects. *JBJS, 61*(5), 756-759.

Bosco, C., Tarkka, I., & Komi, P. (1982). Effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercise. *International journal of sports medicine, 3*(03), 137-140.

Boss, A. P., & Hintermann, B. (2002). Anatomical study of the medial ankle ligament complex. *Foot & ankle international, 23*(6), 547-553.

Bot, S. D., & Van Mechelen, W. (1999). The effect of ankle bracing on athletic performance. *Sports Medicine, 27*(3), 171-178.

Brenton-Rule, A., Bassett, S., Walsh, A., & Rome, K. (2011). The evaluation of walking footwear on postural stability in healthy older adults: an exploratory study. *Clinical Biomechanics, 26*(8), 885-887.

Brockett, C. L., & Chapman, G. J. (2016). Biomechanics of the ankle. *Orthopaedics and Trauma, 30*(3), 232-238. doi:https://doi.org/10.1016/j.mporth.2016.04.015

Brukner, P. D. R. C. O. G., & Khan, K. (2009). *Clinical sports medicine* (Rev. 3rd ed ed.): McGraw-Hill.

Brushoj, C., Larsen, K., Albrecht-Beste, E., Nielsen, M. B., Loye, F., & Holmich, P. (2008). Prevention of overuse injuries by a concurrent exercise program in subjects exposed to an increase in training load: a randomized controlled trial of 1020 army recruits. *Am J Sports Med, 36*. doi:10.1177/0363546508315469

Bullock, S. H., Jones, B. H., Gilchrist, J., & Marshall, S. W. (2010). Prevention of Physical Training–Related Injuries: Recommendations for the Military and Other Active

Populations Based on Expedited Systematic Reviews. *American Journal of Preventive Medicine, 38*(1, Supplement), S156-S181. doi:https://doi.org/10.1016/j.amepre.2009.10.023

Burks, R. T., & Morgan, J. (1994). Anatomy of the lateral ankle ligaments. *The American Journal of Sports Medicine, 22*(1), 72-77.

Cameron, K. L., Owens, B. D., & DeBerardino, T. M. (2010). Incidence of Ankle Sprains Among Active-Duty Members of the United States Armed Services From 1998 Through 2006. *Journal of athletic training, 45*(1), 29-38. doi:10.4085/1062-6050-45.1.29

Caplan, N., Forbes, A., Radha, S., Stewart, S., Ewen, A., Gibson, A. S. C., & Kader, D. (2015). Effects of 1 week of unilateral ankle immobilization on plantar-flexor strength, balance, and walking speed: A pilot study in asymptomatic volunteers. *Journal of Sport Rehabilitation, 24*(2), 156-162.

Caraffa, A., Cerulli, G., Projetti, M., Aisa, G., & Rizzo, A. (1996). Prevention of anterior cruciate ligament injuries in soccer. *Knee surgery, sports traumatology, arthrosCOPy, 4*(1), 19-21.

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science, 6*(1), 59-66. doi:10.1080/19424280.2013.834979

Chander, H., Wade, C., & Garner, J. C. (2015). The influence of occupational footwear on dynamic balance perturbations. *Footwear Science, 7*(2), 115-126.

Cikajlo, I., & Matjačić, Z. (2007). The influence of boot stiffness on gait kinematics and kinetics during stance phase. *Ergonomics, 50*(12), 2171-2182. doi:10.1080/00140130701582104

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K., & Hunt, M. (2010). Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait & Posture, 31*(3), 307-310.

Cloeren, M., & Mallon, T. M. (2004). Managing workers' compensation costs in the military setting: the Army's story. *Clinics in occupational and environmental medicine, 4*(2), vii, 323-339.

Cowan, D. N., Jones, B. H., & Shaffer, R. A. (2003). Musculoskeletal injuries in the military training environment. *Military preventive medicine: mobilization and deployment, 1*.

Dada-Laseinde, E., Canham-Chervak, M., & Jones, B. H. (2009). *US Army Annual Injury Epidemiology Report 2008*. Retrieved from: https://apps.dtic.mil/dtic/tr/fulltext/u2/a523368.pdf

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

Davidson, P. L., Wilson, S. J., Chalmers, D. J., Wilson, B. D., & McBride, D. (2009). Examination of interventions to prevent common lower-limb injuries in the New Zealand Defense Force. *Military Medicine, 174*(11), 1196-1202.

de Noronha, M., Refshauge, K. M., Herbert, R. D., & Kilbreath, S. L. (2006). Do voluntary strength, proprioception, range of motion, or postural sway predict occurrence of lateral ankle sprain? *British Journal of Sports Medicine, 40*(10), 824-828. doi:10.1136/bjsm.2006.029645

DeBusk, H., Hill, C. M., Chander, H., Knight, A. C., & Babski-Reeves, K. (2018). Influence of military workload and footwear on static and dynamic balance performance. *International Journal of Industrial Ergonomics, 64*, 51-58. doi:https://doi.org/10.1016/j.ergon.2017.11.003

Di Giulio, I., Maganaris, C. N., Baltzopoulos, V., & Loram, I. D. (2009). The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. *The Journal of Physiology, 587*(10), 2399-2416.

Dietz, V., Horstmann, G., & Berger, W. (1989). Significance of proprioceptive mechanisms in the regulation of stance *Progress in brain research* (Vol. 80, pp. 419-423): Elsevier.

Dixon, S. J. (2007). Influence of a Commercially Available Orthotic Device on Rear foot Eversion and Vertical Ground Reaction Force When Running in Military Footwear. *Military Medicine, 172*(4), 446-450. doi:10.7205/milmed.172.4.446

Dixon, S. J., Waterworth, C., Smith, C. V., & House, C. M. (2003). Biomechanical analysis of running in military boots with new and degraded insoles. *Med Sci Sports Exerc, 35*(3), 472-479. doi:10.1249/01.mss.0000053733.64049.27

Dizon, J. M. R., & Reyes, J. J. B. (2010). A systematic review on the effectiveness of external ankle supports in the prevention of inversion ankle sprains among elite and recreational players. *Journal of Science and Medicine in Sport, 13*(3), 309-317.

Duddy, R., Duggan, R., Visser, H., Brooks, J., & Klamet, T. (1989). Diagnosis, treatment, and rehabilitation of injuries to the lower leg and foot. *Clinics in sports medicine, 8*(4), 861-876.

Dul, J., & Johnson, G. E. (1985). A kinematic model of the human ankle. *Journal of Biomedical Engineering, 7*(2), 137-143. doi:https://doi.org/10.1016/0141-5425(85)90043-3

Ferguson, A. B. J. (1973). The case against ankle taping. *J Sports Med, 1*(2), 46 - 47.

Finestone, A., Giladi, M., Elad, H., Salmon, A., Mendelson, S., Eldad, A., & Milgrom, C. (1999). Prevention of stress fractures using custom biomechanical shoe orthoses. *Clinical Orthopaedics and Related Research®, 360*, 182-190.

Finestone, A., Novack, V., Farfel, A., Berg, A., Amir, H., & Milgrom, C. (2004). A prospective study of the effect of foot orthoses composition and fabrication on comfort and the incidence of overuse injuries. *Foot & ankle international, 25*(7), 462-466.

Firth, A. D. (2016). Reliability and Validity of the Star Excursion Balance Test for Patients with Chronic Patellar Instability.

Fox, Z. G., Mihalik, J. P., Blackburn, J. T., Battaglini, C. L., & Guskiewicz, K. M. (2008). Return of postural control to baseline after anaerobic and aerobic exercise protocols. *Journal of athletic training, 43*(5), 456-463.

Franklyn-Miller, A., Wilson, C., Bilzon, J., & McCrory, P. (2011). Foot Orthoses in the Prevention of Injury in Initial Military Training. *The American Journal of Sports Medicine, 39*(1), 30-37. doi:10.1177/0363546510382852

Frilander, H., Miranda, H., Mutanen, P., Martelin, T., Pihlajamaki, H., & E, V.-J. (2012). Trends in musculoskeletal disorders and related health care utilisation among conscripts in Finland 1967-2006. *Military Medicine, 177*, 1069-1074.

Fu, W., Fang, Y., Liu, Y., & Hou, J. (2014). The effect of high-top and low-top shoes on ankle inversion kinematics and muscle activation in landing on a tilted surface. *Journal of Foot and Ankle Research, 7*(1), 14. doi:10.1186/1757-1146-7-14

Garner, J. C., Wade, C., Garten, R., Chander, H., & Acevedo, E. (2013). The influence of firefighter boot type on balance. *International Journal of Industrial Ergonomics, 43*(1), 77-81. doi:https://doi.org/10.1016/j.ergon.2012.11.002

Garrison, M., Dembowski, S., & Shepard, N. (2016). Sports and Exercise-Related Injuries in the Military *Musculoskeletal Injuries in the Military* (pp. 43-60): Springer.

Gimmon, Y., Riemer, R., Oddsson, L., & Melzer, I. (2011). The effect of plantar flexor muscle fatigue on postural control. *Journal of Electromyography and Kinesiology, 21*(6), 922-928.

Goodall, R. L., Pope, R. P., Coyle, J. A., & Neumayer, R. (2013). Balance and agility training does not always decrease lower limb injury risks: a cluster-randomised controlled trial. *International Journal of Injury Control and Safety Promotion, 20*(3), 271-281. doi:10.1080/17457300.2012.717085

Goonetilleke, R. (2012). *The Science of Footwear*.

Grenier, J. G., Peyrot, N., Castells, J., Oullion, R., Messonnier, L., & Morin, J.-B. (2012). Energy cost and mechanical work of walking during load carriage in soldiers. *Medicine and science in sports and exercise, 44*(6), 1131-1140.

Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control¹. *Archives of Physical Medicine and Rehabilitation, 85*(4), 589-592. doi:10.1016/j.apmr.2003.06.031

Grimston, S. K., Nigg, B. M., Hanley, D. A., & Engsberg, J. R. (1993). Differences in Ankle Joint Complex Range of Motion as a Function of Age. *Foot & ankle, 14*(4), 215-222. doi:10.1177/107110079301400407

Gruhn, J., Leggat, P., & Müller, R. (1999). Injuries presenting to Army physiotherapy in north Queensland, Australia. *Military Medicine, 164*(2), 145-152.

Guskiewicz, K. M., & Perrin, D. H. (1996). Research and Clinical Applications of Assessing Balance. *Journal of Sport Rehabilitation, 5*(1), 45-63. doi:10.1123/jsr.5.1.45

Hadzic, V., Sattler, T., Topole, E., Jarnovic, Z., Burger, H., & Dervisevic, E. (2009). Risk factors for ankle sprain in volleyball players: A preliminary analysis. *Isokinetics and Exericse Science, 17*(3), 155-160. doi:10.3233/IWS-2009-0347

Hall, S. J. (1999). *Basic Biomechanics*. Singapore: McGraw-Hill.

Halvarsson, A., Hagman, I., Tegern, M., Broman, L., & Larsson, H. (2018). Self-reported musculoskeletal complaints and injuries and exposure of physical workload in Swedish soldiers serving in Afghanistan. *PloS one, 13*(4), e0195548. doi:10.1371/journal.pone.0195548

Hamill, J., & Bensel, C. K. (1992). *Biomechanical Analysis of Military Boots. Phase 1. Materials Testing of Military and Commercial Footwear*. Retrieved from: appa.dtic.mil/dtic/tr/fulltext/u2/a257293.pdf

Hamill, J., & Bensel, C. K. (1996). *Biomechanical analysis of military boots: Phase 2. Volume 1. Human user testing of military and commercial footwear*. Retrieved from: appa.dtic.mil/dtic/tr/fulltext/u2/a304914.pdf

Hamill, J., & Bensel, C. K. (1996). *Biomechanical analysis of military boots: phase III* (Natick/TR-96/013). Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.934.5109&rep=rep1&type=pdf

Hamilton, N., Weimar, W., & Luttgens, K. (2012). *Kinesiology : scientific basis of human motion* (12th ed ed.): McGraw-Hill.

Han, J., Anson, J., Waddington, G., Adams, R., & Liu, Y. (2015a). The role of ankle proprioception for balance control in relation to sports performance and injury. *BioMed research international, 2015*.

Han, J., Anson, J., Waddington, G., Adams, R., & Liu, Y. (2015b). The Role of Ankle Proprioception for Balance Control in relation to Sports Performance and Injury. *BioMed research international, 2015*, 8. doi:10.1155/2015/842804

Harkins, K. M., Mattacola, C. G., Uhl, T. L., Malone, T. R., & McCrory, J. L. (2005). Effects of 2 Ankle Fatigue Models on the Duration of Postural Stability Dysfunction. *Journal of athletic training, 40*(3), 191-194.

Harman E, F. P., Pandorf C, LaFiandra M, Smith T, Bensel C et al. (1999). A comparison of 2 current-issue army boots, 5 prototype military boots, and 5 commercial hiking boots: performance, efficiency, biomechanics, comfort and injury. Technical Report. Report No.: T00-3. Natick, MA: Military Performance Division, U.S. Army Research Institute of Environmental Medicine.

Harper, M. C. (1991). The lateral ligamentous support of the subtalar joint. *Foot & ankle, 11*(6), 354-358.

Hauret, K. G., Bedno, S., Loringer, K., Kao, T.-C., Mallon, T., & Jones, B. H. (2015). Epidemiology of Exercise- and Sports-Related Injuries in a Population of Young, Physically Active Adults: A Survey of Military Servicemembers. *The American Journal of Sports Medicine, 43*(11), 2645-2653. doi:10.1177/0363546515601990

Hauret, K. G., Jones, B. H., Bullock, S. H., Canham-Chervak, M., & Canada, S. (2010). Musculoskeletal Injuries: Description of an Under-Recognized Injury Problem Among Military Personnel. *American Journal of Preventive Medicine, 38*(1, Supplement), S61-S70. doi:https://doi.org/10.1016/j.amepre.2009.10.021

Hauret, K. G., Taylor, B. J., Clemmons, N. S., Block, S. R., & Jones, B. H. (2010). Frequency and causes of nonbattle injuries air evacuated from Operations Iraqi Freedom and Enduring Freedom, US Army, 2001–2006. *American Journal of Preventive Medicine, 38*(1), S94-S107.

Havenetidis, K., Kardaris, D., & Paxinos, T. (2011). Profiles of musculoskeletal injuries among Greek Army officer cadets during basic combat training. *Mil Med, 176*(3), 297-303.

Heagerty, R., Sharma, J., & Clayton, J. (2017). Musculoskeletal Injuries in British Army Recruits: A Retrospective Study of Incidence and Training Outcome in Different Infantry Regiments. *Int J Sports Exerc Med, 3*, 071.

Heir, T. (1998). Musculoskeletal injuries in officer training: one year follow-up. *Military Medicine, 163*(4), 229-233.

Heir, T., & Glomsaker, P. (1996). Epidemiology of musculoskeletal injuries among Norwegian conscripts undergoing basic military training. *Scandinavian journal of medicine & science in sports, 6*(3), 186-191.

Herman, K., Barton, C., Malliaras, P., & Morrissey, D. (2012). The effectiveness of neuromuscular warm-up strategies, that require no additional equipment, for preventing lower limb injuries during sports participation: a systematic review. *BMC medicine, 10*, 75-75. doi:10.1186/1741-7015-10-75

Hertel, J. (2002). Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. *Journal of athletic training, 37*(4), 364.

Hill, C. M., DeBusk, H., Knight, A. C., & Chander, H. (2017). Influence of military-type workload and footwear on muscle exertion during static standing. *Footwear Science, 9*(3), 169-180. doi:10.1080/19424280.2017.1403968

Hollander, I. E., & Bell, N. S. (2010). Physically demanding jobs and occupational injury and disability in the US Army. *Military Medicine, 175*(10), 705-712.

Hølmer, P., Søndergaard, L., Konradsen, L., Nielsen, P. T., & Jørgensen, L. N. (1994). Epidemiology of sprains in the lateral ankle and foot. *Foot & ankle international, 15*(2), 72-74.

Horak, F. B., Henry, S. M., & Shumway-Cook, A. (1997). Postural perturbations: new insights for treatment of balance disorders. *Physical Therapy, 77*(5), 517-533.

Hosoda, M., Yoshimura, O., Takayanagi, K., Kobayashi, R., Minematsu, A., Nakayama, A., Wilson, C. K. (1997). The effect of various footwear types and materials, and of fixing of the ankles by footwear, on upright posture control. *Journal of physical therapy science, 9*(1), 47-51.

Houk, J. C. (1979). Regulation of stiffness by skeletomotor reflexes. *Annual Review of Physiology, 41*(1), 99-114.

Hrysomallis, C. (2007). Relationship between balance ability, training and sports injury risk. *Sports Medicine, 37*(6), 547-556.

Hrysomallis, C. (2011). Balance Ability and Athletic Performance. *Sports Medicine, 41*(3), 221-232. doi:10.2165/11538560-000000000-00000

Hume, P., Hopkins, W., Rome, K., Maulder, P., Coyle, G., & Nigg, B. (2008). Effectiveness of Foot Orthoses for Treatment and Prevention of Lower Limb Injuries. *Sports Medicine, 38*(9), 759-779. doi:10.2165/00007256-200838090-00005

Hume, P. A., & Gerrard, D. F. (1998). Effectiveness of external ankle support. *Sports Medicine, 25*(5), 285-312.

Huson, A. (1987). Joints and movements of the foot: terminology and concepts. *Acta Morphol Neerl Scand, 25*(3), 117-130.

Janssen, K. W., van Mechelen, W., & Verhagen, E. A. (2014). Bracing superior to neuromuscular training for the prevention of self-reported recurrent ankle sprains: a three-arm randomised controlled trial. *Br J Sports Med, 48*(16), 1235-1239.

Jennings, B. M., Yoder, L. H., Heiner, S. L., Loan, L. A., & Bingham, M. O. (2008). Soldiers With Musculoskeletal Injuries. *Journal of Nursing Scholarship, 40*(3), 268-274. doi:doi:10.1111/j.1547-5069.2008.00237.x

Jones, B. H. (1983). Overuse injuries of the lower extremities associated with marching, jogging, and running: a review. *Military Medicine, 148*(10), 783-787.

Jones, B. H., Bovee, M. W., Harris, J. M., & Cowan, D. N. (1993). Intrinsic risk factors for exercise-related injuries among male and female army trainees. *Am J Sports Med, 21*. doi:10.1177/036354659302100512

Kanko, L. (2017). Reliability and Validity of the Star Excursion Balance Test in Patients with Knee Osteoarthritis.

Kaufman, K. R., Brodine, S., & Shaffer, R. (2000). Military training-related injuries: surveillance, research, and prevention. *Am J Prev Med, 18*(3 Suppl), 54-63.

Kawalec, J. S. (2017). 12 - Mechanical testing of foot and ankle implants. In E. Friis (Ed.), *Mechanical Testing of Orthopaedic Implants* (pp. 231-253): Woodhead Publishing.

Khin-Myo-Hla, Ishii, T., Sakane, M., & Hayashi, K. (1999). Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle. *Foot & ankle international, 20*(9), 554-559.

Kiers, H., van Dieën, J., Dekkers, H., Wittink, H., & Vanhees, L. (2013). A systematic review of the relationship between physical activities in sports or daily life and postural sway in upright stance. *Sports Medicine, 43*(11), 1171-1189.

Knapik, J., Harman, E., & Reynolds, K. (1996). Load carriage using packs: a review of physiological, biomechanical and medical aspects. *Applied ergonomics, 27*(3), 207-216.

Knapik J, R. K. (2012). Load carriage in military operations: a review of historical, physiological, biomechanical and medical aspects. In: Friedl K, Santee WR, editors. Military quantitative physiology: problems and concepts in military operational medicine. Office of the Surgeon General and the Borden Institute, Ft. Detrick, MD (pp. 303-337).

Knapik, J. J., Darakjy, S., Hauret, K. G., Canada, S., Scott, S., & Rieger, W. (2006). Increasing the physical fitness of low-fit recruits before basic combat training: an evaluation of fitness, injuries, and training outcomes. *Mi Med, 171*. doi:10.7205/milmed.171.1.45

Knapik, J. J., Darakjy, S., Swedler, D., Amoroso, P., & Jones, B. H. (2008). Parachute Ankle Brace and Extrinsic Injury Risk Factors During Parachuting. *Aviation, space, and environmental medicine, 79*(4), 408-415. doi:10.3357/ASEM.2218.2008

Knapik, J. J., Jones, S. B., Darakjy, S., Hauret, K. G., Bullock, S. H., Sharp, M. A., & Jones, B. H. (2007). Injury rates and injury risk factors among US Army wheel vehicle mechanics. *Military Medicine, 172*(9), 988-996.

Knapik, J. J., Sharp, M. A., Canham-Chervak, M., Hauret, K., Patton, J. F., & Jones, B. H. (2001). Risk factors for training-related injuries among men and women in basic combat training. *Med Sci Sports Exerc, 33*. doi:10.1097/00005768-200106000-00014

Knapik, J. J., Spiess, A., Swedler, D., Grier, T., Darakjy, S., Amoroso, P., & Jones, B. H. (2008). Injury Risk Factors in Parachuting and Acceptability of the Parachute Ankle Brace. *Aviation, space, and environmental medicine, 79*(7), 689-694. doi:10.3357/ASEM.2273.2008

Kopper, B., Csende, Z., Trzaskoma, L., & Tihanyi, J. (2014). Stretch-shortening cycle characteristics during vertical jumps carried out with small and large range of motion. *Journal of Electromyography and Kinesiology, 24*(2), 233-239. doi:https://doi.org/10.1016/j.jelekin.2014.01.001

Kynsburg, A., Pánics, G., & Halasi, T. (2010). Long-term neuromuscular training and ankle joint position sense. *Acta Physiologica Hungarica, 97*(2), 183-191.

Lark, S. D., Buckley, J. G., Bennett, S., Jones, D., & Sargeant, A. J. (2003). Joint torques and dynamic joint stiffness in elderly and young men during stepping down. *Clinical Biomechanics, 18*(9), 848-855.

Larsson, H., Broman, L., & Harms-Ringdahl, K. (2009). Individual risk factors associated with premature discharge from military service. *Military Medicine, 174*(1), 9-20.

Lauder, T. D., Baker, S. P., Smith, G. S., & Lincoln, A. E. (2000). Sports and physical training injury hospitalizations in the army. *American Journal of Preventive Medicine, 18*(3), 118-128.

Levangie, K. P., Norkin, C. C. (2005). *Joint Structure and Function : a comrehensive analysis* (4 ed.). Philadelphia, PA: F. A. Davis Company.

Li, L., Liu, Y., He, J., & Fu, W. (2013). *Effects of shoe collar height on sagittal ankle rom, kinetics and power output during single-leg and double-leg jumps.* Paper presented at the ISBS-Conference Proceedings Archive.

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., & Davis, I. S. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature, 463*. doi:10.1038/nature08723

Lovalekar, M., Abt, J. P., Sell, T. C., Wood, D. E., & Lephart, S. M. (2016). Descriptive Epidemiology of Musculoskeletal Injuries in Naval Special Warfare Sea, Air, and Land Operators. *Military Medicine, 181*(1), 64-69. doi:10.7205/MILMED-D-14-00655

Lundberg, A., Goldie, I., Kalin, B., & Selvik, G. (1989). Kinematics of the ankle/foot complex: plantarflexion and dorsiflexion. *Foot & ankle, 9*(4), 194-200.

Maeda, N., Urabe, Y., Tsutsumi, S., Numano, S., Morita, M., Takeuchi, T., . . . Kobayashi, T. (2016). Effect of Semi-Rigid and Soft Ankle Braces on Static and Dynamic Postural Stability in Young Male Adults. *Journal of Sports Science & Medicine, 15*(2), 352-357.

McArdle, W. D., Katch, F. I., & Katch, V. L. (2015). *Exercise physiology : nutrition, energy, and human performance* (Eighth edition ed.): Wolters Kluwer Health/Lippincott Williams & Wilkins.

McGuine, T. A., Greene, J. J., Best, T., & Leverson, G. (2000). Balance As a Predictor of Ankle Injuries in High School Basketball Players. *Clinical Journal of Sport Medicine, 10*(4), 239-244.

McKay, M. J., Baldwin, J. N., Ferreira, P., Simic, M., Vanicek, N., Burns, J., & Consortium, N. P. (2017). Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology, 88*(1), 36-43.

Michelson, J. D., & Hutchins, C. (1995). Mechanoreceptors in human ankle ligaments. *The Journal of bone and joint surgery. British volume, 77*(2), 219-224.

Milgrom, C., Finestone, A., Schlamkovitch, N., Wosk, J., Laor, A., & Voloshin, A. (1992). Prevention of overuse injuries of the foot by improved shoe shock attenuation. *Clin Orthop., 281*.

Milgrom, C., Shlamkovitch, N., Finestone, A., Eldad, A., Laor, A., Danon, Y. L., . . . Simkin, A. (1991). Risk Factors for Lateral Ankle Sprain: A Prospective Study Among Military Recruits. *Foot & ankle, 12*(1), 26-30. doi:10.1177/107110079101200105

Miller, C. D., Shelton, W. R., Barrett, G. R., Savoie, F., & Dukes, A. D. (1995). Deltoid and syndesmosis ligament injury of the ankle without fracture. *The American Journal of Sports Medicine, 23*(6), 746-750.

Milner, C. E., & Soames, R. W. (1998). The medial collateral ligaments of the human ankle joint: anatomical variations. *Foot & ankle international, 19*(5), 289-292.

Mohammadi, F., & Roozdar, A. (2010). Effects of fatigue due to contraction of evertor muscles on the ankle joint position sense in male soccer players. *The American Journal of Sports Medicine, 38*(4), 824-828.

Molloy, J. M., Feltwell, D. N., Scott, S. J., & Niebuhr, D. W. (2012). Physical training injuries and interventions for military recruits. *Military Medicine, 177*(5), 553-558.

Morris, J. M. (1977). Biomechanics of the foot and ankle. *Clinical orthopaedics and related research*(122), 10-17.

Mulligan, B. R. (1995). *"NAGS"', "SNAGS", "MWMS", Etc.* (3 ed.). Wellington NZ: Plane View Services LTD.

Nardone, A., Tarantola, J., Giordano, A., & Schieppati, M. (1997). Fatigue effects on body balance. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control, 105*(4), 309-320.

Nashner, L. (1976). Adapting reflexes controlling the human posture. *Experimental brain research, 26*(1), 59-72.

Nashner, L. M. (1982). Adaptation of human movement to altered environments. *Trends in neurosciences, 5*, 358-361.

Nashner, L. M. (2014). Practical biomechanics and physiology of balance. *Balance Function Assessment and Management, 431*.

Ness, M. E., Long, J., Marks, R., & Harris, G. (2008). Foot and ankle kinematics in patients with posterior tibial tendon dysfunction. *Gait & Posture, 27*(2), 331-339.

Neves, E. B., Eraso, N. M., Narváez, Y. S., Rairan, F. S. G., & Garcia, R. C. F. (2017). Musculoskeletal Injuries in sergeants training courses from Brazil and Colombia. *Journal of Science and Medicine in Sport, 20*, S117.

Owens, B. D., & Cameron, K. L. (2016). The Burden of Musculoskeletal Injuries in the Military. In K. L. Cameron & B. D. Owens (Eds.), *Musculoskeletal Injuries in the Military* (pp. 3-10). New York, NY: Springer New York.

Paillard, T. (2012). Effects of general and local fatigue on postural control: A review. *Neuroscience & Biobehavioral Reviews, 36*(1), 162-176. doi:https://doi.org/10.1016/j.neubiorev.2011.05.009

Paillard, T., Costes-Salon, C., Lafont, C., & Dupui, P. (2002). Are there differences in postural regulation according to the level of competition in judoists? *British Journal of Sports Medicine, 36*(4), 304-305.

Paillard, T., & Noé, F. (2006). Effect of expertise and visual contribution on postural control in soccer. *Scandinavian journal of medicine & science in sports, 16*(5), 345-348.

Payne, K. A., Berg, K., & Latin, R. W. (1997). Ankle injuries and ankle strength, flexibility, and proprioception in college basketball players. *Journal of athletic training, 32*(3), 221.

Peake, J. B. (2000). Reflections on injuries in the military: The hidden epidemic. *American Journal of Preventive Medicine, 18*(3, Supplement 1), 4-5. doi:https://doi.org/10.1016/S0749-3797(00)00104-5

Peck, K. Y., DiStefano, L. J., Marshall, S. W., Padua, D. A., Beutler, A. I., Sarah, J., . . . Cameron, K. L. (2017). Effect of a Lower Extremity Preventive Training Program on Physical Performance Scores in Military Recruits. *The Journal of Strength & Conditioning Research, 31*(11), 3146-3157.

Perry, J. (1983). Anatomy and biomechanics of the hindfoot. *Clinical orthopaedics and related research*(177), 9-15.

Peterson, S. N., Call, M. H., Wood, D. E., Unger, D. V., & Sekiya, J. K. (2005). Injuries in Naval Special Warfare Sea, Air, and Land Personnel: Epidemiology and Surgical Management. *Operative Techniques in Sports Medicine, 13*(3), 131-135. doi:https://doi.org/10.1053/j.otsm.2005.10.006

Pfeffer, G., Bacchetti, P., Deland, J., Lewis, A., Anderson, R., Davis, W., . . . Frey, C. (1999). Comparison of custom and prefabricated orthoses in the initial treatment of proximal plantar fasciitis. *Foot & ankle international, 20*(4), 214-221.

Piasis, P., Hanley, K., Havenetidis, K., & Bissas, A. (2008). The effects of military boots with and without a shock absorbing insole on the kinematic characteristics during uphill walking and running. *International review of the armed forces medical services, 84*(2), 19-24.

Pohl, M. B., Rabbito, M., & Ferber, R. (2010). The role of tibialis posterior fatigue on foot kinematics during walking. *Journal of Foot and Ankle Research, 3*(1), 6. doi:10.1186/1757-1146-3-6

Pope, R., Herbert, R., & Kirwan, J. (1998). Effects of ankle dorsiflexion range and pre-exercise calf muscle stretching on injury risk in Army recruits. *Aust J Physiother, 44*(3), 165-172.

Pope, R. P., Herbert, R., Kirwan, J. D., & Graham, B. J. (1999). Predicting attrition in basic military training. *Military Medicine, 164*(10), 710-714.

Procter, P., & Paul, J. (1982). Ankle joint biomechanics. *Journal of Biomechanics, 15*(9), 627-634.

Psaila, M., & Ranson, C. (2017). Risk factors for lower leg, ankle and foot injuries during basic military training in the Maltese Armed Forces. *Physical Therapy in Sport, 24*, 7-12. doi:10.1016/j.ptsp.2016.09.004

Renström, P. A., & Lynch, S. A. (1998). Ankle ligament injuries. *Revista Brasileira de Medicina do Esporte, 4*(3), 71-80.

Requiao, L., Nadeau, S., Milot, M., Gravel, D., Bourbonnais, D., & Gagnon, D. (2005). Quantification of level of effort at the plantarflexors and hip extensors and flexor muscles in healthy subjects walking at different cadences. *Journal of Electromyography and Kinesiology, 15*(4), 393-405.

Reynolds, K., Cosio-Lima, L., Bovill, M., Tharion, W., Williams, J., & Hodges, T. (2009). A comparison of injuries, limited-duty days, and injury risk factors in infantry, artillery, construction engineers, and special forces soldiers. *Military Medicine, 174*(7), 702-708.

Ricard, M. D., Schulties, S. S., & Saret, J. J. (2000). Effects of High-Top and Low-Top Shoes on Ankle Inversion. *Journal of athletic training, 35*(1), 38-43.

Richter, R. R., Austin, T. M., & Reinking, M. F. (2011). Foot Orthoses in Lower Limb Overuse Conditions: A Systematic Review and Meta-Analysis—Critical Appraisal and Commentary. *J Athl Train, 46*(1), 103-106. doi:10.4085/1062-6050-46.1.103

Robbins, S., Gouw, G. J., & McClaran, J. (1992). Shoe sole thickness and hardness influence balance in older men. *Journal of the American Geriatrics Society, 40*(11), 1089-1094.

Robbins, S., & Waked, E. (1997). Foot position awareness: The effect of footwear on instability, excessive impact, and ankle spraining. *Critical Reviews™ in Physical and Rehabilitation Medicine, 9*(1).

Robbins, S., & Waked, E. (1998). Factors associated with ankle injuries. Preventive measures. *Sports Med, 25*(1), 63-72.

Rockar Jr, P. A. (1995). The subtalar joint: anatomy and joint motion. *journal of orthopaedic & sports physical therapy, 21*(6), 361-372.

Rodgers, M. M. (1988). Dynamic biomechanics of the normal foot and ankle during walking and running. *Physical Therapy, 68*(12), 1822-1830.

Rodgers, M. M. (1995). Dynamic foot biomechanics. *journal of orthopaedic & sports physical therapy, 21*(6), 306-316.

Rose, W., Bowser, B., McGrath, R., Salerno, J., Wallace, J., & Davis, I. (2011). *Effect of footwear on balance.* Paper presented at the American Society of Biomechanics Annual Meeting. Long Beach, CA.

Roy, T. C., Ritland, B. M., & Sharp, M. A. (2015). A Description of Injuries in Men and Women While Serving in Afghanistan. *Military Medicine, 180*(2), 126-131. doi:10.7205/MILMED-D-14-00321

Sammito, S., Gundlach, N., & Bockelmann, i. (2016). Injuries caused during military dutyand leisure sport activity. *Work, 54*, 121-126.

Sasagawa, S., Ushiyama, J., Masani, K., Kouzaki, M., & Kanehisa, H. (2009). Balance control under different passive contributions of the ankle extensors: quiet standing on inclined surfaces. *Experimental brain research, 196*(4), 537-544.

Scheuffelen, C., Rapp, W., Gollhofer, A., & Lohrer, H. (1993). Orthotic devices in functional treatment of ankle sprain. *International journal of sports medicine, 14*(03), 140-149.

Schiffman, J. M., Bensel, C. K., Hasselquist, L., Gregorczyk, K. N., & Piscitelle, L. (2006). Effects of carried weight on random motion and traditional measures of postural sway. *Applied ergonomics, 37*(5), 607-614. doi:https://doi.org/10.1016/j.apergo.2005.10.002

Schneider, G. A., Bigelow, C., & Amoroso, P. J. (2000). Evaluating risk of re-injury among 1214 army airborne soldiers using a stratified survival model. *American Journal of Preventive Medicine, 18*(3), 156-163.

Schram, B., Pope, R., & Orr, R. (2019). Injuries in Australian Army full-time and part-time personnel undertaking basic training. *BMC Musculoskeletal Disorders, 20*(1), 6.

Schulze, C., Lindner, T., Schulz, K., Finze, S., Kundt, G., Mittelmeier, W., & Bader, R. (2011). The Influence in Airforce Soldiers Through Wearing Certain Types of Army-Issue Footwear on Muscle Activity in the Lower Extremities. *Open Orthop J, 5*, 302-306. doi:10.2174/1874325001105010302

Schulze, C., Lindner, T., Woitge, S., Schulz, K., Finze, S., Mittelmeier, W., & Bader, R. (2014). Influence of footwear and equipment on stride length and range of motion of ankle, knee and hip joint. *Acta Bioeng Biomech, 16*(4), 45-51.

Schwartz, O., Kanevsky, B., Kutikov, M. A. J. S., Olsen, C. H., & Dudkiewicz, I. (2018). Medical Attrition from Commanders Training in the Israeli Defense Forces (IDF): A Cross-sectional Study on 23,841 Soldiers. *Military Medicine*. doi:10.1093/milmed/usy004

Schwartz, O., Libenson, T., Astman, N., & Haim, L. (2014). Attrition due to orthopedic reasons during combat training: rates, types of injuries, and comparison between infantry and noninfantry units. *Mil Med, 179*(8), 897-900. doi:10.7205/milmed-d-13-00567

Schwartz, O., Malka, I., Olsen, C. H., Dudkiewicz, I., & Bader, T. (2018). Overuse Injuries in the IDF's Combat Training Units: Rates, Types, and Mechanisms of Injury. *Military Medicine, 183*(3-4), e196-e200.

Schwarz, N. A., Kovaleski, J. E., Heitman, R. J., Gurchiek, L. R., & Gubler-Hanna, C. (2011). Arthrometric measurement of ankle-complex motion: normative values. *J Athl Train, 46*(2), 126-132. doi:10.4085/1062-6050-46.2.126

Sekulic, D., Spasic, M., Mirkov, D., Cavar, M., & Sattler, T. (2013). Gender-Specific Influences of Balance, Speed, and Power on Agility Performance. *The Journal of Strength & Conditioning Research, 27*(3), 802-811. doi:10.1519/JSC.0b013e31825c2cb0

Sell, T. C., Pederson, J. J., Abt, J. P., Nagai, T., Deluzio, J., Wirt, M. D., . Lephart, S. M. (2013). The addition of body amor diminishes dynamic postural stability in military soldiers. *Military Medicine, 178*(1), 76-81.

Sharma, J., Greeves, J. P., Byers, M., Bennett, A. N., & Spears, I. R. (2015). Musculoskeletal injuries in British Army recruits: a prospective study of diagnosis-specific incidence and rehabilitation times. *BMC Musculoskeletal Disorders, 16*(1), 106. doi:10.1186/s12891-015-0558-6

Sherrard, J., Lenne, M., Cassell, E., Stokes, M., & Ozanne-Smith, J. (2004). Injury prevention during physical activity in the Australian Defence Force. *J Sci Med Sport, 7*. doi:10.1016/s1440-2440(04)80049-5

Shumway-Cook, A., & Horak, F. B. (1986). Assessing the influence of sensory interaction on balance: suggestion from the field. *Physical Therapy, 66*(10), 1548-1550.

Shumway-Cook, A. W. a. W., M. H. (2013). *Motor Control: Translating Research into Clinical Practice* (4 ed.). Baltimore: Lippincott Williams & Wilkins, Md, USA.

Siegler, S., Block, J., & Schneck, C. D. (1988). The mechanical characteristics of the collateral ligaments of the human ankle joint. *Foot & ankle, 8*(5), 234-242.

Smith, G. S., Dannenberg, A. L., & Amoroso, P. J. (2000). Hospitalization due to injuries in the military. Evaluation of current data and recommendations on their use for injury prevention. *Am J Prev Med, 18*. doi:10.1016/s0749-3797(99)00171-3

Smith, T. A., & Cashman, T. M. (2002). The Incidence of Injury in Light Infantry Soldiers. *Military Medicine, 167*(2), 104-108. doi:10.1093/milmed/167.2.104

Soucie, J., Wang, C., Forsyth, A., Funk, S., Denny, M., Roach, K., . . . Network, H. T. C. (2011). Range of motion measurements: reference values and a database for comparison studies. *Haemophilia, 17*(3), 500-507.

Stauffer, R. N., Chao, E., & Brewster, R. C. (1977). Force and motion analysis of the normal, diseased, and prosthetic ankle joint. *Clinical orthopaedics and related research*(127), 189-196.

Stephens, M. M., & Sammarco, G. J. (1992). The stabilizing role of the lateral ligament complex around the ankle and subtalar joints. *Foot & ankle, 13*(3), 130-136.

Strowbridge, N., & Burgess, K. (2002). Sports and training injuries in British soldiers: the Colchester Garrison Sports Injury and Rehabilitation Centre. *Journal of the Royal Army Medical Corps, 148*(3), 236-243.

Surve, I., Schwellnus, M. P., Noakes, T., & Lombard, C. (1994). A fivefold reduction in the incidence of recurrent ankle sprains in soccer players using the Sport-Stirrup orthosis. *The American Journal of Sports Medicine, 22*(5), 601-606.

Taanila, H., Suni, J., Pihlajamäki, H., Mattila, V. M., Ohrankämmen, O., Vuorinen, P., & Parkkari, J. (2009). Musculoskeletal disorders in physically active conscripts: a one-year follow-up study in the Finnish Defence Forces. *BMC Musculoskeletal Disorders, 10*(1), 89.

Tomlinson, J. P., Lednar, W. M., & Jackson, J. D. (1987). Risk of Injury in Soldiers. *Military Medicine, 152*(2), 60-64. doi:10.1093/milmed/152.2.60

Trojian, T. H., & McKeag, D. B. (2006). Single leg balance test to identify risk of ankle sprains. *British Journal of Sports Medicine, 40*(7), 610-613. doi:10.1136/bjsm.2005.024356

Tropp, H., Askling, C., & Gillquist, J. (1985). Prevention of ankle sprains. *The American Journal of Sports Medicine, 13*(4), 259-262.

Vander, A. J., Sherman, J. H., Luciano, D. S. (1991). *Human Physiology: The Mechanisms of Body Function* (5 ed.). New York: McGraw-Hill.

Verhagen, E., van der Beek, A., Twisk, J., Bouter, L., Bahr, R., & van Mechelen, W. (2004). The effect of a proprioceptive balance training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med, 32*. doi:10.1177/0363546503262177

Verhagen, E. A. L. M., van der Beek, A. J., & van Mechelen, W. (2001). The Effect of Tape, Braces and Shoes on Ankle Range of Motion. *Sports Medicine, 31*(9), 667-677. doi:10.2165/00007256-200131090-00003

Viladot, A., Lorenzo, J. C., Salazar, J., & Rodriguez, A. (1984). The subtalar joint: embryology and morphology. *Foot & ankle, 5*(2), 54-66.

Wang, H.-K., Chen, C.-H., Shiang, T.-Y., Jan, M.-H., & Lin, K.-H. (2006). Risk-factor analysis of high school basketball–player ankle injuries: A prospective controlled cohort study evaluating postural sway, ankle strength, and flexibility. *Archives of physical medicine and rehabilitation, 87*(6), 821-825.

Warburton, M. (2001). Barefoot running*5*(3). Retrieved from http://sportsci.org/jour/0103/mw.htm

Wardle, S. L., Greeves, Julie P. (2017). Mitigating the risk of musculoskeletal injury; A systematic review of the most effective injury prevention strategies for military personnel. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2017.09.014

Waterman, B. R., Belmont, P. J., Cameron, K. L., DeBerardino, T. M., & Owens, B. D. (2010). Epidemiology of Ankle Sprain at the United States Military Academy. *The American Journal of Sports Medicine, 38*(4), 797-803. doi:10.1177/0363546509350757

Whiting, W. C., Zernicke, R. F. (2008). *Biomechanics of Musculoskeletal Injury* (2 ed.). Champaign, IL: Human Kinetics.

Wilkinson, D. M., Blacker, S. D., Richmond, V. L., Horner, F. E., Rayson, M. P., Spiess, A., & Knapik, J. J. (2011). Injuries and injury risk factors among British army infantry soldiers during predeployment training. *Injury Prevention, 17*(6), 381-387. doi:10.1136/ip.2010.028233

Willems, T. M., Witvrouw, E., Delbaere, K., Mahieu, N., Bourdeaudhuij, L. D., & Clercq, D. D. (2005). Intrinsic Risk Factors for Inversion Ankle Sprains in Male Subjects: A Prospective Study. *The American Journal of Sports Medicine, 33*(3), 415-423. doi:10.1177/0363546504268137

Williams K. M., B. S. K., Hagy J., Kaufman K. (1997). Biomechanical properties of infantry combat boot development. Technical Report. (Report No.: 97-26

ed.). San Diego: Naval Health Research Center.

Winter, D., & Yack, H. (1987). EMG profiles during normal human walking: stride-to-stride and inter-subject variability. *Electroencephalography and clinical neurophysiology, 67*(5), 402-411.

Winter, D. A. (1995). *ABC (anatomy, biomechanics and control) of balance during standing and walking*: Waterloo Biomechanics.

Winter, D. A., Patla, A. E., & Frank, J. S. (1990). Assessment of balance control in humans. *Med Prog Technol, 16*(1-2), 31-51.

Withnall, R., Eastaugh, J., & Freemantle, N. (2006). Do shock absorbing insoles in recruits undertaking high levels of physical activity reduce lower limb injury? A randomized controlled trial. *Journal of the Royal Society of Medicine, 99*(1), 32-37.

Wohleber, M., Keenan, K., Perlsweig, K., Simonson, A., Connaboy, C., Nindl, B., & Beals, K. (2017). Musculoskeletal, physiological, and balance characteristics associated with prospective lower extremity injury type in Special Operations Forces. *Journal of Science and Medicine in Sport, 20*, S22. doi:https://doi.org/10.1016/j.jsams.2017.09.054

Wright, I., Neptune, R., van den Bogert, A. J., & Nigg, B. (2000). The influence of foot positioning on ankle sprains. *Journal of Biomechanics, 33*(5), 513-519.

Yang, H.-R., Kim, M.-K., & Yoo, K.-T. (2015). The effects of the length of rain boots on balance during treadmill walking. *Journal of physical therapy science, 27*(10), 3261-3266.

Yentes, J. M., Kurz, M. J., & Stergiou, N. (2014). Lower extremity injury in female basketball players is related to a large difference in peak eversion torque between barefoot and shod conditions. *Journal of Sport and Health Science, 3*(3), 227-232.

Chapter 3: Incidences and Causative Factors of Lower Limb Injuries in the New Zealand Army

3.1 Chapter Overview

A high incidence of lower limb injuries was brought to the attention to the New Zealand Army. In order to determine what the incidences truly were and whether this was a regular occurrence or an aberration AEP (Accredited Employer Provider), data was investigated to identify the scale of the problem. Before any interventions could be addressed it was necessary to identify what physiological structures were most effected and possibly why. This following chapter highlights the epidemiology of the lower limb injury problem of the New Zealand Army.

3.2 Abstract

Objective

To examine long-term musculoskeletal injury trends in the New Zealand Army and determine the most common injuries and the activities as a causative factor. This will be useful for identifying activities causing injuries.

Methods

Eleven years of reported musculoskeletal injury data for the New Zealand Army (n=20461) was examined. Activities as causative factors were derived from a filtered narrative, completed by the soldier at time of injury. Frequency data and Chi square analysis was carried out on injury anatomical site by activity.

Results

Analysis shows a significant proportion of injuries are lower limb injuries (45%) and this rate has remained static over 11 years. The ankle has the highest injury rate, with most of these occurring during military physical training and individual sports during sporting activities.

Conclusion

Regardless of several interventions over 11 years, the overall injury rates did not change. Of the physical training and individual sport activities, running resulted in the most ankle injuries. These results will help inform defence forces when injuries are likely to occur. Future research is required to determine ankle injury aetiology.

Implications for Public Health

This study will provide the New Zealand Army with information for the development of a strategy to prevent lower limb injuries, particularly to the ankle joint.

3.3 Introduction

Musculoskeletal injuries are a significant problem in military populations (Andersen et al., 2016; Davidson et al., 2008; Kaufman et al., 2000). For New Zealand, this results in approximately 20% of the total number of New Zealand Army (NZA) Regular Force personnel not able to be deployed at any given time (Annual Report on the Health of the New Zealand Army 2013, unpublished). Additionally, they are the most common cause of discontinuing military service (Frilander et al., 2012). The overall costs of injuries to any armed forces are loss of manpower, loss of training time, loss of duty time, reduction in force effectiveness or readiness and an increase in medical costs (Wallace et al., 2011). Data extracted from the New Zealand Defence Force's Accredited Employer Programme (AEP) indicates that minor (Grade 1) to moderate (Grade 2) musculoskeletal injuries, such as a sprain or strain, are estimated to cost the NZA between $1 – 1.5 M per annum. However, this does not take into consideration the true cost to the NZA in terms of loss of manpower and training days.

Military commanders may well accept that current injury rates are an inevitable outcome of military training, as it includes many activities such as loaded running, walking, climbing and marching, often performed at high intensity levels, predisposing soldiers to injury (Davidson et al., 2008). Nonetheless, injuries remain one of the NZA's greater challenges, as the potential exists for injury related factors to adversely affect deployability of combat personnel in a tactical or kinetic operation. Military injury statistics have been reported previously, for example a snapshot of New Zealand Defence Force regular force members' lower limb injuries from 2002-2003 (Davidson et al., 2008) reported the largest number of lower limb injuries were at the ankle (37.1%).

Studies of between 8 - 52 weeks duration examining injuries in defence forces of other nations have reported similar results (Kaufman et al., 2000). As a result of injuries in the US Army, physical training programmes were redesigned (Knapik et al., 2009). The US Army implemented the Physical Readiness Training and Fitness Assessment Programme (PRT) (Molloy et al., 2012) during US Army Basic Combat Training and the Ordnance Advanced Individual Training for an operational infantry unit. The programme was evaluated by the US Army Centre for Health Promotions (Knapik et al., 2009). These programmes have been successful in reducing the number of musculoskeletal injuries during initial military training; however, the long-term effects of these programmes are not known.

Few longitudinal studies document ankle and foot injury trends over many years. Knapik et al. (2012) completed a study examining the demographics and physical risk factors for stress fractures in US Army recruits over the period from 1997 to 2007. A report by the US Army Public Health Centre ("US Army Public Health Center: Health of the Force Report," 2016) documents the number of musculoskeletal injuries in US Army soldiers with more than half of all injuries being lower extremity injuries. However, they did not document or highlight when or if interventions had taken place during that time, as numerous studies have suggested (Franklyn-Miller et al., 2011; Parkkari et al., 2011; Zambraski & Yancosek, 2012), and if the trends changed accordingly.

A review by Andersen et al. (2016) reported that musculoskeletal injury rates in the military are still a significant issue despite substantial research regarding intervention strategies to mitigate injuries. Therefore, there is a need to track possible patterns or trends over a number of years, particularly noting when any intervention strategies were put in place to reduce injury to properly assess their efficacy. Furthermore, a long-term understanding of any injury trend is required before investigation in aetiology, changes in policy, or further interventions to improve the number of military personnel for deployment and reduce associated costs are implemented. This study aims to identify long-term trends in the occurrence of lower limb injuries in the NZ military population over 11 years, and whether any alteration in the trend was due to an implemented intervention directed at reducing lower limb injury risk.

3.4 Methods

Data from 2005 to 2015 were extracted from the New Zealand Defence Force (NZDF) Accredited Employer Programme (AEP), which is affiliated to the New Zealand Government Accident Compensation Corporation Act (ACC) 2001. The AEP allows an employer to act on behalf of the ACC, managing workplace injuries for their employees and providing entitlements under the 2001 Act for work-related personal injuries and illnesses. All injuries are legally required under the Act to be recorded through the AEP process.

All injuries requiring medical attention are captured and classified according to the Read Classification System (Chisholm, 1990) used by the NZDF. Lower limb injuries are defined in the Read System as injuries to the hip, thigh, knee, lower leg, ankle, foot and toe. Although the AEP data does include hip and thigh injuries, for the purposes of this study, “lower limb” was confined to the knee, lower leg, ankle and foot. Each AEP entry is recorded as a new injury event; therefore, an individual may have more than one AEP event within a year. Reoccurring injuries to specific anatomical sites is indicative of not addressing the aetiology of the injury. It is also important to note these data refer to reported injury events and not a different individual for each injury as the outcome remains that the person is not available for deployment.

In order to determine causal factors of the injuries, the narrative given on the AEP form completed by the soldier was searched to identify the activity at the time of the injury. The narrative includes statements such as “Running during unit PT and stepped into a hole and felt pain in left calf” and “Rolled my left ankle while doing an 8 km pack march”. Narratives were filtered using Microsoft© Excel 2016 to uncover the contributing activity, e.g.:

a. “Running during unit physical training (PT) and felt pain in left calf”.

    (1) Injury – lower limb (left calf)

    (2) Contributing activity in which it occurred – running

b. “Rolled my left ankle while doing an 8 km pack march”

    (1) Injury – lower limb (ankle)

    (2) Contributing activity – military training (pack march)

Three main activity categories were identified from the narratives, 1. Military Training; 2. Sport; and 3. Other (Table 3.1).

Military training activities were further divided into six categories (Table 3.1): combat drill, military core skills training, pack marching, physical training, walking/patrolling and accident/other. This categorisation is useful in that it identifies specific groups of training activities, which may be causative. Each of these categories are distinctly different activities. For example, pack marching, which is a loaded activity versus combat drill, which includes contact activities. Patrolling is walking with boots, wearing full uniform and carrying various loads, while physical training is structured exercise in sport fatigues (T-shirt, shorts and training shoes) to enhance aerobic and anaerobic fitness and includes calisthenics to increase body strength. The physical training category also includes running in sport fatigues as a form of exercise to maintain and improve aerobic fitness. This is often performed at the soldiers' leisure or during structured physical training sessions. Pack marching involves wearing full military uniform, military boots and carriage of equipment and weaponry in urban and field environments. Military training encompasses training in individual military core skills such as parade ground drill, whereas combat drill involves fully equipped soldiers engaged in physical contact activities such as close quarter combat and riot training. Accidents/other refer to incidental or unplanned events; examples of accidents include unintended collisions, trips or falls during military training. These injuries are usually acute by nature. "Other" refers to injuries having no reported activity or contributing factor reported in the AEP narrative given by the soldier e.g., "hurt my left leg", and "woke up this morning and felt pain in my ankle".

To determine during which sporting activity ankle and other lower limb injuries occurred, different sports were grouped together according to the sport type (Table 3.1): indoor court, contact, individual, field and other sports. The sports identified are common to New Zealand; NZA personnel participate in them on an official basis. Some of these sports may be different in other countries e.g., netball, rugby union and rugby league, touch rugby and cricket. Categories also allowed for sufficient sample size analysis in this study. "Other" sports refer to minor unofficial NZA sporting codes with few participants. These include sports such as rock climbing and ultimate frisbee.

Table 3.1. Main Categories and Activities

Military Training (N = 3262)	**Sport** (N = 2769)	**Other** (N = 860)
Assaulting	Basketball	Accident
Battle drill	Boxing	Falling/Tripping/Slipping
Battle efficiency testing	Cricket	Collision
Combat fitness testing	Cycling	Exposure
Close quarter combat	Handball	Lifting
Parade ground drill	Rugby League	Motor vehicle accident
Jumping	Rugby Union	Overuse
Pack marching	Running	
Parachuting	Skiing	
Physical Training	Snowboarding	
Patrolling	Soccer	
Rappelling	Softball	
Required fitness testing	Squash	
Riot training	Swimming	
Ropes	Tennis	
Walking	Touch	
	Volleyball	

The time versus lower limb injury rate plots (Figure 3.1) denote when the NZA implemented specific physical training or footwear-related interventions. Cross tabulation analysis was carried out using Chi-Square statistical analysis and significant relationships ($p < 0.001$) were determined between: (A) Injury Site and Main Activity; (B) Injury Site and Military Training Activities; and (C) Injury Site and Sporting Activities.

3.5 Results

Data from the past 11 years (Figure 3.1) revealed there has been little change in injury rates over this period despite changes to footwear (2009, 2010, 2014, 2015) and the implementation of a balance and proprioceptive training programme during initial military training (2013). On average, 40% of all NZA soldiers were injured annually, and

45% of these injuries are to the lower limb. The ankle joint had the highest proportion of all the lower limb injuries (Figures 3.2a-c).

Cross tabulation analysis of: A. *Injury Site and Main Activity* showed the ankle had the highest incidence of injury in military training and sport activities whereas the knee had the highest number of injuries in the category 'Other' (X^2 (6, N = 860) = 91.56, $p < 0.001$) (Figure 3.2a); B. *Injury Site and Military Training Activities* revealed the ankle joint had the greatest amount of injuries (X^2 (15, N = 3262) = 142.49, $p < 0.001$) (Figure 3.2b); C. *Injury Site and Sporting Activities* revealed that the ankle joint was the site with the highest amount of injuries for indoor court sports, individual sports and field sports. The knee is the site with the greatest number of injuries for contact sports; the lower leg and knee are the injury sites with the greatest number of injuries in other sports (X^2 (12, N = 2769) = 221.62, $p < 0.001$) (Figure 3.2c).

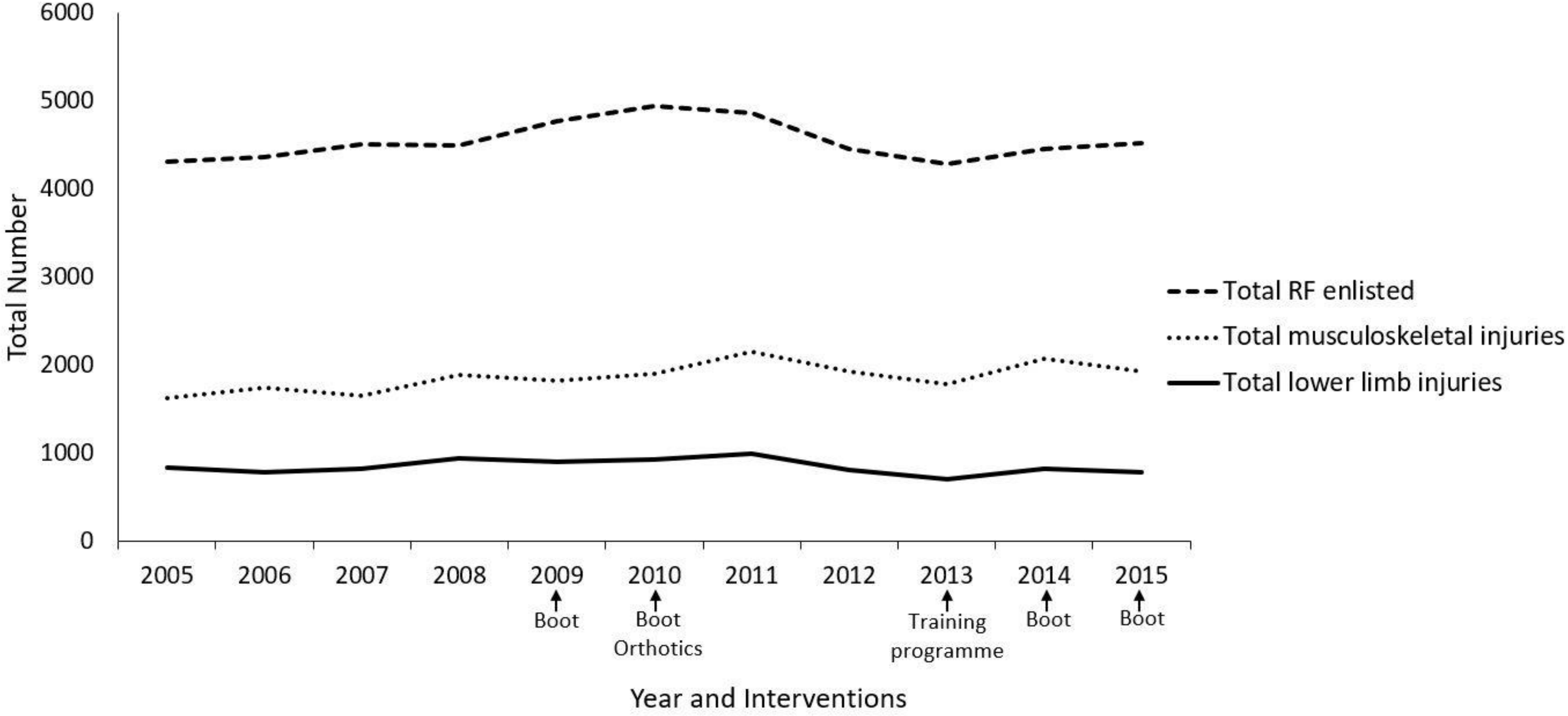


Figure 3.1. Trends from New Zealand Defence Force AEP data from 2005-2015 for total number of regular force (RF) personnel, total number of musculoskeletal injuries, and total number of lower limb injuries

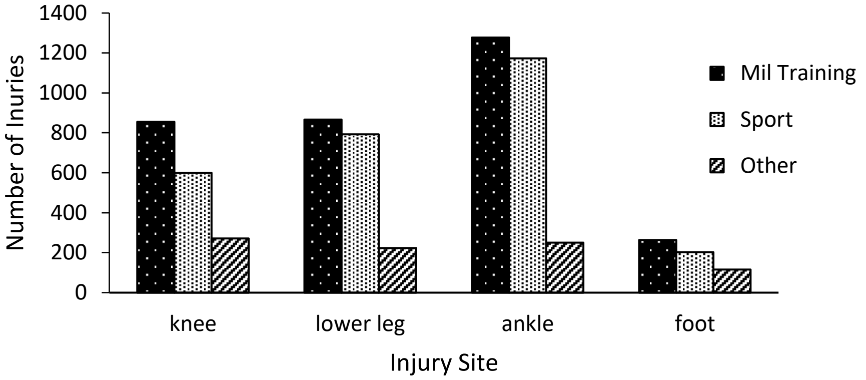


Figure 3.2a. Main Activity

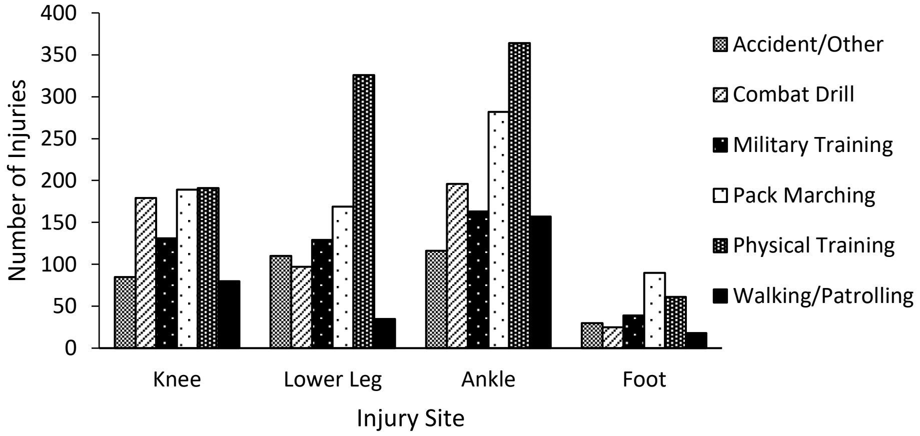


Figure 3.2b. Military Training Avtivities

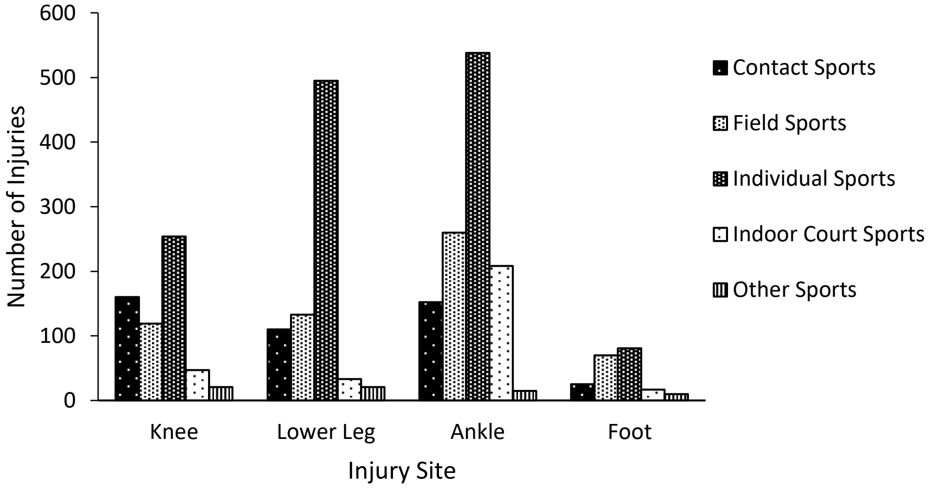


Figure 3.2c. Sporting Activities

Figure 3.2a – c. Injury sites and causative activities. Main activities identified (a), military training activities (b), and (c) sports.

3.6 Discussion

This research represents one of only a few to describe long-term lower limb injury trends in the military and is the first to do so for the NZA. It is also the first to note when interventions were implemented over the period. Eleven years of NZA injury data show an unchanging trend of high numbers of lower limb injuries. Moreover, the ankle joint is still the most injured joint during military and sporting activities, with running as the most common activity leading to ankle injury in the NZA. Lower limb injuries, particularly the ankle joint, account for the highest proportion of all injuries sustained in the NZA regardless of multiple interventions over the intervening years.

At present, approximately 40% of all NZA soldiers are injured or re-injured annually, of this 40% total injury rate, 45% are to the lower limb. Similarity can be found in the recent study by Schwartz et al. (2014) who reported that lower limb injuries accounted for 44.5% of all injuries in the Israeli Defence Force during up to 7 months basic training. Furthermore, our findings are in agreement with Davidson et al. (2008) who identified the ankle as the most common lower limb musculoskeletal injury site in the NZDF. Of the three military services making up the NZDF, the Royal New Zealand Navy (RNZN); the New Zealand Army; and the Royal New Zealand Air Force (RNZAF), the NZA is the service having the highest proportion of ankle injuries. Previous research (Andersen et al., 2016; Frilander et al., 2012; Havenetidis et al., 2011; Sammito et al., 2016; Wallace et al., 2011) has also highlighted the ankle joint as the most common injury site in military populations. These injuries were attributed to challenging training programmes and other physical activities of military training and operations, but did not specify which specific military training activities resulted in ankle injury. A report by the US Army

Public Health Centre (Hauschild et al., 2018) noted the ankle was the most common site for acute and traumatic injuries, but was the third most injured site (behind the knee and hip) for all injuries. However, these are only reported for new recruits in a calendar year. Further studies are situation specific for injuries, for example Roy et al. (2012) reported low back and other body regions have higher injury rates in a combat team on deployment; or vehicle mechanics had a greater number of lower back and knee injuries (Knapik et al., 2007) noting these injuries are trade specific and do not take total number of injuries for US Army personnel into consideration, neither are any interventions discussed. Our current study did not distinguish between new recruits, situation or time in service. Moreover, it has shown additional information that running during PT, or as an activity on its own, was the most common contributor to ankle injury.

It was thought that lower limb injuries and particularly ankle injuries would be most prevalent in contact sports such as rugby union and rugby league, or those with a high degree of running and jumping on hard surfaces such as basketball as previously reported by Borowski et al. (2008) and Cumps et al. (2007). While these factors were prominent, the significant injury inducing activity was simply running. Furthermore, investigations of injury trends in rugby have reported the head/neck/shoulder region of the body similar numbers of injuries as the lower limb albeit lower limb injuries required the longest average absence from play (Bottini et al., 2000; Gabbett, 2000).

One could assume that the ankle joint has been compromised or the nature of training is damaging the ankle joint. The ankle may be unstable due to a lack in strength and/or proprioception therefore predisposing it to injury. Training regimes do not appear to have strengthened the joint sufficiently to meet the demands of military training. It is possible new recruits are arriving for military training with already “weakened” ankle joints which predisposes them to lower limb and ankle injuries early in the military training programme. This is supported by reported attrition rates due to lower limb musculoskeletal injury of potential new recruits who underwent a medical examination up to one year prior to the day of compulsory recruitment in the Israeli Defence Force (Schwartz et al., 2014). Similarly, Goodall et al. (2013) reported injuires to the knee (24%) and ankle (14%) during Australian Army recuit training.

Despite research reporting that soldiers may be predisposed to ankle injuries (Orr et al., 2017; Schulze et al., 2011), no definitive evidence exists regarding the possible mechanisms that if identified in this population, could be reversed. Our data show unequivocally that the trend of lower limb injuries has been static over the past 11 years (Figure 3.1), and this is despite interventions such as changes to footwear (military boots and running shoes). This is supported by studies whereby examining changes to training shoes as an intervention confirmed that assigning running shoes based on the shape of the plantar surface of the foot had little influence on injury risk (Knapik et al., 2010). This included assigning to recruits motion control, stability, or cushioned shoes based on static foot type. Finestone and Milgrom (2008) also found that shoe modifications and orthoses were not effective in lowering the incidence of injuries in the Israeli Army. A systematic review by Wardle (2017) investigating the mitigation of musculoskeletal injuries in military populations found no clear indication of the effectiveness of footwear modifications.

Changes to physical training programmes such as the introduction of more controlled warm-up and cool-down protocols, the inclusion of balance board training (Davidson et al., 2009) or combined balance and agility training have all been used as interventions to decrease lower limb injuries in military populations (COPpack et al., 2011; Goodall et al., 2013; Herman et al., 2012). None of the above-mentioned interventions were followed up for long term effectiveness, or lower limb injury data examined for decreasing trends. Knapik et al. (2009) documented a training programme intervention that included proprioception-balance-agility components to reduce injury. The inclusion of balance and agility training as an intervention in the military is normally implemented as an extra training requirement. This type of additional structured balance and agility training for recruit physical training did not significantly reduce lower limb, knee and ankle, or knee and ankle ligament injury rates, probably due to an existing high training load, and may even have hastened the onset of injury (Goodall et al., 2013). The NZA implemented a similar such intervention in 2013 (see Figure 3.1); it did not affect the overall trend in ankle injury rates.

Further training related interventions include the reduction of the cumulative training load and marching distance, and a gradual increase in training intensity to reduce the incidence of injuries (Kaufman et al., 2000). The modification of intensity, frequency and duration of basic military training activities and an improvement in equipment resulted in a reduction of overuse and stress fracture injury while achieving recruit fitness levels (Sherrard et al., 2004). The US Army Physical Readiness Training programme has been successful in reducing injury rates when compared to traditional Army physical training programmes (Knapik et al., 2009). However, most physical training intervention programmes are implemented during basic military training and no long-term effect has yet been established.

Shock absorbing insoles and foot orthotic devices have had substantial attention as a mitigating factor in preventing lower limb injuries in military populations; however, results are inconclusive as to their effectiveness. The NZA undertook a trial in 2010 to assess the feasibility of addressing lower limb injuries by issuing orthotics (Baxter et al., 2012). During this trial, shock-absorbing insoles seemed to be of benefit for reducing stress fracture-type overuse injuries, but not a reduction in all lower limb injuries (Wardle, 2017). In an earlier study investigating the use of insoles, a potentially successful insole was identified, however the study also acknowledged that further research was required to determine any definitive results in the use of an insole for injury mitigation (Dixon et al., 2003). Similarly, a trial was conducted by Franklyn-Miller et al. (2011) to investigate the use of customised orthoses to reduce the incidence of lower limb injuries during military training. The trial demonstrated a significant decrease in exercise-related lower limb injuries during a single training period. However, a critical analysis by Richter et al. (2011) of a review by Collins et al. (2007) regarding the use of orthoses, found there was insufficient evidence to recommend foot orthoses for the prevention of lower limb injuries. Furthermore, the systematic review by Baxter et al. (2012) investigating the use of orthotics as an injury prevention strategy for military personnel indicated that no strong conclusions can be made on the use of orthotics as a preventive measure for overuse injury in the military. It must be stated that an overriding factor with studies investigating the use of orthotics is they are conducted over short time periods, typically between 12 and 15 weeks (Baxter et al., 2012), which may mean the efficacy of their use could be ‘lost’ in injury statistics covering longer periods of +52 weeks.

It is important to note that the proportion of time spent in each category of training has not been quantified. This is recognised as a limitation; however, this is an observational study to understand trends and associated activities, and not to determine specificity in those activities. Nevertheless, one of the outcomes of any significant injury pattern findings will be to construct future research around the proportion of training categories. A change in exercise duration for certain categories may well reduce injury rates.

A further limitation is not distinguishing whether the injuries were sustained by recruits or trained servicemen. As stated in the discussion, several studies report higher injuries in recruits which may bias the result. Nevertheless, the aim of this study was to report the trend of lower limb injuries over a number of years, and it does not appear to change.

This study did not list the underlying factors which precedes an injury initiating event, as set out in Meeuwisse's multifactorial injury causation model (Meeuwisse, 1994). It reports the trend of events that lead to the injury and therefore provides scope to work backwards to identify those susceptible via internal risk factors or identify external factors.

3.7 Implications for Public Health

This paper has important implications as it addresses the fact that interventions have been carried out regarding the high rate of ankle injuries in the NZA, yet no significant decreases in the number of ankle injuries has taken place over 11 years. Before any further appropriate injury prevention strategies and training programmes can be put in place, it is important that the causes and mechanisms of injuries are understood and thoroughly assessed. A case in point is that the activity inciting the greatest number of ankle injuries was running. However, it does not mean that soldiers should run less, but rather that further research is required to understand why.

Continued efforts to ameliorate preventable ankle injuries in the military setting, will have personal, economic and organisational benefits.

3.8 Conclusion

This study is unique in identifying unchanged lower-limb injury data for over a decade, despite interventions of changes to boots or running shoes and alterations to recruit training. Furthermore, this study confirms that injury occurrences to the lower limb and particularly the ankle joint are the most prevalent injuries in the NZA. The majority of these injuries occur during running whether it is military physical training or sports. Further investigations are required to define the aetiology of these lower limb injuries, particularly the ankle joint, are recommended before initiating future risk reduction interventions.

3.9 References

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Baxter, M. L., Ribeiro, D. C., & Milosavljevic, S. (2012). Do orthotics work as an injury prevention strategy for the military? *Physical Therapy Reviews, 17*(4), 241-251. doi:10.1179/1743288X12Y.0000000013

Borowski, L. A., Yard, E. E., Fields, S. K., & Comstock, R. D. (2008). The epidemiology of US high school basketball injuries, 2005-2007. *Am J Sports Med, 36*(12), 2328-2335. doi:10.1177/0363546508322893

Bottini, E., Poggi, E., Luzuriaga, F., & Secin, F. (2000). Incidence and nature of the most common rugby injuries sustained in Argentina (1991–1997). *Br J Sports Med, 34*(2), 94-97. doi:10.1136/bjsm.34.2.94

Chisholm, J. (1990). The read classification. *British Medical Journal, 300*(6372), 1092.

Collins, N., Bisset, L., McPoil, T., & Vicenzino, B. (2007). Foot orthoses in lower limb overuse conditions: a systematic review and meta-analysis. *Foot & ankle international, 28*(3), 396-412.

COPpack, R. J., Etherington, J., & Wills, A. K. (2011). The Effects of Exercise for the Prevention of Overuse Anterior Knee Pain:A Randomized Controlled Trial. *The American Journal of Sports Medicine, 39*(5), 940-948. doi:10.1177/0363546510393269

Cumps, E., Verhagen, E., & Meeusen, R. (2007). Prospective Epidemiological Study of Basketball Injuries During One Competitive Season: Ankle Sprains and Overuse Knee Injuries. *J Sports Sci Med, 6*(2), 204-211.

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

Davidson, P. L., Wilson, S. J., Chalmers, D. J., Wilson, B. D., & McBride, D. (2009). Examination of interventions to prevent common lower-limb injuries in the New Zealand Defense Force. *Military Medicine, 174*(11), 1196-1202.

Dixon, S. J., Waterworth, C., Smith, C. V., & House, C. M. (2003). Biomechanical analysis of running in military boots with new and degraded insoles. *Med Sci Sports Exerc, 35*(3), 472-479. doi:10.1249/01.mss.0000053733.64049.27

Finestone, A., & Milgrom, C. (2008). How stress fracture incidence was lowered in the Israeli army: a 25-yr struggle. *Medicine and science in sports and exercise, 40*(11 Suppl), S623-629. doi:10.1249/mss.0b013e3181892dc2

Franklyn-Miller, A., Wilson, C., Bilzon, J., & McCrory, P. (2011). Foot Orthoses in the Prevention of Injury in Initial Military Training. *The American Journal of Sports Medicine, 39*(1), 30-37. doi:10.1177/0363546510382852

Frilander, H., Miranda, H., Mutanen, P., Martelin, T., Pihlajamaki, H., & E, V.-J. (2012). Trends in musculoskeletal disorders and related health care utilisation among conscripts in Finland 1967-2006. *Military Medicine, 177*, 1069-1074.

Gabbett, T. (2000). Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med, 34*(2), 98-103. doi:10.1136/bjsm.34.2.98

Goodall, R. L., Pope, R. P., Coyle, J. A., & Neumayer, R. (2013). Balance and agility training does not always decrease lower limb injury risks: a cluster-randomised controlled trial. *International Journal of Injury Control and Safety Promotion, 20*(3), 271-281. doi:10.1080/17457300.2012.717085

Hauschild, V. D., Lee, T., Richardson, M., Hauret, K., & Jones, B. H. (2018). *Application of the Taxonomy of Injuries: Analysis of Army Recruit Injuries, CY 2016*. Retrieved from: https://apps.dtic.mil/dtic/tr/fulltext/u2/1049222.pdf

Havenetidis, K., Kardaris, D., & Paxinos, T. (2011). Profiles of musculoskeletal injuries among Greek Army officer cadets during basic combat training. *Mil Med, 176*(3), 297-303.

Herman, K., Barton, C., Malliaras, P., & Morrissey, D. (2012). The effectiveness of neuromuscular warm-up strategies, that require no additional equipment, for preventing lower limb injuries during sports participation: a systematic review. *BMC medicine, 10*, 75-75. doi:10.1186/1741-7015-10-75

Kaufman, K. R., Brodine, S., & Shaffer, R. (2000). Military training-related injuries: surveillance, research, and prevention. *Am J Prev Med, 18*(3 Suppl), 54-63.

Knapik, J., Montain, S. J., McGraw, S., Grier, T., Ely, M., & Jones, B. H. (2012). Stress Fracture Risk Factors in Basic Combat Training. *Int J Sports Med, 33*(11), 940-946. doi:10.1055/s-0032-1311583

Knapik, J. J., Brosch, L. C., Venuto, M., Swedler, D. I., Bullock, S. H., & Gaines, L. S. (2010). Effect on injuries of assigning shoes based on foot shape in air force basic training. *Am J Prev Med, 38*. doi:10.1016/j.amepre.2009.10.013

Knapik, J. J., Jones, S. B., Darakjy, S., Hauret, K. G., Bullock, S. H., Sharp, M. A., & Jones, B. H. (2007). Injury rates and injury risk factors among US Army wheel vehicle mechanics. *Military Medicine, 172*(9), 988-996.

Knapik, J. J., Rieger, W., Palkoska, F., Van Camp, S., & Darakjy, S. (2009). United States Army physical readiness training: rationale and evaluation of the physical training doctrine. *J Strength Cond Res, 23*(4), 1353-1362. doi:10.1519/JSC.0b013e318194df72

Meeuwisse, W. H. (1994). Assessing Causation in Sport Injury: A Multifactorial Model. *Clinical Journal of Sport Medicine, 4*(3), 166-170.

Molloy, J. M., Feltwell, D. N., Scott, S. J., & Niebuhr, D. W. (2012). Physical training injuries and interventions for military recruits. *Military Medicine, 177*(5), 553-558.

Orr, R. M., Coyle, J., Johnston, V., & Pope, R. (2017). Self-reported load carriage injuries of military soldiers. *International Journal of Injury Control and Safety Promotion, 24*(2), 189-197. doi:10.1080/17457300.2015.1132731

Parkkari, J., Taanila, H., Suni, J., Mattila, V. M., Ohrankammen, O., & Vuorinen, P. (2011). Neuromuscular training with injury prevention counselling to decrease the risk of acute musculoskeletal injury in young men during military service: a population-based, randomised study. *BMC medicine, 9*. doi:10.1186/1741-7015-9-35

Richter, R. R., Austin, T. M., & Reinking, M. F. (2011). Foot Orthoses in Lower Limb Overuse Conditions: A Systematic Review and Meta-Analysis—Critical Appraisal and Commentary. *J Athl Train, 46*(1), 103-106. doi:10.4085/1062-6050-46.1.103

Roy, T. C., Knapik, J. J., Ritland, B. M., Murphy, N., & Sharp, M. A. (2012). Risk factors for musculoskeletal injuries for soldiers deployed to Afghanistan. *Aviation, space, and environmental medicine, 83*(11), 1060-1066.

Sammito, S., Gundlach, N., & Bockelmann, i. (2016). Injuries caused during military dutyand leisure sport activity. *Work, 54*, 121-126.

Schulze, C., Lindner, T., Schulz, K., Finze, S., Kundt, G., Mittelmeier, W., & Bader, R. (2011). The Influence in Airforce Soldiers Through Wearing Certain Types of Army-Issue Footwear on Muscle Activity in the Lower Extremities. *Open Orthop J, 5*, 302-306. doi:10.2174/1874325001105010302

Schwartz, O., Libenson, T., Astman, N., & Haim, L. (2014). Attrition due to orthopedic reasons during combat training: rates, types of injuries, and comparison between infantry and noninfantry units. *Mil Med, 179*(8), 897-900. doi:10.7205/milmed-d-13-00567

Sherrard, J., Lenne, M., Cassell, E., Stokes, M., & Ozanne-Smith, J. (2004). Injury prevention during physical activity in the Australian Defence Force. *J Sci Med Sport, 7*. doi:10.1016/s1440-2440(04)80049-5

U.S. Army Public Health Center: Health of the Force Report. (2016).

Wallace, R. F., Wahi, M. M., Hill, O. T., & Kay, A. B. (2011). Rates of ankle and foot injuries in active-duty U.S. Army soldiers, 2000-2006. *Mil Med, 176*(3), 283-290.

Wardle, S. L., Greeves, Julie P. (2017). Mitigating the risk of musculoskeletal injury; A systematic review of the most effective injury prevention strategies for military personnel. *Journal of Science and Medicine in Sport*. doi:https://doi.org/10.1016/j.jsams.2017.09.014

Zambraski, E. J., & Yancosek, K. E. (2012). Prevention and rehabilitation of musculoskeletal injuries during military operations and training. *J Strength Cond Res, 26 Suppl 2*, S101-106. doi:10.1097/JSC.0b013e31825cf03b

Chapter 4: Changes in Lower Limb Strength and Ankle Joint Range of Movement after One Year of Military Boot-Wear

4.1 Chapter Overview

Having now understood the scale of the lower limb problem, it is important to understand the aetiology and mechanisms leading to these injuries. This is the first of two chapters examining the aetiology, and it looks specifically at the fundamental biomechanical parameters of strength and range of motion. This chapter is set out as a paper ready for publication and includes limitations in the discussion.

4.2 Abstract

Purpose

Why the ankle joint is the most common musculoskeletal injury site in military populations is uncertain. This study investigates the possibility that chronic wearing of the high cut military boot for prolonged periods weakens the ankle joint and is a major contributor to the high number of ankle injuries.

Methods

One hundred and fifty newly enlisted male recruits volunteered to participate (age 22.2 ± 2.8 years; weight 80 ± 11.4 kg; height 178.8 ± 6.3 cm), were injury free and had a base level of fitness. The dominant leg (preferred kicking leg) ankle joint was assessed before being issued with military boots and commencing any military training, and reassessed after 12 months. Ankle dorsiflexion and plantarflexion strength (Newtons) and strength endurance were assessed by isokinetic contractions at 60°/s and 120°/s. Passive inversion and eversion ranges of movement (ROM) were measured while active plantar- and dorsi-flexion ROM were recorded during strength tests. Work fatigue was the percentage of work in the first third relative to work in the last third of the test.

Results

Significant decreases in plantarflexion ($p < 0.05$) and dorsiflexion strength ($p < 0.05$), inversion/eversion range (3.4° and 3.1° respectively), and plantarflexion/dorsiflexion isokinetic range of motion by 4.3°. Work fatigue of the plantarflexors significantly increased ($p < 0.05$).

Conclusions

After 12 months of military training the significant decrement in ankle strength and endurance, particularly for the plantarflexors, which normally provides power in dynamic activities, was mirrored by decreased ankle ROM over which maximum force could be developed. The boot appears to be weakening the ankle joint and reducing its function.

4.3 Introduction

It has previously been documented that one of the most common musculoskeletal injury sites in military populations is the ankle joint (Frilander et al., 2012; Havenetidis et al., 2011; Wallace et al., 2011). Similarly, the authors also identified this in the New Zealand Army (NZA) when 11 years of data injury data were examined. From the same data it was revealed the highest incidence occurs during running without military boots, however, previously published research indicates these injuries were attributed to challenging exercise training programmes and other physical activities of military training and operations (Frilander et al., 2012; Havenetidis et al., 2011; Wallace et al., 2011). Furthermore, the insole of the boot was found to affect the rate of loading while running and was proposed to increase the injury risk, particularly overuse injuries (Dixon et al., 2003). In terms of who gets injured the most, it appears that new recruits sustain some of the highest statistics of lower limb musculoskeletal injury (males 0.42 and females 0.93 per 100 person days) (Knapik et al., 2001) during basic training, with risk factors listed as female gender, aerobic fitness, smoking, extremes in flexibility and participation in sporting activities (Knapik et al., 2001; Zambraski & Yancosek, 2012). No study has yet investigated the effect of wearing military boots for long periods on the function of the ankle and foot. The only similar study is a systematic review of the kinematic, kinetic and muscle activity differences during walking barefoot and with shoes by Franklin et al. (2015).

Military personnel are subjected to high levels of physiological workloads, such as pack marches, which include walking and load carriage while wearing military boots (DeBusk et al., 2018). The boots are designed to protect the foot, attenuate shock absorption and control medio-lateral foot motion (Andersenet al., 2016). The extended upper part of the boot, the section covering the medial and lateral malleolus, is referred to as the boot shaft, and it ties together the actions of the lower leg, the ankle and the foot (Hamill & Bensel, 1996). Böhm and Hösl (2010) determined the shaft of the military boot has two design constraints; it must be rigid to support the ankle joint while being flexible enough to allow sufficient range of motion (ROM) to achieve efficient locomotion. However, previously published research has reported that wearing military boots may predispose military populations to lower limb injuries, particularly stiff combat boots, as these may cause lower leg muscle fatigue and reduce ankle joint mobility (Piasis et al., 2008). This fatigue has been found to be accentuated during pack marching (Piasis et al., 2008) and is supported by a study comparing athletic shoes to military boots by Jones et al. (1984) who found that wearing military boots increased energy expenditure and therefore increased fatigue. Furthermore, a study by Cikajlo and Matjačić (2007) suggested the significant influence of boots on the kinematics and kinetics of the leg appeared to be limited to the ankle joint. Harkins et al. (2005) further stated that instead of relying on the ankle muscles for stability, corrective action of the proximal joints occurs at the knee and hip, which may also lead to injuries in these joints. This is important to note as once postural stability is compromised as a result of ankle fatigue the soldier may be susceptible to further injury (Harkins et al., 2005).

Our previous work identified the ankle to be the site of the majority of lower limb injuries, and published research indicates the prolonged wearing of the military boot as the probable cause. Robbins and Waked (1998) postulated that the intrinsic foot muscles became lazy when wearing boots (particularly rigid boots). They postulated that while wearing footwear, the sense of foot position is distorted which accounts for ankle sprains when the boot is not worn. Similarly, Warburton (2001) suggested that the natural structures of the foot are weakened by long-term footwear which leads to the reliance on footwear to support the foot which is not the same as the support provided by a well-functioning foot.

Therefore, this study aimed to accurately determine any chronic changes in strength and flexibility after one year of boot wearing by new recruits. Determining the extent of any strength and range of motion deficits will help identify specific areas that could be remedied with either better training programmes or other footwear interventions, with a long-term view of reducing ankle injuries.

4.4 Methods

4.4.1 Participants

One hundred and fifty new enlisted male recruits volunteered to participate however due to military commitments such as courses, exercises and deployments only 122 completed the study (22.2 ± 2.8 years [mean ± SD], height 178 ± 0.63 cm, weight 80 ± 11.4 kg). Each participant gave written informed consent, and the institutional ethics committee granted ethics for this study (Massey University Human Ethics Committee: Southern A, Application 16/53). Each recruit was expected to have a base level of fitness as determined by the entry level requirements for basic military training in the NZA, and be injury free at the time of enlistment, which was established as part of the standard medical examination by the Defence Health Centre’s physicians on entry into the armed forces. In addition to normal military training activities, such as parade ground drill and battle activities, all participants partook in structured physical training during the time between pre- and post-testing, which included activities such as a combination of body weight strength training, calisthenics, running (e.g., cross-country, shuttle sprints) and pack marching.

4.4.2 Strength and Fatigue Measures

Each participant was assessed for ankle joint function in the dominant leg before being issued with their uniform, in particular, their military boots and before commencing any military training (NZA All Arms Recruit Training). They were reassessed after 12 months of military training (and boot wearing). Ankle dorsiflexion and plantarflexion strength and fatigue were assessed by isokinetic contractions using a Biodex System 4 Dynamometer with the plantar/dorsiflexion footplate and Biodex Advantage Software package (Biodex System 4 Quick-Set, Biodex Medical Systems, Inc. Shirley, New York, USA). The dynamometer was calibrated before each testing session. Reliability of isokinetic dynamometry has been established by several investigations to determine muscle strength (Hageman et al., 1989; Levene et al., 1991; Levene et al., 1992) and muscle fatigue (Amaral et al., 2014; Holmbäck & Lexell, 2007; Porter et al., 2002).

Leg dominance was defined as the preferred leg for kicking a ball. All participants were required to perform a prescribed pre-test warm-up, which consisted of two 10 m shuttle walks followed by five sub-maximal efforts plus one maximal effort of plantarflexion to dorsiflexion at 60˚/s (1.05 rads/s) on the Biodex chair. The pre-test warm-up allowed the participant to become familiar with the speed of the dynamometer lever arm and the application of maximum force. The Biodex set-up and positioning for plantar-flexion/dorsiflexion testing were in accordance with the Biodex Multi-Joint System Pro Operation Manual (Biodex Medical Systems, Inc. New York) with knee flexion at 60º and hip flexion at 90˚ (Long & Hopkins, 2009). Knee and hip joint angles were adjusted by changing the distance between the footplate, the chair and the height of the support arm under the knee for each participant. Each individual participant's position on the Biodex was recorded for settings in the retest measures. The axis of rotation was adjusted to pass through the body of the talus, fibular malleolus and through or just below the tibia. The same investigator made all measurements and adjustments. Testing was carried out at speeds of 60°/s (1.05 rads/s) and 120°/s (2.10 rads/s). Testing at 60°/s included five consecutive repetitions of plantarflexion to dorsiflexion, while 15 consecutive repetitions were performed at 120°/s to assess muscle fatigue, testing started with the foot in full plantarflexion. Rest periods of 60 seconds were allowed between warm-up and testing, and 30 seconds between testing speeds of 60°/s and 120°/s. In all cases, the lower speed was tested first. Peak torque measured in Newton-metres (Nm) was recorded for the strength test. Muscle fatigue, measured as work fatigue (WF) was the percentage of work in the first third relative to work in the last third of the test. For this study, the term fatigue is defined as the failure to maintain force or power output (Edwards, 1981). This definition of fatigue is accepted and similar to that used in a previous study by Holmbäck and Lexell (2007) determining the test-retest reliability of isokinetic strength and fatigue measurements using the Biodex System.

Participants were verbally encouraged during each test to exert maximum voluntary effort by contracting as hard and as fast as possible, move the ankle joint through its fullest range of movement possible and were also allowed visual feedback to help with motivation during testing (Dvir, 2004). A flexible low-cut training shoe was worn by all participants during testing to allow for full range of ankle motion.

4.4.3 Range of Motion Measures

All inversion/eversion range of motion measures were performed with participants barefoot. Active inversion and eversion ranges of movement were assessed with a bubble inclinometer (Baseline® Bubble Inclinometer, Fabrication Enterprises Inc. White Plains, New York 10602, USA). The Bubble Inclinometer is placed horizontally across the cuneiforms of the foot. The measurement method used is outlined in Exercise and Sports Science Australia (ESSA) Student Manual for Health, Exercise and Sport Assessment 2014 (Coombes & Skinner, 2014). The use of a bubble inclinometer has been shown to be a reliable method to measure joint range of movement (Charlton et al., 2015; Gabbe et al., 2014). Active plantarflexion and dorsiflexion were recorded on the Biodex system 4 Dynamometer with the participants' foot strapped in the plantar/dorsiflexion footplate. Subjects wore training shoes in order for the foot to work as a rigid lever throughout the full range of movement (Poulis & Soames, 2003). Training shoes ensured subjects had free ankle movement and limited metatarsal joint involvement. While performing ankle plantar/dorsiflexion participants were encouraged to perform the movement throughout the full range of movement.

4.4.4 Calculations and Statistical Analysis

The Shapiro-Wilk test was used to test the normality of data across all dependent variables. Data conformed to normal distribution on analysis and therefore parametric analysis was used. Paired sample t-tests were used to compare pre- and post-tests for peak torque, percentage fatigue and the range of motion in each plane, the level of significance was set at $p \leq 0.05$ and t-values with degrees of freedom denoted conventionally as *t(df)*. All statistical analyses were performed using SPSS (version 25; IBM SPSS Inc, Chicago, IL). Results are presented as mean ± standard deviation. Cohen's *d* statistic (Cohen, 1988) was calculated to determine the size of the effect of one year of boot-wear on plantarflexion and dorsiflexion peak torque. Based on Cohen's cut-offs for effect sizes 0.20 are small, 0.50 medium, and 0.80 are large (Cohen, 1992). WF is described as the relative (%) loss of work in the first third to the last third of the ten contractions (Holmbäck & Lexell, 2007) and was obtained from the Biodex results based on the following equation (Bosquet et al., 2010):

$$WF = 100 - \left(\frac{Average\ performance\ of\ last\ 3\ repetitions}{Average\ performance\ of\ first\ 3\ repetitions}\right) x100$$

Bivariate correlations of WF with pre- and post-plantarflexion (P) and dorsiflexion (D) directional movements through the total P-D range of motion were conducted using Pearson's correlation. Similarly, the pre- and post-plantarflexion peak torque was correlated with the plantarflexion movement through the total P-D range. The correlations were plotted and R^2 values calculated.

4.5 Results

Peak plantar flexion strength (triceps surae) measured at 60°/s decreased from 90.5 Nm (± 22.7) to 81.2 Nm (± 22.4) after 12 months of military training (Figure 4.1). This indicates a significant ($t(121) = 12.47$, $p < 0.001$) mean decrease in strength of 9.3 Nm (± 11.1). The effect size for plantarflexion ($d = 0.4$). The initial dorsiflexion strength (tibialis anterior) at 60°/s was 20.50 Nm (± 5.50) before military training and 20.08 Nm (± 4.9)

12 months after military training indicating an average decrease of 0.42 Nm ($t(121) = 5.46$, $p < 0.001$). The effect size for dorsiflexion ($d = 0.2$) was found to be a small effect.

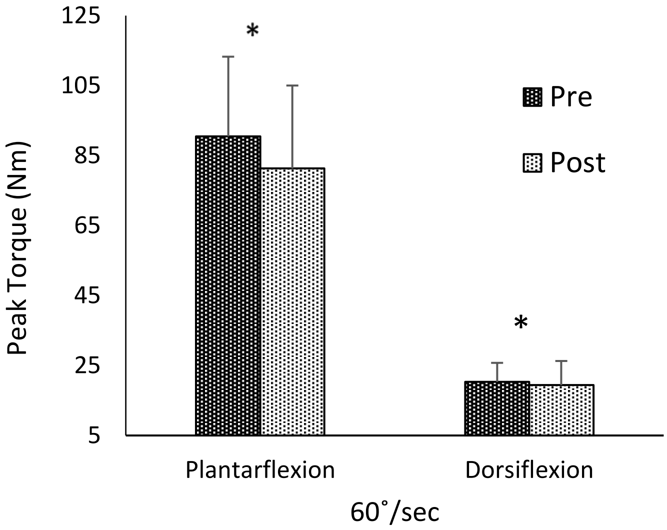


Figure 4.1. Pre and post peak torque at 60˚/sec. *Denotes significant difference pre and post (p < .05).

Average WF of the plantar flexors measured at 120°/s was significantly increased from 21.9% (± 7.0) to 30.15% (± 9.1) from pre- to post-training ($t(102) = -8.84$, $p < 0.001$), with a mean fatigue index increase of 8.2% (± 9.5). The average fatigue index of the dorsiflexors at 120°/s was 36.2% (± 8.4) pre- and 42.5% (± 8.5) post-training indicating a significant increase in WF ($t(102) = -13.1$, $p < 0.001$) (Figure 4.2). Although 122 recruits completed the WF tests, only 103 test results were analysed due to 19 incomplete WF data sets which were excluded from the analysis.

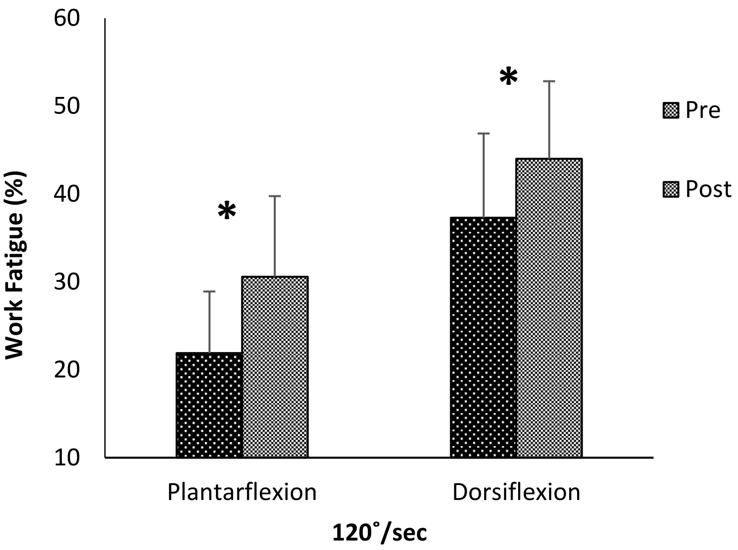


Figure 4.2. Pre and post work fatigue at 120˚/sec. *Denotes significant difference pre and post (*p* < .05). The effect size for plantarflexion (*d* = 1.05) and dorsiflexion (*d* = 0.74).

Ankle joint range of movement (inversion and eversion) significantly decreased after 12 months (Figure 4.3). Pre-military training and boot-wear inversion was 19.7° (± 5.7) and post-training 16.3° (± 4.9), a significant mean decrease of 3.4° ($t(121) = 8.84$, $p < 0.001$). Eversion was measured at 12.3° (± 4.2) pre- and 9.2° (± 3.5) post-training, also a significant decrease, 3.1° (± 3.8) ($t(121) = 10.1$, $p < 0.001$). Active plantarflexion and dorsiflexion were measured as a single movement with the combined total range of movement recorded at 60°/s being 59.3° (± 7.3) pre-training and 55.1° (± 7.6) post, a significant mean decrease of 4.2° (± 5.4) ($t(121) = 8.43$, $p < 0.001$). Plantarflexion/dorsiflexion at the faster speed of 120°/s was 61.3° (± 7.1) and 57.1° (± 7.5) pre- and post-training respectively (Figure 4.4). This indicates a significant mean decrease of 4.3° (± 6.0) ($t(121) = 7.7$, $p < 0.001$).

Negative correlations with WF for a total P-D range of motion for pre- and post-plantarflexion and dorsiflexion directional movements are shown in Figures 4.6a and b respectively. The pre- and post-R^2 values in both movements show strong correlations with WF (i.e., R^2 values > 0.05), and the post-R^2 value was always slightly higher. The correlation between plantarflexion peak torque and total P-D range of movement in the plantarflexion range also showed strong correlations for pre- ($R^2 = 0.64$), and significantly stronger for post- ($R^2 = 0.85$) one year boot-wear (Figure 4.5).

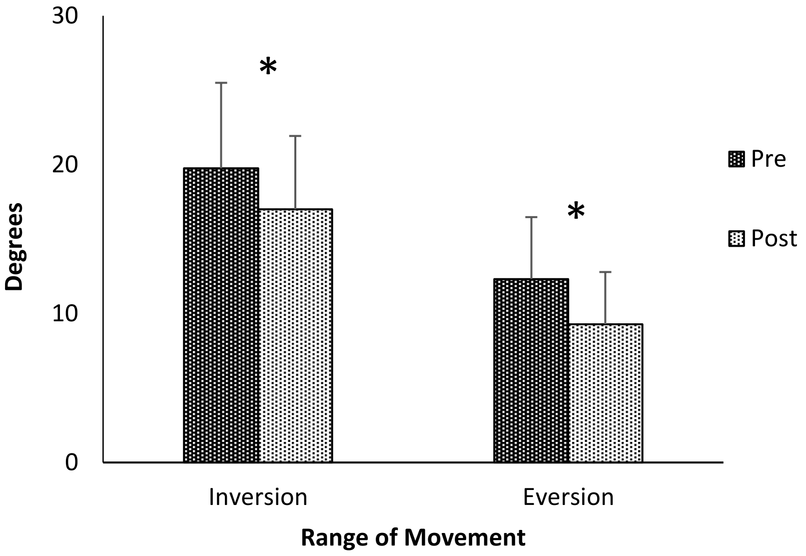


Figure 4.3. Pre and post range of movement. *Denotes significant difference pre and post ($p < .05$). The effect size for inversion ($d = 0.93$) and eversion ($d = 0.73$).

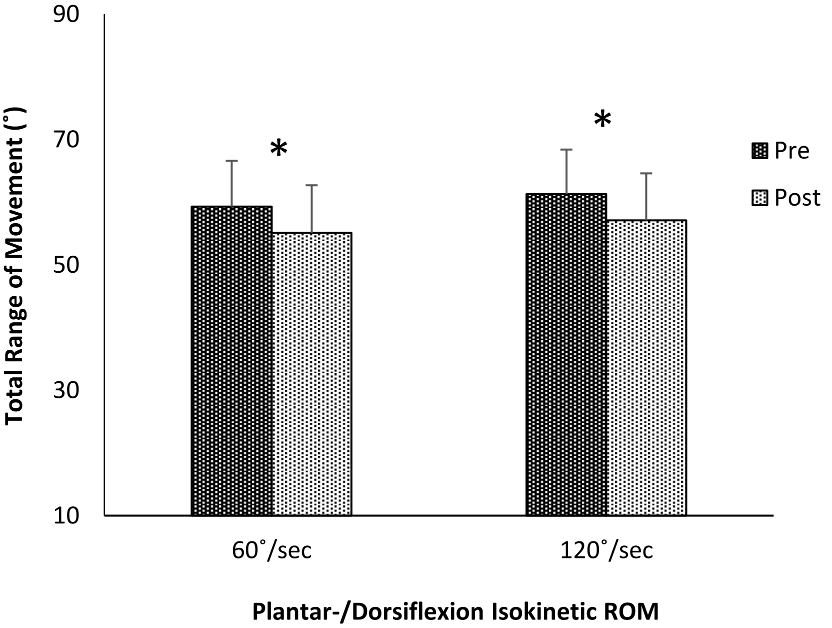


Figure 4.4. Pre and post active isokinetic range of movement. *Denotes significant difference pre and post ($p < .05$). The effect size for range of movement at 60˚/sec ($d = 0.06$) and 120˚/sec ($d = 0.73$).

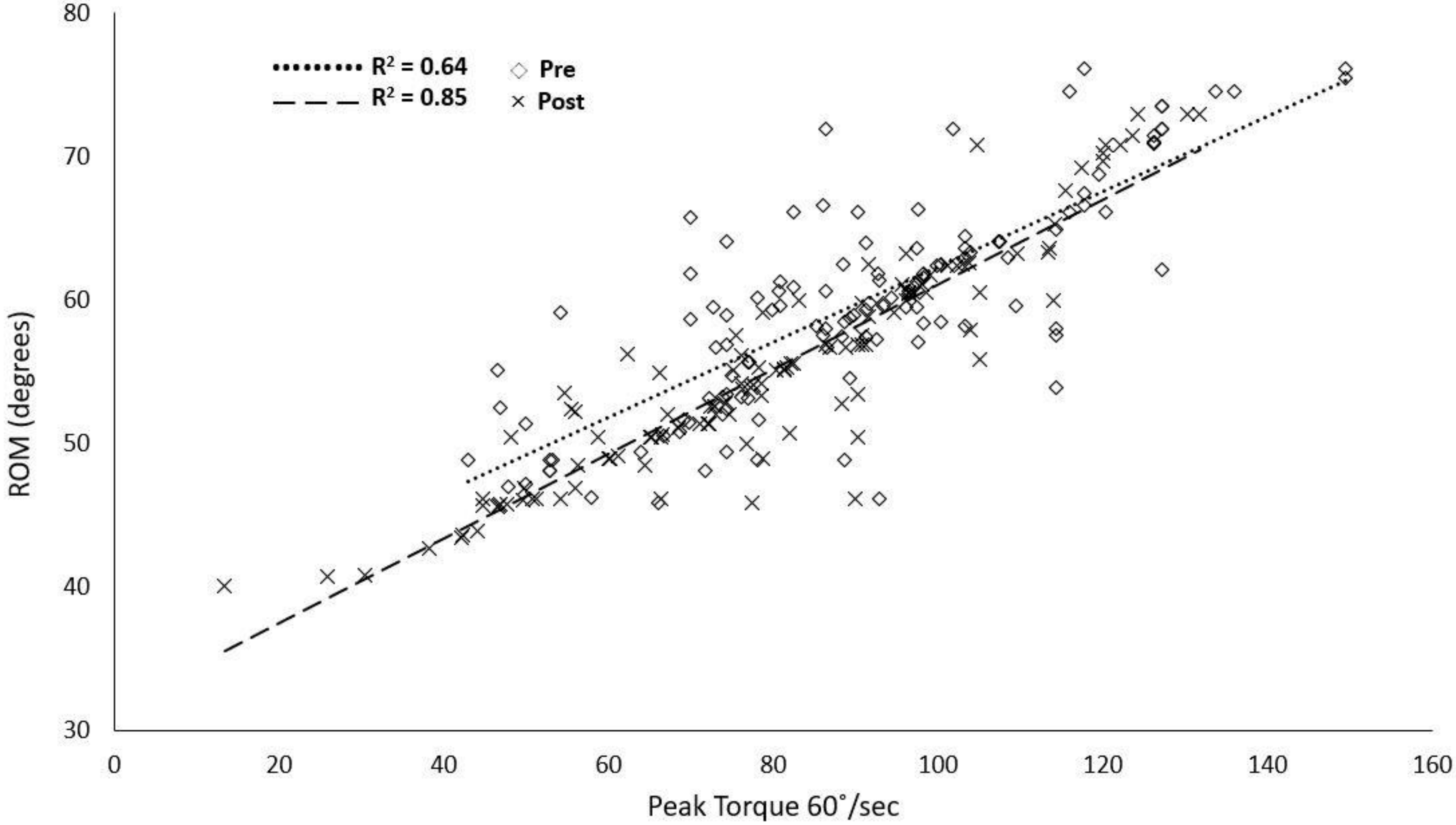


Figure 4.5. Pearson’s correlation coefficient analysis of the association between peak torque and plantarflexion ROM

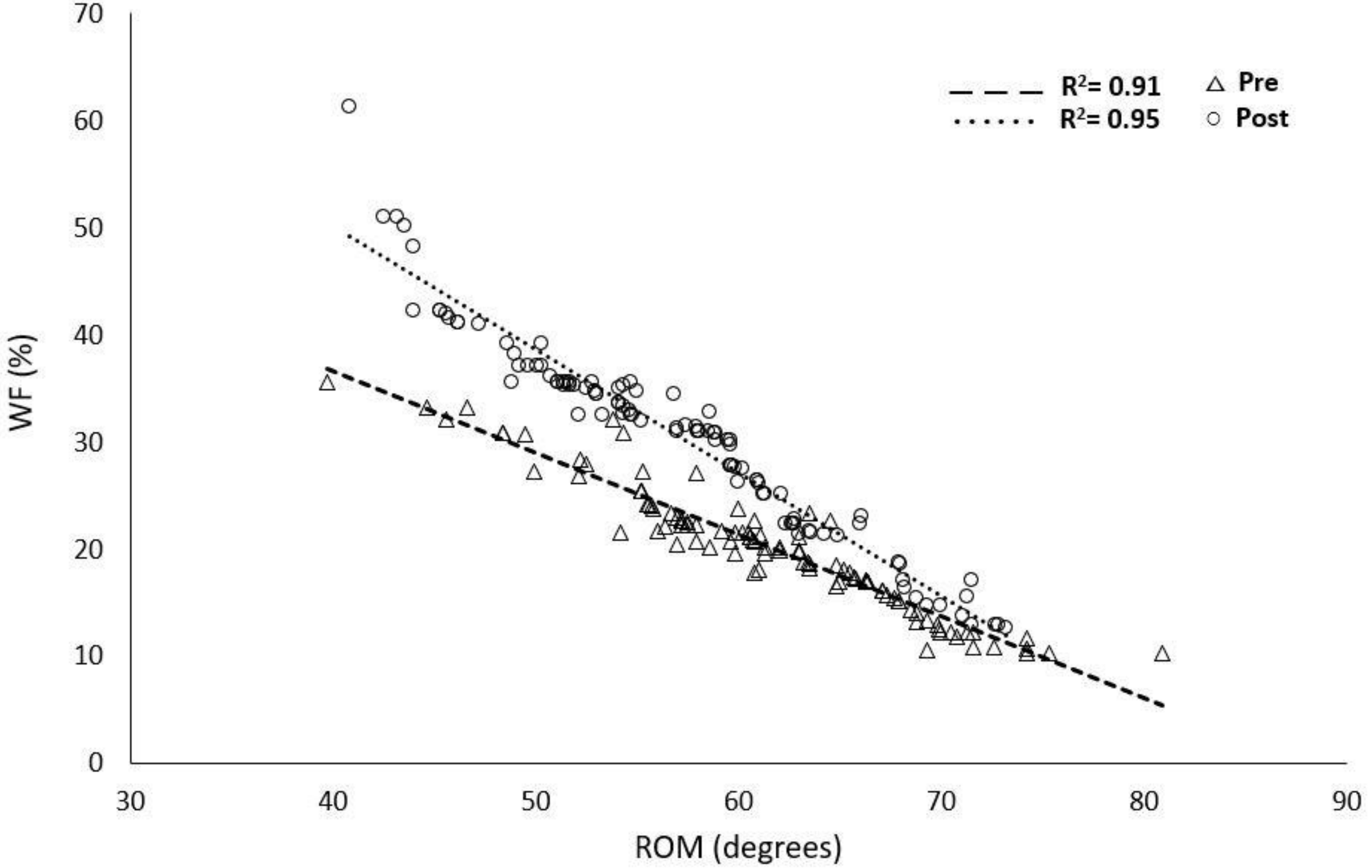


Figure 4.6a. Pearson's correlation coefficient analysis of the association between pre and post work fatigue and plantarflexion range of movement

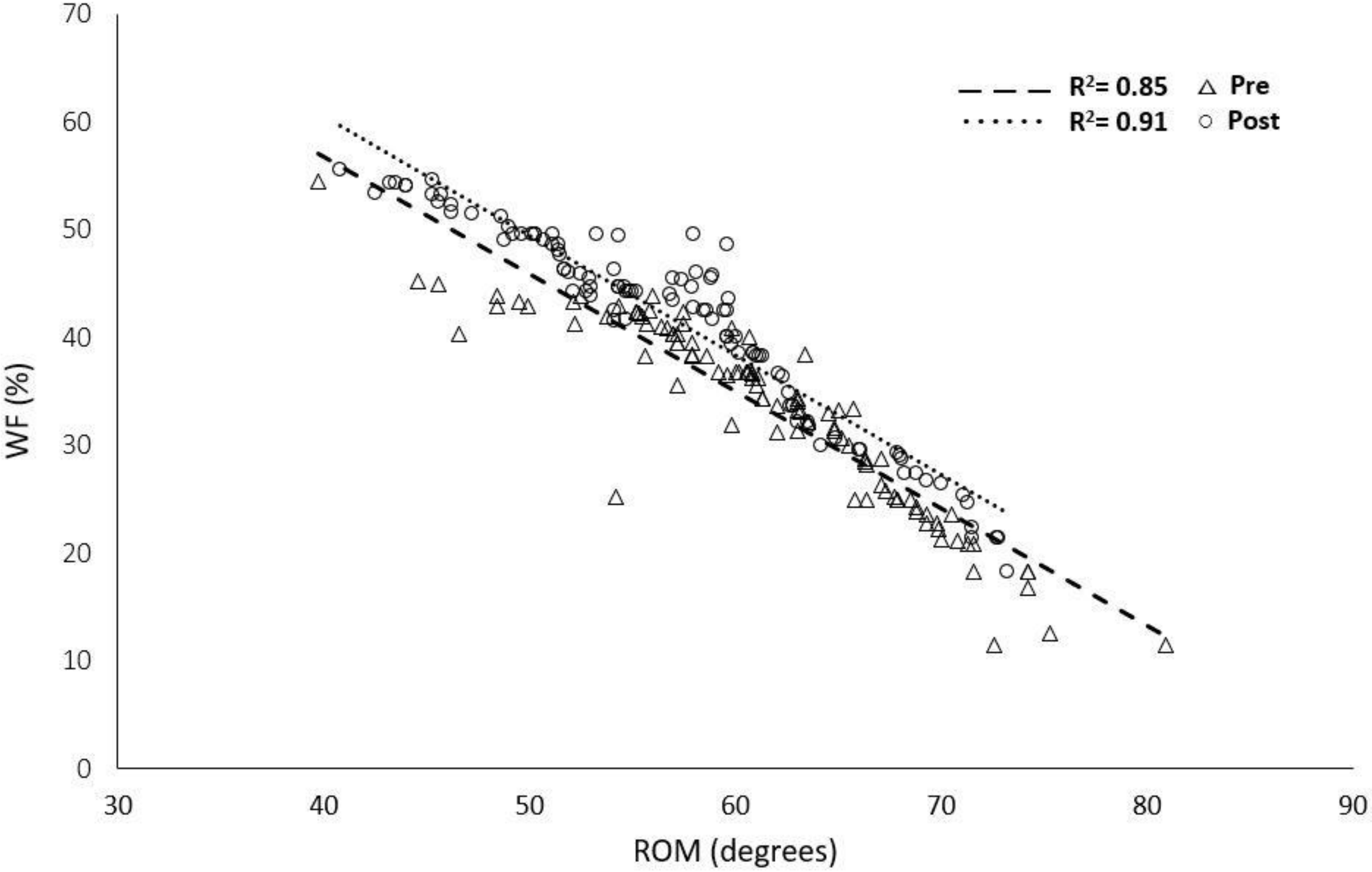


Figure4.6b. Pearson's correlation coefficient analysis of the association between pre and post work fatigue and dorsiflexion range of movement

4.6 Discussion

This is the first study to show chronic musculoskeletal maladaptation due to one type of footwear over a year. Specifically, this study is unique in showing plantarflexor force was significantly reduced after one year of basic and Corps military training wearing military boots. The range over which the force could develop was significantly reduced in the sagittal plane (plantar/dorsiflexion). Furthermore, this significant loss of maximal plantarflexor force and range of movement is linked to the increase in fatigue of these muscles. This has implications for the loss of forward movement propulsion power during dynamic activities. Just as important, was the loss of inversion/eversion range of motion for medial-lateral stability, indicating that there is less movement range before catastrophic failure when twisting or turning of the ankle.

The force production by the plantarflexors (gastrocnemius and soleus muscles) in this study was similar to that reported in a study measuring calf muscle strength in normal non-military subjects by Trappe et al. (2001). They reported mean peak torque of 88.5 ± 21.5 Nm at 60°/s, which is comparable to this study (90.5 ± 22.7 Nm). However, their range was 57 to 114.5 Nm, which would include our recorded decrease after 12 months of boot wearing (79.5 ± 23.7 Nm). Nevertheless, the 13% decrease in plantarflexion force in this present study was significant (Figure 4.1). The difference in current results compared to those of Trappe et al. (2001) may be because over 25% of their participants were female, and there was a wide range of exercise habits from sedentary to swimmers and weightlifters. In this present study, there are no female participants, and the activities of swimming or only weightlifting were not part of the recruit training programme or training within the following months leading to one year of military training. Dorsiflexor strength was also significantly different pre- to one year post-training in this study (Figure 4.1). It is worth noting that in this study we reported less change in dorsiflexion compared to plantarflexion strength. This is evident when comparing the effect sizes of these movements as there was a small effect size with dorsiflexion (*d* = 0.2) compared to the effect size for plantarflexion which was small (*d* = 0.4) (Cohen, 1992b). These changes probably reflect the actions of the muscle groups.

The decreased plantarflexor force is associated with the significantly decreased P-D range of motion (Figure 4.4). The strong correlation of force to P-D range is shown in Figures 4.6a and b, and agrees with previous studies where a restriction of the ankle plantar-flexion range of movement decreased motor performance when wearing high support sport shoes (Brizuela et al., 1997), or combat boots (Schulze et al., 2014). In this study we attributed the loss of range of motion with musculoskeletal adaptations from habitually wearing the boot constantly over one year. This supports the findings of Franklin et al. (2015) who reported that long term use of normal footwear resulted in a decrease in habitual ROM of the foot and ankle when comparing non-military habitual barefoot walkers with habitual shod walkers. The implications of the reduced P-D range of motion and associated decreased plantarflexion force production is a decreased propulsive force, and this agrees with findings reported by Cikajlo and Matjačić (2007). Arnold and Delp (2011) attributed decreasing force generation to a decrease in muscle fibre length in the lower limb muscles when examining human muscle fibre length during walking. Furthermore, Gajdosik (2001) reported muscle length adaptations result from changes in the numbers of sarcomeres in series and suggested optimal muscle function is probably enhanced by increasing muscle length. It is speculated that the decrease in force production in this study is due to shortened muscles as a result of habitually less ROM leading to a loss of skeletal muscles fibres in series. We have concentrated on the shaft of the boot crossing the ankle joint and therefore restricting dorsiflexion-plantarflexion range, however, the stiffness of the military boot sole also has an effect on the dynamic function of the ankle (DeBusk et al., 2018). Stiffness is inherent in the sole of the boot to protect the sole of the foot. The stiffer sole negatively affects economy of gait and running (Roy & Stefanyshyn, 2006) and is thought to reduce metatarsal joint movement which limits ground clearance of the foot and also affects push-off power (Cikajlo & Matjačić, 2007). The significant increase in work fatigue in both plantarflexors (Figure 4.6a) and dorsiflexors (Figure 4.6b) particularly at the lower angles of movement, and post- one year of boot-wear, can lead to greater risk of medial-tibial stress related injuries. This is supported by Schulze et al. (2011) who observed increased neuromuscular activity in the tibialis anterior and rectus femoris muscles when wearing combat boots, and surmised that increased muscle activity in these specific muscle groups might influence the occurrence of specific strain related disorders such as medial tibial stress syndrome (shin splints) and patella-femoral pain. Pohl et al., (2010) further suggested it may be the chronic fatiguing of the tibialis posterior muscle that leads to deficiencies in force output, which are associated with greater forefoot abduction and dorsiflexion. Once fatigue of the tibialis posterior occurs then compensatory engagement of other muscles such as the tibialis anterior and muscles supporting the knee and hip takes place, which can then lead to muscular imbalances and injuries (Christina et al., 2001; Pohl et al., 2010). Plantarflexor and dorsiflexor electro-myographical studies are required to determine the levels of muscle activation pre- and post- significant periods of boot-wear.

Inversion and eversion ROM were significantly decreased by 17.3% and 25% respectively after one year of military boot-wear. The pre-training inversion and eversion ranges of motion in this study (Figure 4.2) were the same as those reported for normative data for men by Schwarz et al. (2011). The significant decreases were equivalent to two standard deviations from normal values for both inversion and eversion (Schwarz et al., 2011), an approximately 20% reduction in inversion and eversion range of motion. Inversion/eversion movements are utilised extensively for maintaining balance. Strength ratios across a joint are clinically relevant for stability as co-activation of opposing muscles across a joint contribute in maintaining dynamic joint stability (Lin et al., 2008). In this sense, significant invertor weakness has been found in persons with chronic unstable ankle joints (Hartsell et al., 1999; Munn etal., 2003). Lin et al. (2008) further surmised that inadequate rapid invertor muscle contraction prior to the joint moving beyond its functional range, can exceed the lateral tensile strength of the ligaments resulting in injury. In fact, it has been reported that inversion injuries account for approximately 25% of musculoskeletal injuries, and 50% of all sport-related injuries (Czajka et al., 2014). This has implications for military personnel as Bohm and Hosl (2010) indicated that lateral ligament injuries frequently occur in activities such as walking, pack marching and running indicating inversion injuries during military activities.

Lateral ankle sprains, caused by inversion of the ankle joint (Morrison & Kaminski, 2007) are the most common form of ankle injuries in the military (Wallace et al., 2011). Therefore, to reduce lateral ankle injuries in military populations the specific function of the military boot shaft is to restrict excessive inversion as a protective measure (Bohm & Hosl, 2010), acting like a pseudo–splint. It is interesting to note in a study on the effects of tape, braces and shoes on ankle ROM, Verhagen et al. (2001) found that superior mechanical restriction of ankle ROM does not necessarily imply a greater preventative effect. Moreover, as that range of motion maladaptation over time has occurred, the removal of the boot makes the ankle joint even more vulnerable to injury during activities, particularly highly dynamic sports that require rapid changes in direction. Indeed, injury during recreational sports is one of the reported significant risk factors in military personnel (Zambraski & Yancosek, 2012) and is reported as one of the main activities causing lower limb and ankle injuries (Davidson et al., 2008; Owens & Cameron, 2016).

It is unknown how soon the mal-adaptations occur, and while this study was over a 12-month duration, the changes could occur in less time, but there are no studies determining how soon after enlisting that ankle injury begin to occur. A limitation to this study was the lack of a control group, but the paired analysis of the changes of boot wearing over one year are very robust and undoubtedly significant. A further limitation of this study is that data was not recorded for other notable lifestyle risk factors such as smoking as reported by Bulzacchelli et al., (2014), or distance covered in basic training (Zambraski & Yancosek, 2012). However, the group examined in this pre-post study were very homogenous, of very similar height, weight, age and underwent the same training and activities over the year. Other confounding variables such as injuries and weight during the year before retesting might have influenced the post-testing results. Bearing in mind that the cohort were a very homogenous group of military recruits, the mean of the percentage changes for anthropometric or injury variables of individuals was not expected to be significantly different pre- to post measures. Considering sport as another physical activity variable, it was not known what external sports were participated in, however as these were new recruits and other than physical training sport per se was not part of initial military training. Further work would take into consideration the effects of more confounding factors.

Moreover, this study focused on the specific musculoskeletal deficits associated with one year of military boot-wear and not cataloguing risk factors per se, which have been well reported previously (Knapik et al., 2001; Zambraski & Yancosek, 2012). In this present study, participants performed five consecutive maximal effort isokinetic repetitions at 60º/sec followed by a 30-second rest period then completed 15 consecutive maximal effort isokinetic repetitions at 120º/sec. This is not a conventional fatigue protocol when compared to Jahjah et al. (2018) and Holmbäck and Lexell (2007), nonetheless, we did record a significant decrement in force and increase in percentage WF.

4.7 Conclusion

In conclusion, this unique study documents the biomechanical repercussions of what can be speculated to be musculoskeletal maladaptations as a result of wearing the military boot by new recruits over one year, and provides some evidence for the large number of ankle injuries and increased lower limb injury risk seen in military personnel. It is clear the stiff and high shaft of the military boot restricts movement and over time decreases the normal habitual range of motion in all planes of ankle motion. This attenuation in ROM decreases the ability to develop peak torque over functional ranges so that not only does the soldier have a reduced range over which to produce optimum/maximal force, but the peak force is also less. This results in greater work fatigue of muscles surrounding the ankle joint and eventual instability and unable to rapidly correct perturbations while wearing the boot or not. Ultimately the boot is weakening the ankle joint and reducing its function.

4.8 References

Amaral, G. M., Marinho, H. V. R., Ocarino, J. M., Silva, P. L. P., Souza, T. R. d., & Fonseca, S. T. (2014). Muscular performance characterization in athletes: a new perspective on isokinetic variables. *Brazilian Journal of Physical Therapy, 18*, 521-529.

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Arnold, E. M., & Delp, S. L. (2011). Fibre operating lengths of human lower limb muscles during walking. *Philosophical Transactions of the Royal Society B: Biological Sciences, 366*(1570), 1530-1539.

Bohm, H., & Hosl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *J Biomech, 43*. doi:10.1016/j.jbiomech.2010.05.029

Böhm, H., & Hösl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *Journal of Biomechanics, 43*(13), 2467-2472. doi:https://doi.org/10.1016/j.jbiomech.2010.05.029

Bosquet, L., Maquet, D., Forthomme, B., Nowak, N., Lehance, C., & Croisier, J. L. (2010). *Effect of the Lengthening of the Protocol on the Reliability of Muscle Fatigue Indicators* (Vol. 31).

Bulzacchelli, M. T., Sulsky, S. I., Rodriguez-Monguio, R., Karlsson, L. H., & Hill, M. A. J. O. T. (2014). Injury During U.S. Army Basic Combat Training: A Systematic Review of

Risk Factor Studies. *American Journal of Preventive Medicine, 47*(6), 813-822. doi:https://doi.org/10.1016/j.amepre.2014.08.008

Charlton, P. C., Mentiplay, B. F., Pua, Y. H., & Clark, R. A. (2015). Reliability and concurrent validity of a Smartphone, bubble inclinometer and motion analysis system for measurement of hip joint range of motion. *J Sci Med Sport, 18*(3), 262-267. doi:10.1016/j.jsams.2014.04.008

Christina, K. A., White, S. C., & Gilchrist, L. A. (2001). Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. *Human Movement Science, 20*(3), 257-276. doi:https://doi.org/10.1016/S0167-9457(01)00048-3

Cikajlo, I., & Matjačić, Z. (2007). The influence of boot stiffness on gait kinematics and kinetics during stance phase. *Ergonomics, 50*(12), 2171-2182. doi:10.1080/00140130701582104

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. *Hillsdale, Lawrence Erlbaume*(ed 2).

Cohen, J. (1992a). *A power primer*. Washington, DC, US: American Psychological Association.

Cohen, J. (1992b). A power primer. *Psychological bulletin, 112*(1), 155.

Coombes, J., & Skinner, T. (2014). ESSA's Student Manual for Health, Exercise and Sport Assessment. Chatsworth, NAW, Australia: Mosby.

Czajka, C. M., Tran, E., Cai, A. N., & DiPreta, J. A. (2014). Ankle sprains and instability. *Med Clin North Am, 98*(2), 313-329. doi:10.1016/j.mcna.2013.11.003

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

DeBusk, H., Hill, C. M., Chander, H., Knight, A. C., & Babski-Reeves, K. (2018). Influence of military workload and footwear on static and dynamic balance performance. *International Journal of Industrial Ergonomics, 64*, 51-58. doi:https://doi.org/10.1016/j.ergon.2017.11.003

Dixon, S. J., Waterworth, C., Smith, C. V., & House, C. M. (2003). Biomechanical analysis of running in military boots with new and degraded insoles. *Med Sci Sports Exerc, 35*(3), 472-479. doi:10.1249/01.mss.0000053733.64049.27

Dvir, Z. (2004). *Isokinetics : muscle testing, interpretation, and clinical applications*. Edinburgh; New York: Churchill Livingstone.

Edwards, R. H. (1981). Human muscle function and fatigue. *Human muscle fatigue: physiological mechanisms*, 1-18.

Franklin, S., Grey, M. J., Heneghan, N., Bowen, L., & Li, F.-X. (2015). Barefoot vs common footwear: A systematic review of the kinematic, kinetic and muscle activity differences during walking. *Gait & Posture, 42*(3), 230-239. doi:https://doi.org/10.1016/j.gaitpost.2015.05.019

Frilander, H., Miranda, H., Mutanen, P., Martelin, T., Pihlajamaki, H., & E, V.-J. (2012). Trends in musculoskeletal disorders and related health care utilisation among conscripts in Finland 1967-2006. *Military Medicine, 177*, 1069-1074.

Gabbe, B. J., Bennell, K. L., Wajswelner, H., & Finch, C. F. Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport, 5*(2), 90-97. doi:10.1016/j.ptsp.2004.01.003

Gajdosik, R. L. (2001). Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clinical Biomechanics, 16*(2), 87-101. doi:https://doi.org/10.1016/S0268-0033(00)00061-9

Hageman, P. A., Mason, D. K., Rydlund, K. W., & Humpal, S. A. (1989). Effects of Position and Speed on Eccentric and Concentric lsokinetic Testing of the Shoulder Rotators. *journal of orthopaedic & sports physical therapy, 11*(2), 64-69. doi:10.2519/jospt.1989.11.2.64

Hamill, J., & Bensel, C. K. (1996). *Biomechanical analysis of military boots: phase III* (Natick/TR-96/013). Retrieved from University of Massachusetts, Amherst:

Harkins, K. M., Mattacola, C. G., Uhl, T. L., Malone, T. R., & McCrory, J. L. (2005). Effects of 2 Ankle Fatigue Models on the Duration of Postural Stability Dysfunction. *Journal of athletic training, 40*(3), 191-194.

Hartsell, H., & Spaulding, S. (1999). Eccentric/concentric ratios at selected velocities for the invertor and evertor muscles of the chronically unstable ankle. *British Journal of Sports Medicine, 33*(4), 255-258.

Havenetidis, K., Kardaris, D., & Paxinos, T. (2

011). Profiles of musculoskeletal injuries among Greek Army officer cadets during basic combat training. *Mil Med, 176*(3), 297-303.

Holmbäck, A. M., & Lexell, J. (2007). Reproducibility of isokinetic ankle dorsiflexor strength and fatigue measurements in healthy older subjects. *Isokinetics & Exercise Science, 15*(4), 263-270.

Jahjah, A., Seidenspinner, D., Schüttler, K., Klasan, A., Heyse, T. J., Malcherczyk, D., & El-Zayat, B. F. (2018). The effect of ankle tape on joint position sense after local muscle fatigue: a randomized controlled trial. *BMC Musculoskeletal Disorders, 19*(1), 8. doi:10.1186/s12891-017-1909-2

Jones, B. H., Toner, M. M., Daniels, W. L., & Knapik, J. J. (1984). The energy cost and heart-rate response of trained and untrained subjects walking and running in shoes and boots. *Ergonomics, 27*(8), 895-902. doi:10.1080/00140138408963563

Knapik, J. J., Sharp, M. A., Canham-Chervak, M., Hauret, K., Patton, J. F., & Jones, B. H. (2001). Risk factors for training-related injuries among men and women in basic combat training. *Med Sci Sports Exerc, 33*(6), 946-954.

Levene, J. A., Hart, B. A., Seeds, R. H., & Fuhrman, G. A. (1991). Reliability of Reciprocal Isokinetic Testing of the Knee Extensors and Flexors. *journal of orthopaedic & sports physical therapy, 14*(3), 121-127. doi:10.2519/jospt.1991.14.3.121

Levene, K. E., Genrich, P., Burns, R., & Fyke, D. (1992). The mechanical and physiological realiability of selected isokinetic dynamometers. *Isokinetic Exericse Science, 2*, 182-190.

Lin, W.-H., Liu, Y.-F., Hsieh, C., & Lee, A. (2008). *Ankle eversion to inversion strength ratio and static balance control in the dominant and non-dominant limbs of young adults* (Vol. 12).

Long, B., & Ty Hopkins, J. (2009). *Superficial Moist Heat's Lack of Influence on Soleus Function* (Vol. 18).

Morrison, K. E., & Kaminski, T. W. (2007). Foot Characteristics in Association With Inversion Ankle Injury. *Journal of athletic training, 42*(1), 135-142.

Munn, J., Beard, D. J., Refshauge, K. M., & Lee, R. Y. W. (2003). Eccentric muscle strength in functional ankle instability. *Medicine and science in sports and exercise, 35*(2), 245-250. doi:10.1249/01.mss.0000048724.74659.9f

Owens, B. D., & Cameron, K. L. (2016). The Burden of Musculoskeletal Injuries in the Military. In K. L. Cameron & B. D. Owens (Eds.), *Musculoskeletal Injuries in the Military* (pp. 3-10). New York, NY: Springer New York.

Piasis, P., Hanley, K., Havenetidis, K., & Bissas, A. (2008). The effects of military boots with and without a shock absorbing insole on the kinematic characteristics during uphill walking and running. *International review of the armed forces medical services, 84*(2), 19-24.

Pohl, M. B., Rabbito, M., & Ferber, R. (2010). The role of tibialis posterior fatigue on foot kinematics during walking. *Journal of Foot and Ankle Research, 3*(1), 6. doi:10.1186/1757-1146-3-6

Porter, M. M., Holmbäck, A. M., & Lexell, J. (2002). Reliability of Concentric Ankle Dorsiflexion Fatigue Testing. *Canadian Journal of Applied Physiology, 27*(2), 116-127. doi:10.1139/h02-009

Poulis, S., & Soames, R. W. (2003). Plantarflexion/dorsiflexion strength and isokinetic range of motion following injury to the ankle lateral collateral ligament. *Isokinetics & Exercise Science, 11*(2), 117.

Powden, C. J., Hoch, J. M., & Hoch, M. C. (2015). Reliability and minimal detectable change of the weight-bearing lunge test: A systematic review. *Man Ther, 20*(4), 524-532. doi:10.1016/j.math.2015.01.004

Robbins, S., & Waked, E. (1998). Factors associated with ankle injuries. Preventive measures. *Sports Med, 25*(1), 63-72.

Roy, J. P., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Med Sci Sports Exerc, 38*(3), 562-569. doi:10.1249/01.mss.0000193562.22001.e8

Salamh, P. A., & Kolber, M. (2014). The reliability, minimal detectable change and concurrent validity of a gravity-based bubble inclinometer and iphone application for measuring standing lumbar lordosis. *Physiother Theory Pract, 30*(1), 62-67. doi:10.3109/09593985.2013.800174

Schulze, C., Lindner, T., Schulz, K., Finze, S., Kundt, G., Mittelmeier, W., & Bader, R. (2011). The Influence in Airforce Soldiers Through Wearing Certain Types of Army-Issue Footwear on Muscle Activity in the Lower Extremities. *Open Orthop J, 5*, 302-306. doi:10.2174/1874325001105010302

Schulze, C., Lindner, T., Woitge, S., Schulz, K., Finze, S., Mittelmeier, W., & Bader, R. (2014). Influence of footwear and equipment on stride length and range of motion of ankle, knee and hip joint. *Acta Bioeng Biomech, 16*(4), 45-51.

Schwarz, N. A., Kovaleski, J. E., Heitman, R. J., Gurchiek, L. R., & Gubler-Hanna, C. (2011). Arthrometric measurement of ankle-complex motion: normative values. *J Athl Train, 46*(2), 126-132. doi:10.4085/1062-6050-46.2.126

Trappe, S. W., Trappe, T. A., Lee, G. A., & Costill, D. L. (2001). Calf muscle strength in humans. *Int J Sports Med, 22*(3), 186-191. doi:10.1055/s-2001-16385

Verhagen, E. A. L. M., van der Beek, A. J., & van Mechelen, W. (2001). The Effect of Tape, Braces and Shoes on Ankle Range of Motion. *Sports Medicine, 31*(9), 667-677. doi:10.2165/00007256-200131090-00003

Wallace, R. F., Wahi, M. M., Hill, O. T., & Kay, A. B. (2011). Rates of ankle and foot injuries in active-duty U.S. Army soldiers, 2000-2006. *Mil Med, 176*(3), 283-290.

Warburton, M. (2001). Barefoot running*5*(3). Retrieved from http://sportsci.org/jour/0103/mw.htm

Zambraski, E. J., & Yancosek, K. E. (2012). Prevention and rehabilitation of musculoskeletal injuries during military operations and training. *J Strength Cond Res, 26 Suppl 2*, S101-106. doi:10.1097/JSC.0b013e31825cf03b

Chapter 5: Changes in Balance and Lower Limb Muscle Activity after One Year of Military Boot-Wear

5.1 Chapter Overview

This is the second of the aetiology chapters examining the mechanics of lower limb injuries with particular reference to physiological changes, and neural activity. This chapter has been written for publication and is set out as a manuscript ready for submission/review.

5.2 Abstract

Purpose

Medial Tibial Stress Syndrome (MTSS) and acute ankle injuries are two of the most common injuries in military populations. Nearly all acute ankle injuries are caused through inversion, however, the research on the aetiology as to why there are so many inversion injuries or MTSS is lacking.

The aim of this study was to identify any changes in balance and muscle activity after 12 months of military boot-wear as a possible cause of injury.

Methods

One hundred and twenty-two volunteer male recruits volunteered to participate in this study, however only one hundred and twenty-two participants completed the study (age: 22.2 ± 2.8 years; height: 178.8 ± 6.3 cm; mass: 80.0 ± 11.4 kg). Participants performed the stork balance test with eyes closed on a force platform (AMTI portable AccuGait, Massachusetts, USA). Postural sway (movement of Centre of Pressure; COP) was quantified using 95% ellipse area, and magnitude of movements in anterior-posterior and medial-lateral directions using AMTI software (AMTI BioAnalysis v1.1). Bipolar surface electrodes were used to record the Electromyographical activity (Delsys Trigno wireless system, USA) of Tibialis Anterior, Medial and Lateral Gastrocnemius of the supporting limb using area under the curve, mean signal and variability about the mean. Paired sample t-tests were used for pre-post comparisons, while repeated measures analysis of variance was used to compare activity between muscles. Significance set at $p < 0.05$.

Results

Post one year of boot-wear, all participants significantly increased (~double) the 95% ellipse area ($p < 0.05$). There was also a significant increase ($p < 0.05$) in the Anterior-Posterior movement of COP compared with Medial-Lateral sway. There were significant increases in gastrocnemius activity (Gastrocnemius-Medial (GAS-M): $p < 0.001$; Gastrocnemius-Lateral (GAS-L): $p = 0.006$) and variability (GAS-M: $p = 0.020$; GAS-L: p = 0.011) in pre- than post balance test. In contrast, no difference was observed in Tibialis Anterior (TA) muscle activation ($p = 0.231$) and variability ($p = 0.431$) between pre- and post- boot wearing for 1-year. In addition, TA activation was significantly greater than GAS-M and GAS-L in both pre- and post-balance test ($p < 0.001$).

Conclusions

After wearing military boots for one year, balance is significantly compromised, with larger movement of the COP in the anterior-medial direction. It appears Tibialis Anterior remains active while activity of the Medial and Lateral Gastrocnemius increases, indicating an increase in work to maintain stability. The decrease in medial-lateral muscle engagement likely contributes towards the high rates of inversion injuries, while the overworked Tibialis Anterior to maintain balance can lead to MTSS.

5.3 Introduction

The ankle joint has been identified as one of the most often injured sites in military populations (Cameron et al., 2010; Havenetidis et al., 2011; Soheil et al., 2010) and ankle sprain is the most common injury in active-duty military service members (Najafipour et al., 2017; Waterman et al ., 2010). Similarly, ankle sprains and strains were found to be the commonest lower limb injury in New Zealand Defence Force personnel (Davidson et al., 2008).

Military boots are worn to combat ankle and lower limb injuries and to protect the foot and ankle joint (Hamill & Bensel, 1992, 1996). The safety design properties to protect the foot and ankle include the stiffness and thickness of the boot sole to reduce shock during foot strike, and the height of the boot shaft (Cikajlo & Matjačić, 2007) to control medio-lateral foot motion (Hamill & Bensel, 1992, 1996). The general concept that boot shafts raised above the ankle joint increases support around the ankle and offers greater balance is supported by the majority of the literature (Bohm & Hosl, 2010; Chander et al., 2014; Chander et al., 2015). Despite these protective characteristics of military boots, they are also thought to result in adverse effects (Andersen et al., 2016) and can alter the way the foot moves (Dobsonet al., 2017). In particular, when studying the effect of firefighter boots when being worn, Garner et al., (2013) found normal gait and balance is affected. Furthermore, when wearing military boots these protective design characteristics also affect neural activation of the lower extremity muscles when the boot is worn (Hill et al., 2017).

When considering the sole of the boot Perry et al., (2007) suggested that soft midsole material requires an increase in muscle activity to stabilize the body during dynamic balance. Furthermore, Robbins et al., (1994) found midsole hardness and thickness affected balance in men; they found thick-soft soles to have a destabilising effect whereas thin-hard soles provide superior stability.

There have been numerous studies looking at the acute effects of different boot styles and high-top shoes on foot and ankle function (Böhm & Hösl, 2010; Cikajlo & Matjačić, 2007; Ricard et al., 2000; Schulze et al., 2011). When comparing different types of footwear Fu et al., (2014) found high top footwear covering the ankle joint alters muscle activation of the primary plantar flexors and invertors when jumping and landing when compared with low top shoes. This effect may therefore be unfavourable for establishing ankle joint stability. When investigating the acute influence of occupational footwear such as low top shoes, tactical boots and work boots on dynamic balance Chander et al. (2015) found significantly lower muscle activity was demonstrated in the medial hamstring, vastus medialis, tibialis anterior and medial gastrocnemius when maintaining balance while wearing tactical boots. Interestingly Böhm and Hösl (2010) found that stiff boot shafts increase agonist-antagonist co-contraction when walking. Similarly, when Schulze et al. (2011) investigated the influence of wearing combat boots on serving soldiers an increase in neuromuscular activity in the tibialis anterior and rectus femoris muscles was found when walking on a treadmill. They stated that increased muscle activity in these specific muscle groups may influence the occurrence of certain strain related disorders such as medial tibial stress syndrome (shin splints) and patella-femoral pain.

These previously mentioned studies compare ankle musculature in different footwear in an acute setting but it is yet to be determined how the ankle joint and adjoining musculoskeletal structures adapt to long-term boot-wear and how these adaptations affect balance and muscle activity. Therefore, the aim of this study is to document the extent of any changes in ankle joint muscle activity and balance deficits due to chronic wearing of military boots, to help identify specific areas that could be remedied to reduce the high number of ankle injuries.

5.4 Methods

5.4.1 Participants

One hundred and fifty healthy male military recruits volunteered to participate in this study, however due to military commitments such as courses, military exercises and deployments only 122 completed it (age: 22.2 ± 2.8 years; height: 178.8 ± 6.3 cm; mass: 80.0 ± 11.4 kg). Each participant gave written informed consent, and the institutional ethics committee granted ethics for this study (Massey University Human Ethics Committee: Southern A, Application 16/53). Participants had no previous surgery or history of injury in the lower extremities within the previous year. All participants had no evidence of a leg-length discrepancy (> 1cm) nor balance deficits (Lima et al., 2014). They also had passed the entry level physical fitness requirements for the NZ Army (Defence Force Orders (DFO)(A) Vol 7, Book 1, 2016) and medically cleared for military service (DFO(A) Vol 3, Chapter 1, 2017). All participants partook in normal military training activities as well as a structured physical training (PT) programme to improve and maintain physical fitness. Structured PT included activities such as a combination of body weight strength training, calisthenics, running (e.g., cross-country, shuttle sprints) and pack marching.

5.4.2 Procedures

Each participant was assessed for ankle joint function in the dominant leg (preferred kicking leg; Maulder and Cronin (2005)) before being issued with their uniform, in particular, their military boots and before commencing any All Arms Recruit Training. They were reassessed after 12 months of military training (and boot wearing). The experimental protocol consisted of a 10-metre unshod shuttle walking trial (4 x back and forth) at the participants own self-selected comfortable speed, followed by a static postural control test of a single leg stance position held for 14 seconds on dominant foot on a force platform (AMTI, Watertown, MA, USA). The contralateral leg was elevated, aligned with the ipsilateral malleolus and with the hands held on the hips. The participants were instructed to stand as still as possible with their eyes closed to eliminate the over-riding visual sensory feedback (Goldie, Evans, & Bach, 1992). To measure the effects of wearing boots during the single-leg balance task, force data and electromyography of the tibialis anterior (TA), medial and lateral head of gastrocnemius (GAS-M and GAS-L) were acquired pre- and post-12 months of military boot-wear.

Electromyography signals were collected from three channels of a 16-channel wireless Delsys EMG system (Delsys Inc. Boston, MA, USA) to record the selected muscles. The EMG electrodes were placed parallel to the muscle’s fibres with 2 cm inter-electrode distance and before their placement, the skin surface was prepared by shaving and abrading with alcohol pads (Figure 5.1). EMG data (input impedance: > 100 MΩ; CMRR: > 100 dB; baseline noise: < 1µV RMS; gain: 500) were collected at a sampling rate of 1500 Hz. To enable the normalisation of the EMG signals, amplitude was normalised to the data collected during a 10-metre walking trial at the participants own self-selected comfortable speed (Cronin et al., 2015).

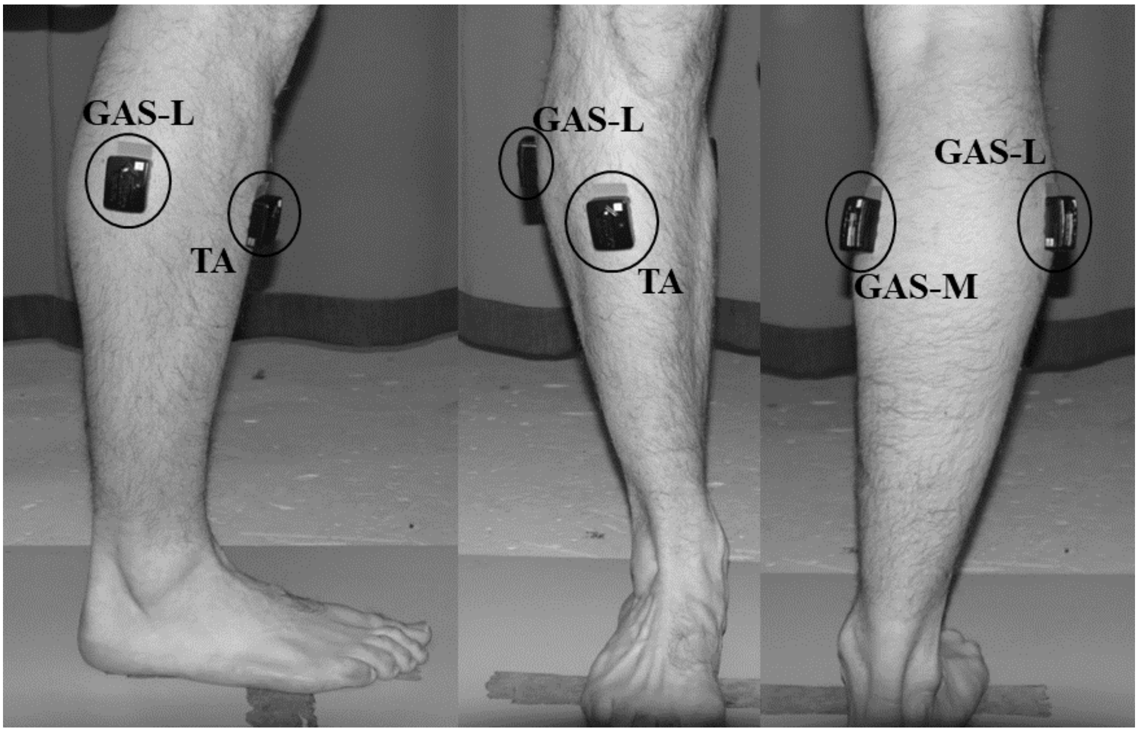


Figure 5.1. Positions of the tibialis anterior (TA), gastrocnemius medialis (GAS-M) and gastrocnemius lateralis (GAS-L) EMG electrodes.

Three-dimensional forces (in the vertical, anterior-posterior and medial-lateral axes) were digitally sampled at 1500 Hz using an AccuGait portable force platform (AMTI, Watertown, MA, USA). Ground reaction forces (GRF) data were used to calculate COP area and COP speed as the standard variables for measuring balance in quiet standing (Jancova, 2008).

5.4.3 EMG and Force Platform Data Processing

EMG data were rectified and filtered using a bidirectional (zero-lag) 8th order Butterworth bandpass filter (10-500 Hz). The first and last seconds of EMG data for each trial were removed and the intervening 12 seconds of EMG data were analysed from the balance tests. Amplitude was normalised to the data collected during the 10-metre walking trial at comfortable speeds. All EMG data were reported as a percentage of root mean square (RMS) values obtained from the walking trial, allowing data to be compared between pre and post-tests.

To assess total EMG activity over the course of the test phase, area under the normalised RMS EMG curve (RMS-iEMG) relative to phase duration was reported. RMS-iEMG controls for potential differences in the EMG signal between participants and pre-post comparisons (Walaszek et al., 2017). The variability of data around the mean value of muscle activity (%RMS-iEMG) was calculated (Yaghoubi et al., 2018). The EMG data processing was performed using Matlab R2015b (Mathworks Inc., Natick, MA, USA) and MRXP Master Edition, version 1.08.17 (Noraxon USA Inc., Scottsdale, AZ).

The mean of COP data was measured from each time series. The COP data were filtered with a fourth-order 10 Hz low-pass zero-lag Butterworth filter, data processing was performed using BioAnalysis (AMT, Inc., Watertown, MA, USA). COP area and COP speed in the anterior-posterior and medial-lateral directions were measured for each single leg balance trial. The COP area was estimated by fitting an ellipse that encompassed 95% of the total COP data (Duarte & Freitas, 2010; Freitas, Prado, & Duarte, 2005). The COP speed was calculated by dividing the COP resultant displacement by the total 14 seconds single leg standing period of the trial in each direction (A-P and M-L). The mean of three trials of quiet standing for 14 seconds followed by 60 seconds of rest in the pre- and post-conditions was measured for each participant.

5.4.4 Statistical Analysis

Data was summarized using descriptive statistics. The Shapiro-Wilk test was used to test the normality of data across all dependent variables (SPSS Statistics version 22 software, IBM Crop, New York, USA). Data conformed to normal distribution. A 2x3 repeated measures analysis of variance (ANOVA) was used to compare the level of activation between the three muscles and pre-post balance tests. To compare the effects of military boot-wear on muscle activity, COP area and COP speed, a paired t-test was used before and after the 12 months of military boot-wear. A significance level of $p < 0.05$ was used for all statistical tests, and t-values with degrees of freedom denoted conventionally as *t(df)*. Due to the variability of the participants' characteristics, the height and weight were considered as covariates for static postural balance tests.

5.5 Results

Although 122 recruits completed the pre and post-tests, not all data sets were analysed due to occasional faulty recordings from electronic equipment during the re-tests. The degrees of freedom (n-1) indicate actual sample sizes analysed. The results of COP area ($t(108) = -13.4$, $p < 0.001$) and speed of movement to correct COP disturbances in A-P ($t(108) = -5.0$, $p < 0.001$) and M-L ($t(108) = -5.6$, $p = 0.013$) directions were significantly increased in post- 1-year test in comparison to pre-test (Figure 5.2). COP speed in the M-L direction was significantly larger than the A-P direction in pre- and post-tests. In addition, COP speed in M-L was significantly greater than A-P direction during both pre- and post-balance test ($p < 0.001$) (Figures 5.3 A and B). There were significant increases in gastrocnemius activity (GAS-M: $t(78) = 3.8$, $p < 0.001$; GAS-L: $t(78) = 3.0$, $p = 0.006$) and variability (GAS-M: $p = 0.020$; GAS-L: $p = 0.011$) in post- compared with pre-balance test (Figures 5.4 and 5.5). In contrast, no difference was observed in TA muscle activation (*t*(78) = 1.878, *p* = 0.231) and variability (*t*(80) = -0.4, *p* = 0.431) between pre- and post-boot wearing for 1 year. However, TA activation was significantly greater than either GAS-M and GAS-L in both pre- and post-balance test (*p* < 0.001).

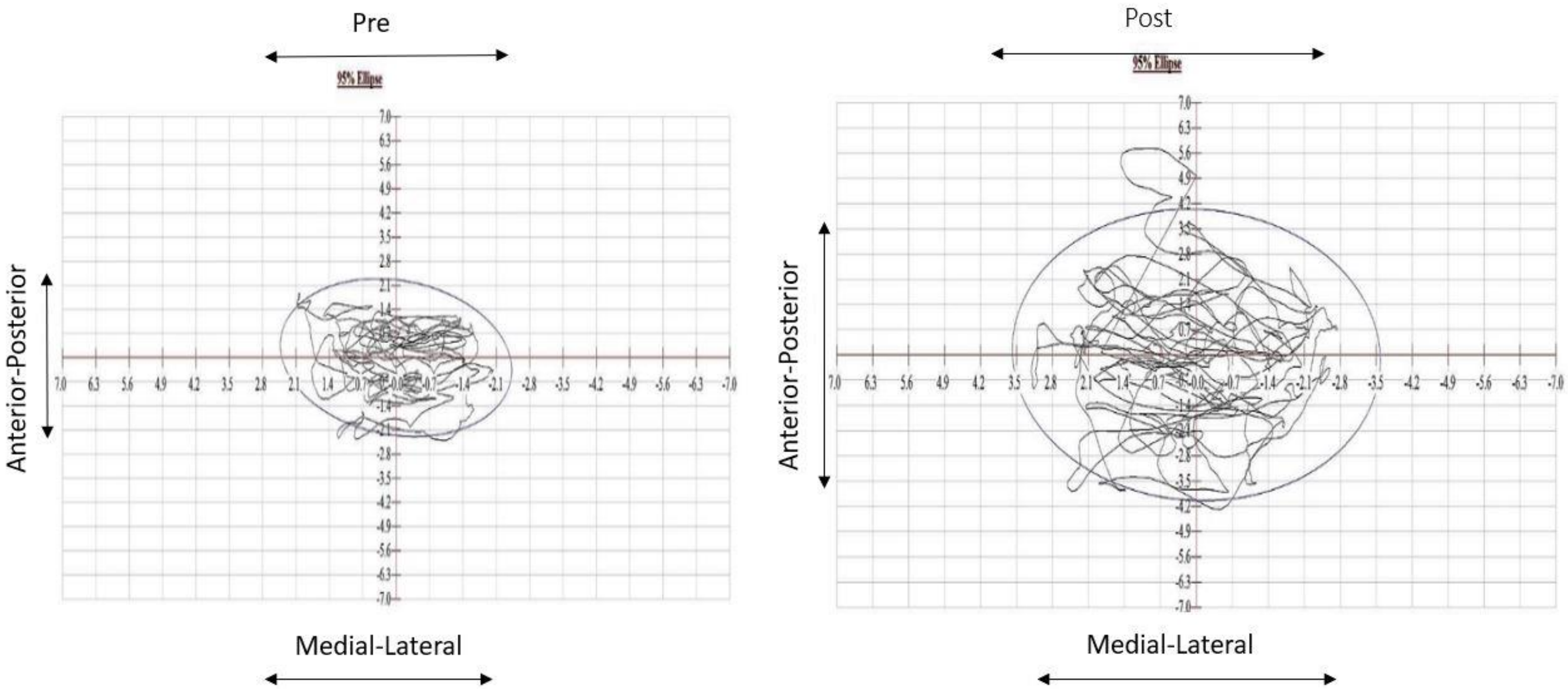


Figure 5.2. Typical centre of pressure as 95% of ellipse area pre-post one-year of boot wearing.

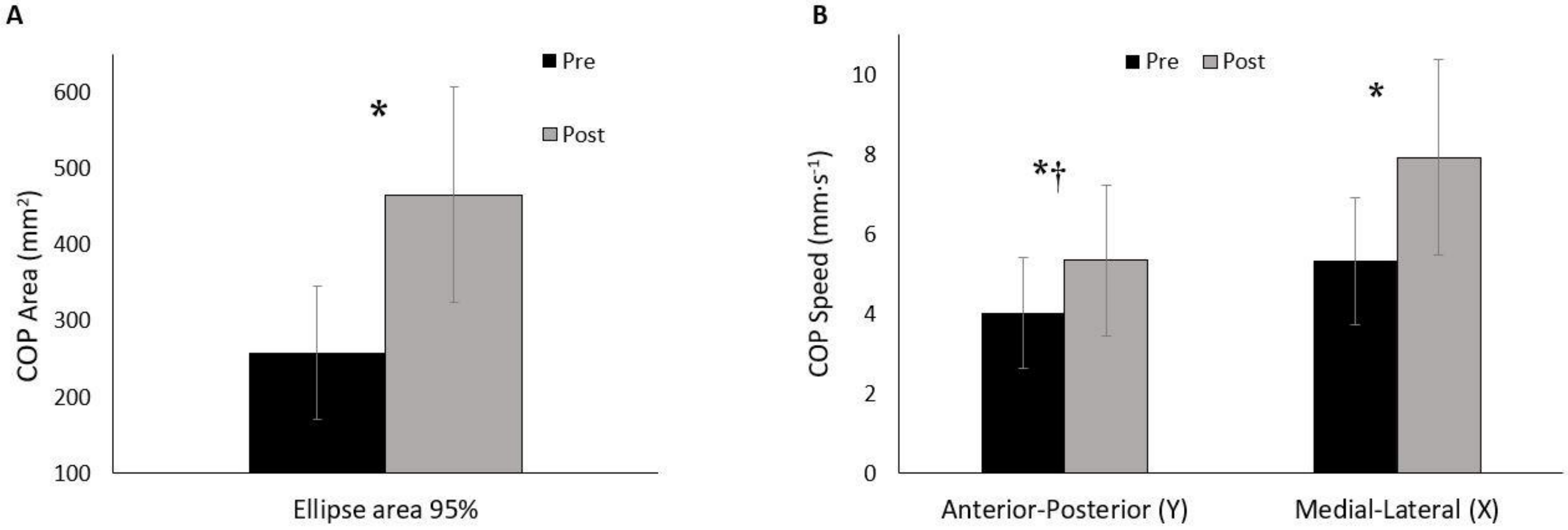


Figure 5.3. (A) Centre of pressure as 95% of ellipse area; (B) Centre of pressure sway speed in each direction (Anterior-Posterior and Medial-Lateral). * indicates significant differences between pre-post ($p < 0.001$). †indicates significant differences between directions ($p < 0.001$) of A-P versus M-L.

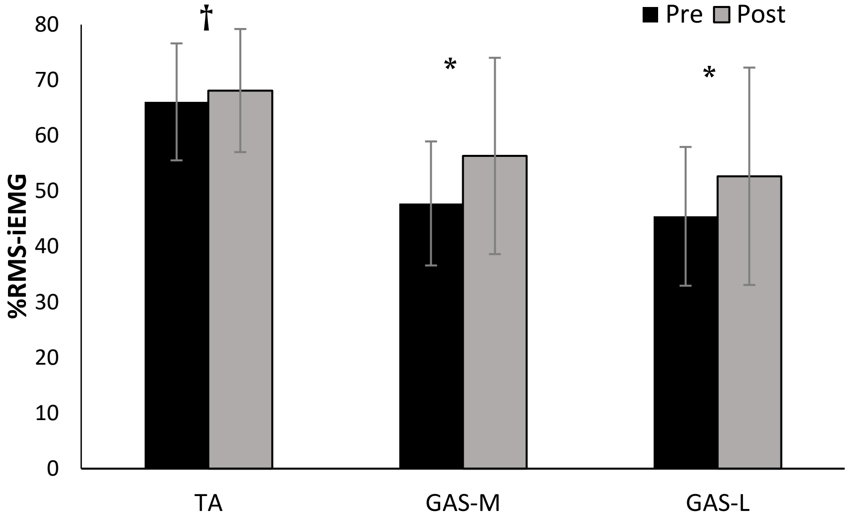


Figure 5.4. %EMG activation pattern of tibialis anterior (TA), gastrocnemius medialis (GAS-M) and gastrocnemius lateralis (GAS-L) at pre and post eyes closed quiet standing balance test. * indicates significant differences between pre-post ($p < 0.05$). † indicates significant differences between TA and both gastrocnemius muscles ($p < 0.05$).

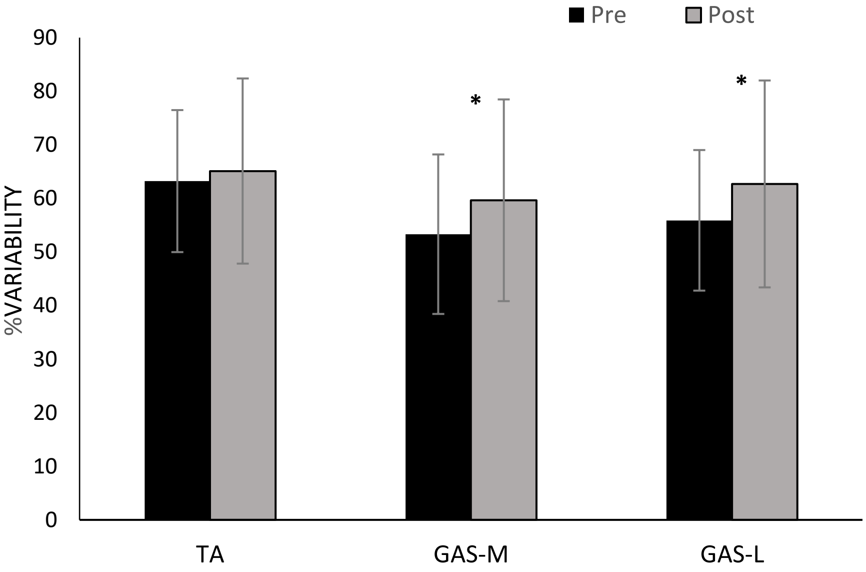


Figure 5.5. %EMG variability of tibialis anterior (TA), gastrocnemius medialis (GAS-M) and gastrocnemius lateralis (GAS-L) at pre and post eyes closed quiet standing balance test. * indicates significant differences between pre-post ($p < 0.05$).

5.6 Discussion

The purpose of this study was to assess the long-term effects of wearing military boots for at least 12 months on stability and muscle activity during postural balance control. There was a significant increase in muscle activity of the plantarflexors to cope with the large sway patterns for COP. This indicated worsening balance control, which likely contributes to the large number of lower limb and ankle injuries in the military.

It appears the medial and lateral gastrocnemius are required to work harder to maintain static balance due to adaptations from wearing boots for more than one year. It could be that the plantarflexors are relying on the boot for functional stability, therefore when not wearing the boot the muscles surrounding the ankle joint, particularly the plantarflexors had to increase activation to maintain balance. This is supported by Hill et al. (2017) who found that when wearing standard footwear with no high stiff shaft there was greater lower limb muscle activity while maintaining balance. However, when performing quiet standing when wearing boots, the high boot shaft appeared to provide support and stability to the ankle (Bohm & Hosl, 2010; Chander et al., 2014) and therefore a lower muscle activation was observed (Fu et al., 2014; Hill et al., 2017). Although in this present study the EMG for balance was measured barefoot both pre- and post- 1-year boot-wear, what we have captured is the adaptation to wearing the boot, so that when it is not worn there is inherent instability that needs a greater activation response of the muscles to correct.

Interestingly, the dorsiflexor muscles were not similarly affected as the plantarflexors (Figures 5.4 and 5.5), even though during normal anterior-posterior (A-P) sway the primary ankle muscles activated for balance and postural control are both the ankle plantar flexors and dorsiflexors (Hill et al., 2017). The dissimilarities in the level of activation from pre- to post- 1-year boot-wear is probably due to differences in the habitual use of both groups of muscles. Bok et al. (2013) found a significant association between declining ankle plantarflexor strength and AP sway about the COP in the elderly. Meaning plantarflexors have a role in supporting the weight of the body and providing stability at the ankle joint and feet for standing and gait, whereas dorsiflexor muscles work against gravity during the swing phase of gait to clear the feet from the floor. They found static balance may be more related to plantarflexion strength than dorsiflexion strength. Similarly, when analysing gastrocnemius EMG-activity and sway data from quiet and perturbed standing, Borg et al., (2007) suggested that gastrocnemius is to a large extent responsible for the phasic control of the anterior–posterior balance during quiet standing. Furthermore, the larger differences in the magnitude of increased activation (Figure 5.4), percentage variability of activation (Figure 5.5) for gastrocnemius muscles, and speed of movement of COP (Figure 5.3B) in the medial-lateral direction are indicative of plantarflexors working hard to maintain medial-lateral balance. Loss of balance in this direction is associated with inversion and eversion ankle injuries, the cause of sprains and strains, which are some of the most common lower limb injuries in the military (Davidson et al., 2008).

In speculating that the plantarflexors are reliant on the boot for functional stability, implies a detraining effect or adaptation. Detraining is characterised by a change of fibre type profile, with the relative percentages of type I and II fibres playing a key role in reactive balance as quick movements are needed to accommodate unexpected perturbations (Miller et al., 2015). In a study by Miller et al. (2015) investigating the relationship between muscle fibre type and reactive balance, those with lower type II fibres were found to be at greater risk of falls where reactive balance was critical. In this current study the muscles are not only activated more, but also the speed of sway about the COP (Figures 5.3A and B) indicated they are moving significantly faster to correct sway about the COP. This would imply a shift towards more type II muscle fibres, which agrees with findings of Scott, Stevens, and Binder–Macleod (2001), whereby a decreased use of skeletal muscle can lead to a conversion of muscle fibre types in the slow oxidative to fast oxidative fibres. This underlying muscle fibre morphology is only speculation as we did not biopsy for muscle fibre type per se.

Similarities in balance outcomes can be seen in the study by Warnica et al. (2014) who found wearing an ankle foot orthotic crossing the ankle joint for 30 seconds decreased sway about the COP, indicating more stability during quiet standing when the ankle was supported by wearing an ankle orthotic. Furthermore, Warnica et al. (2014) found that when not wearing an ankle foot orthotic, muscle activation was increased along with sway amplitude, indicating an increased effort to stabilise around the COP. When considering the characteristics of the military boot, the assumption can be made that the boot is serving the same purpose as an orthotic for the ankle joint.

It is interesting to note that a large percentage of ankle injuries in military personnel occur during sport and running (Knapik et al., 2007; Sammito et al., 2016; Waterman et al., 2010) when not wearing a military boot. Footwear invariably affects human balance and the design features either aid or reduce balance performance (Chander et al., 2015). This study shows an increase in sway about the COP by ~100% (Figure 5.2), indicating a decrease in stability and balance. There was no significant decrease in tibialis anterior activation or variability but there were for medial and lateral gastrocnemius muscles. If tibialis anterior functions as the stabiliser, and medial and lateral gastrocnemius are prime movers, these results indicate the gastrocnemius muscles have to work harder to maintain balance when not wearing a boot.

Motor output of the postural function is linked mainly to neuromuscular system efficiency, the structural and functional characteristics of antigravity muscles such as the tibialis anterior and gastrocnemius may also influence postural performance (Paillard, 2017). In decreasing functionality of the lower limb there is lessening of the motor output of the postural function leading to an increased effort to ensure body balance (Paillard, 2017).

The limitations of this study are the lack of biopsy to note any microarchitectural changes of the muscles to confirm increases or decreases in fibre types, size or number. However, the scope of the study was to confirm changes in function of ankle joint due to boot wearing, and the results indicate detrimental or maladaptations have occurred over the one year of boot-wear. A further limitation is that only the activity of surface prime mover muscles were measured by EMG due to the logistics of capturing the activity of deeper postural muscles. Nevertheless, the diminished balance and larger COP area indicate the postural muscles were also negatively affected by chronic boot-wear.

Further limitations would be more information regarding other confounding variables such as injuries and weight during the year before retesting that may have influenced the post-testing results. Bearing in mind that the cohort were a very homogenous group of military recruits, the percentage in changes were not expected to make any significant differences for group means. Considering sport as another physical activity variable, other than physical training, sport per se is not part of initial military training. Further work would take into consideration the effects of more confounding factors.

5.7 Conclusion

In conclusion, this study has shown that wearing a military boot for more than 12 months negatively affects balance and stability when not wearing the boot. Muscles are having to work harder when the protective boot is removed, particularly the plantarflexors to maintain medial-lateral balance. These findings are part of the aetiology of for the high number of lower limb musculoskeletal injuries in the military.

5.8 References

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Bohm, H., & Hosl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *J Biomech, 43*. doi:10.1016/j.jbiomech.2010.05.029

Böhm, H., & Hösl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *Journal of Biomechanics, 43*(13), 2467-2472. doi:https://doi.org/10.1016/j.jbiomech.2010.05.029

Bok, S.-K., Lee, T. H., & Lee, S. S. (2013). The Effects of Changes of Ankle Strength and Range of Motion According to Aging on Balance. *Ann Rehabil Med, 37*(1), 10-16. doi:10.5535/arm.2013.37.1.10

Borg, F., Finell, M., Hakala, I., & Herrala, M. (2007). Analyzing gastrocnemius EMG-activity and sway data from quiet and perturbed standing. *Journal of Electromyography and Kinesiology, 17*(5), 622-634. doi:https://doi.org/10.1016/j.jelekin.2006.06.004

Cameron, K. L., Owens, B. D., & DeBerardino, T. M. (2010). Incidence of Ankle Sprains Among Active-Duty Members of the United States Armed Services From 1998 Through 2006. *Journal of athletic training, 45*(1), 29-38. doi:10.4085/1062-6050-45.1.29

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science, 6*(1), 59-66. doi:10.1080/19424280.2013.834979

Chander, H., Wade, C., & Garner, J. C. (2015). The influence of occupational footwear on dynamic balance perturbations. *Footwear Science, 7*(2), 115-126.

Cikajlo, I., & Matjačić, Z. (2007). The influence of boot stiffness on gait kinematics and kinetics during stance phase. *Ergonomics, 50*(12), 2171-2182. doi:10.1080/00140130701582104

Cronin, N. J., Kumpulainen, S., Joutjärvi, T., Finni, T., & Piitulainen, H. (2015). Spatial variability of muscle activity during human walking: The effects of different EMG normalization approaches. *Neuroscience, 300*, 19-28. doi:https://doi.org/10.1016/j.neuroscience.2015.05.003

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

Dobson, J. A., Riddiford-Harland, D. L., Bell, A. F., & Steele, J. R. (2017). Work boot design affects the way workers walk: A systematic review of the literature. *Applied Ergonomics, 61*, 53-68. doi:https://doi.org/10.1016/j.apergo.2017.01.003

Duarte, M., & Freitas, S. M. S. F. (2010). Revision of posturography based on force plate for balance evaluation. *Brazilian Journal of Physical Therapy, 14*, 183-192.

Freitas, S. M. S. F., Prado, J. M., & Duarte, M. (2005). The use of a safety harness does not affect body sway during quiet standing. *Clinical Biomechanics, 20*(3), 336-339. doi:https://doi.org/10.1016/j.clinbiomech.2004.12.002

Fu, W., Fang, Y., Liu, Y., & Hou, J. (2014). The effect of high-top and low-top shoes on ankle inversion kinematics and muscle activation in landing on a tilted surface. *Journal of Foot and Ankle Research, 7*(1), 14. doi:10.1186/1757-1146-7-14

Garner, J. C., Wade, C., Garten, R., Chander, H., & Acevedo, E. (2013). The influence of firefighter boot type on balance. *International Journal of Industrial Ergonomics, 43*(1), 77-81. doi:https://doi.org/10.1016/j.ergon.2012.11.002

Goldie, P. A., Evans, O. M., & Bach, T. M. (1992). Steadiness in one-legged stance: Development of a reliable force-platform testing procedure. *Archives of Physical Medicine and Rehabilitation, 73*(4), 348-354. doi:10.1016/0003-9993(92)90008-K

Hamill, J., & Bensel, C. K. (1992). *Biomechanical Analysis of Military Boots. Phase 1. Materials Testing of Military and Commercial Footwear*. Massachusetts University Amhurst Biomechanics Lab.

Hamill, J., & Bensel, C. K. (1996). *Biomechanical analysis of military boots: Phase 2. Volume 1. Human user testing of military and commercial footwear*. Massachusetts University Amhurst Biomechanics Lab.

Havenetidis, K., Kardaris, D., & Paxinos, T. (2011). Profiles of musculoskeletal injuries among Greek Army officer cadets during basic combat training. *Mil Med, 176*(3), 297-303.

Hill, C. M., DeBusk, H., Knight, A. C., & Chander, H. (2017). Influence of military-type workload and footwear on muscle exertion during static standing. *Footwear Science, 9*(3), 169-180. doi:10.1080/19424280.2017.1403968

Jancova, J. (2008). Measuring the balance control system--review. *Acta Medica (Hradec Kralove), 51*(3), 129-137.

Knapik, J. J., Jones, S. B., Darakjy, S., Hauret, K. G., Bullock, S. H., Sharp, M. A., & Jones, B. H. (2007). Injury rates and injury risk factors among US Army wheel vehicle mechanics. *Military Medicine, 172*(9), 988-996.

Lima, B. N., Lucareli, P. R., Gomes, W. A., Silva, J. J., Bley, A. S., Hartigan, E. H., & Marchetti, P. H. (2014). The acute effects of unilateral ankle plantar flexors static-stretching on postural sway and gastrocnemius muscle activity during single-leg balance tasks. *Journal of sports science & medicine, 13*(3), 564.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Physical Therapy in Sport, 6*(2), 74-82. doi:https://doi.org/10.1016/j.ptsp.2005.01.001

Miller, A. I., Heath, E. M., Dickinson, J. M., & Bressel, E. (2015). Relationship between muscle fiber type and reactive balance: a preliminary study. *Journal of motor behavior, 47*(6), 497-502.

Najafipour, F., Najafipour, F., & Hassan, M. (2017). The Risk Factors for Ankle Sprain in Cadets at a Male Military School in Iran: A Retrospective Case-control Study. *in depth, 4*(5), 7-8.

Paillard, T. (2017). Relationship between Muscle Function, Muscle Typology and Postural Performance According to Different Postural Conditions in Young and Older Adults. *Frontiers in physiology, 8*, 585-585. doi:10.3389/fphys.2017.00585

Perry, S. D., Radtke, A., & Goodwin, C. R. (2007). Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination. *Gait & Posture, 25*(1), 94-98.

Ricard, M. D., Schulties, S. S., & Saret, J. J. (2000). Effects of High-Top and Low-Top Shoes on Ankle Inversion. *Journal of athletic training, 35*(1), 38-43.

Robbins, S., Waked, E., Gouw, G. J., & McClaran, J. (1994). Athletic footwear affects balance in men. *British Journal of Sports Medicine, 28*(2), 117-122. doi:10.1136/bjsm.28.2.117

Sammito, S., Gundlach, N., & Bockelmann, i. (2016). Injuries caused during military dutyand leisure sport activity. *Work, 54*, 121-126.

Schulze, C., Lindner, T., Schulz, K., Finze, S., Kundt, G., Mittelmeier, W., & Bader, R. (2011). The Influence in Airforce Soldiers Through Wearing Certain Types of Army-Issue Footwear on Muscle Activity in the Lower Extremities. *Open Orthop J, 5*, 302-306. doi:10.2174/1874325001105010302

Scott, W., Stevens, J., & Binder–Macleod, S. A. (2001). Human Skeletal Muscle Fiber Type Classifications. *Physical Therapy, 81*(11), 1810-1816. doi:10.1093/ptj/81.11.1810

Soheil, N., Sadeghian, M., Tayebi, A., Aa, K. Z., & Asgari, A. R. (2010). *Epidemiology of physical injuries resulted from military training course* (Vol. 12).

Walaszek, M. C., Ransom, A. L., Capehart, S., Pohl, M. B., Shapiro, R., & Bollinger, L. M. (2017). External loading alters trunk kinematics and lower extremity muscle activity in a distribution-specific manner during sitting and rising from a chair. *Journal of Electromyography and Kinesiology, 34*, 102-108. doi:https://doi.org/10.1016/j.jelekin.2017.04.005

Warnica, M. J., Weaver, T. B., Prentice, S. D., & Laing, A. C. (2014). The influence of ankle muscle activation on postural sway during quiet stance. *Gait & Posture, 39*(4), 1115-1121. doi:https://doi.org/10.1016/j.gaitpost.2014.01.019

Waterman, B. R., Belmont, P. J., Cameron, K. L., DeBerardino, T. M., & Owens, B. D. (2010). Epidemiology of Ankle Sprain at the United States Military Academy. *The American Journal of Sports Medicine, 38*(4), 797-803. doi:10.1177/0363546509350757

Yaghoubi, M., Lark, S. D., Page, W. H., Fink, P. W., & Shultz, S. P. (2018). Lower extremity muscle function of front row rugby union scrummaging. *Sports biomechanics*, 1-13.

Chapter 6: Can 10 Weeks of Shoe Wear Reverse Years of Neuromuscular Adaptation Due to Military Boot-Wear?

6.1 Chapter Overview

Now that the aetiology mechanisms have been examined, the conclusion has been reached that physiological adaptations have taken place due to the habitual wearing of the boot. This next chapter investigates whether these adaptations can be reversed by wearing a flexible shoe with the intention of reducing future lower limb injuries.

6.2 Abstract

Background

Previous comparisons of boot versus shoe wear have always been acute ‘one-off’ measures, and do not account for any habitual wear physiological adaptions. This study compares lower limb biomechanical and muscle electrical activity of habitual boot wearers pre- and post- 10 weeks of flexible shoe wear.

Methods

Sixty-five habitual boot wearing regular force military male personnel were measured for lower limb (tibialis anterior, medial and lateral gastrocnemius [GAS-M and GAS-L]) strength, fatigue and range of motion (ROM) pre- and post- 10-week flexible shoe wear. In addition, muscle electrical activity (EMG) and postural balance via centre-of-pressure area were also recorded. Work fatigue was was measured as the percentage of work in the first third relative to work in the last third of the endurance test.

Results

Post- 10 weeks from transitioning from a minimum of two years habitual boot-wear to shoe wear, all participants significantly improved their balance, as shown by a decrease in the 95% ellipse area ($t(64) = 12.33$, $p < 0.001$). There was also a significant decrease (t(64) = 6.0, $p < 0.001$) in the Anterior-Posterior and Medial-Lateral movement ($t(64) = 3.0$, $p = 0.004$) of COP. There were significant decreases in gastrocnemius activity (Gastrocnemius-Medial (GAS-M): $p = 0.019$; Gastrocnemius-Lateral (GAS-L): $p = 0.001$) and variability (GAS-M: $p = 0.020$; GAS-L: $p = 0.011$) in the post-shoe wear balance test. In contrast, no difference was observed in Tibialis Anterior (TA) muscle activation ($p = 0.367$) and variability ($p = 0.151$) between pre and post shoe wearing for 10 weeks. In

addition, TA activation was significantly greater than GAS-M and GAS-L in both pre- and post-balance test ($p < 0.001$). There were significant increases in plantar flexion strength ($t(64) = -10.5$, $p < 0.001$), dorsiflexion strength ($t(64) = -10.54$, $p < 0.001$), inversion/eversion range (4.9° and 5.2° respectively), and plantarflexion/dorsiflexion isokinetic range of motion by 3.8° after wearing shoes for 10 weeks. Work fatigue of the plantarflexors significantly decreased ($p < 0.05$).

Conclusions

The results indicate an increased stabilisation by transitioning to habitually wearing a flexible shoe after years of boot-wear mal-adaptations. The implications may lead to decreased lower limb injuries associated with prolonged boot-wear.

6.3 Introduction

Many reviews have listed multiple potential causes of lower limb injuries in the armed forces (Andersen et al., 2016; Davidson et al., 2008; Kaufman et al., 2000), and in some cases footwear has been included on those lists (Andersen et al., 2016; Böhm & Hösl, 2010; Cikajlo & Matjačić, 2007). Footwear has been examined particularly as either a cause or protection for lower limb injuries, with several attributes highlighted that can alter gait and performance. These attributes include boot shaft height and stiffness, boot or shoe sole thickness, flexibility and shape, or hardness of materials of the upper shoe/boot.

Studies comparing different types of footwear have shown decreased ankle range of motion (Schulze et al., 2014). Although Schulze et al. reported decreased ankle ROM due to the military boot, they did not report any difference in electrical muscle activity compared with wearing shoes and most athletic footwear or barefoot (Schulze et al., 2011). The reduced ROM is due to the physical biomechanical restriction, but the lack of difference in muscle electrical activity is most likely due to the lack of time for habituation of neuromuscular adaptation to have occurred from one type of footwear to another.

The soles of footwear have been shown to absorb and disperse sensory information from the ground surface when compared to bare feet, this contributes to delays in postural response latencies (Hosoda et al., 1997). Furthermore, it is postulated that sole thickness affects the proprioceptive ability of the foot for postural balance. For example, in an older adult study between barefoot and two shoe types, Brenton-Rule et al. (2011) found postural sway differences of shoes to barefoot, but not between shoe types. It implied there is an insulating effect of shoes for proprioceptive information. Both shoes were athletic but varied in type of sole. Enhanced sole flexibility has been intimated to be a negative attribute for military. For example, Arndt et al. (2003) compared two types of military boot differing in sole flexibility, but concluded the more flexible sole led to greater fatigue due to greater strain rates, particularly at the second metatarsal. Similarly Dobson et al. (2015) found less muscle activity was required for the same walking pattern when wearing stiffer soled leather lace-up boots, which provided more shank support, compared to more flexible gumboots. Furthermore, Sinclair and Taylor (2014) reported sole flexibility was associated with more overuse injuries due to higher impact loading, and ankle joint eversion and tibial rotation when comparing an athletic shoe to an army boot.

In comparing height of the shaft, a low-cut shoe versus boot study by Chander et al. (2014) found increased postural sway in the low-cut shoe versus tactical boot. This was a measure of COP movement allowed by constraint of the footwear, not about balance itself. They concluded that the small excursion of COP by tactical boots would create more stability and lower injury rates. Similar results were found by Hamill & Bensel (1996) who reported greater COP excursion with a lower shaft, and Yang et al. (2015) who also found shaft length affected standing balance. A higher shaft height inhibits ROM at the ankle and ball of foot flexion-extension (Park et al., 2015), but Simeonov et al. (2008) also found the higher shaft increased perception of stability as a result of the stiffness of the boot shaft covering the ankle joint. The implication is it reduces injuries by increasing stability, at least while wearing the boot. This is supported by Riddell (1990) who associated the higher shaft with a lower number of injuries.

A more flexible shaft due to different construction materials has been shown to allow more ankle movement (ROM), and can increase risk of sprain/strain injuries (Cikajlo & Matjačić, 2007; Neely, 1998), which points towards a stiffer shaft to minimise injury. However, Cikajlo and Matjačić (2007) reported more power generated at the ankle with more flexible shaft, which shows increased function, but not necessarily increased or reduced injury risk.

There is no denying that different footwear, particularly the boot versus the shoe, show differences in performance in the acute setting i.e., one-off measure. However, prolonged wearing of footwear, such as boots with high stiff shafts and inflexible soles, causes measurable inherent and internal physiological structural adaptations over time. Consequently, a single measure for stability, or muscle electrical activity while wearing a shoe (or barefoot) compared with a habitual boot wearer does not give a clear indication of the benefits (or negative effects) of the flexible shoe for military personnel. Only by continued wearing of the flexible shoe footwear can a true comparison to habitual boot-wear be possible.

This study purposefully examines the biomechanics and electrical muscle activity of the unshod foot after years of wearing military boots. Furthermore, it aims to show if any adaptations can be reversed by changing to more flexible shoe footwear, and the time frame involved. This has implications for reducing injury risk, particularly overuse injuries due to military boot-wear.

6.4 Methods

6.4.1 Participants

From an initial eighty recruited volunteers, sixty-five healthy male military personnel completed this study (age: 37.6 ± 10 years; height: 1.76 ± 0.4 m; mass: 84.5 ± 11 kg). The participants in the study had no previous surgery and no history of injury in the lower extremities within the last year. All participants had no evidence of a leg-length discrepancy (more than 1 cm) nor balance deficits (Lima et al., 2014). All participants participated in regular unit physical training (PT) which consisted of running, calisthenics and on occasion, resistance training. Additional activities included field training and pack marches. All participants were habitual boot wearers for a minimum of 24 months.

All participants provided written consent after the study was explained to them and they had received written information to consider. This study was approved by the institutional Human Ethics Committee (Massey University HEC Southern A Application 16/53).

6.4.2 Protocol

Prior to the data collection, the participants were asked to identify their preferred leg to kick a ball (Maulder & Cronin, 2005) for determining the dominant leg. The experimental protocol consisted of strength, range-of-motion, postural control balance and muscle electrical activation measurements. All participants were required to perform a prescribed pre-test warm-up, which consisted of a repeated 10-metre shuttle walk (4 x back and forth) at the participants own self-selected speed. All measures were conducted pre- and post- 10 weeks of wearing a lightweight trail shoe with a 6 mm heel drop (Figure 6.1) (Salomon Sense Mantra 3®).

Figure 6.1. Salomon Sense Mantra 3 shoe used for the trial (Reproduced with permission from Salomon)

Strength and fatigue were assessed by isokinetic dynamometry using a Biodex System 4 Dynamometer with the plantar/dorsiflexion footplate and Biodex Advantage Software package (Biodex System 4 Quick-Set, Biodex Medical Systems, Inc. Shirley, New York, USA). The Biodex set-up and positioning for plantar-flexion/dorsiflexion testing was in accordance with the Biodex Multi-Joint System Pro Operation Manual with knee flexion at 30⁰. Knee and hip joint angles were adjusted by changing the distance between the footplate, the chair and the height of the support arm under the knee for each participant. Each individual participant's position on the Biodex was recorded for settings in the retest measures. Testing was carried out at speeds of 60°/s (1.05 rads/s) and 120°/s (2.10 rads/s). A pre-test warm-up of five sub-maximal efforts plus one maximal effort of plantarflexion to dorsiflexion at 60˚/s (1.05 rads/s) on the Biodex chair was performed. The pre-test warm-up allowed the participant to become familiar with the speed of the dynamometer lever arm and the application of maximum force. Strength testing at 60°/s included five consecutive repetitions of plantarflexion to dorsiflexion, while 15 consecutive repetitions were performed at 120°/s to assess muscle fatigue. Peak torque measured in Newton-metres (Nm) was recorded for the strength test. Muscle fatigue, measured as work fatigue (WF) was the percentage of work in the first third relative to work in the last third of the test. For this study, the term fatigue is defined as the failure to maintain force or power output (Edwards, 1981). According to Holmbäck and Lexell (2007), WF is described as the relative (%) loss of work in the first third to the last third of the ten contractions and was obtained from the Biodex results based on the following equation (Bosquet et al., 2010):

$$WF = 100 - \left(\frac{Average\ performance\ of\ last\ 3\ repetitions}{Average\ performance\ of\ first\ 3\ repetitions}\right) x100$$

All inversion/eversion range of motion measures were performed with participants barefoot. Active inversion and eversion ranges of movement were assessed with a bubble inclinometer (Baseline® Bubble Inclinometer, Fabrication Enterprises Inc. White Plains, New York 10602, USA). The measurement method used is outlined in ESSA's Student Manual for Health, Exercise and Sport Assessment 2014 (Coombes & Skinner, 2014). Active plantarflexion and dorsiflexion were recorded on the Biodex system 4 Dynamometer with the participants' foot strapped in the plantar/dorsiflexion footplate. Subjects wore flexible training shoes in order for the foot to work as a rigid lever throughout the full range of movement (Poulis & Soames, 2003).

Postural control tests involved a single leg stance position held for 14s on the dominant foot whilst standing on the force plate (AMTI, Watertown, MA, USA) with the hands held on the hips. The other elevated leg, aligned with the contralateral malleolus. The participants were instructed to stand as still as possible with their eyes closed to minimise visual sensory feedback. There were three 14 seconds trials separated by

60 seconds rest periods at both pre- and post-intervention. Force data and electromyography (EMG) of the supporting limb for tibialis anterior (TA), medial and lateral gastrocnemius (GAS-M and GAS-L) were recorded. EMG was collected separately during the 10m shuttle warm-up walking at a self-selected speed.

Electromyography signals were collected by three channels from a 16-channel wireless Delsys EMG system (Delsys Inc. Boston, MA, USA) to record the selected muscles. The EMG electrodes were placed parallel to the muscle's fibres with 2 cm inter-electrode distance and before their placement, the skin surface was prepared by shaving and abrading with alcohol pads. EMG data (input impedance: > 100 MΩ; CMRR: > 100 dB; baseline noise: < 1µV RMS; gain: 500) were collected at a sampling rate of 1500 Hz.

Three-dimensional forces (in the vertical, anterior-posterior and medial-lateral axes) were digitally sampled at 1500 Hz using the AccuGait portable force platform (AMTI, Watertown, MA, USA). Ground reaction forces (GRF) data were used to calculate centre of pressure (COP) area and COP speed as the standard variables for measuring balance in quiet standing (Jancova, 2008; Riemann & Schmitz, 2012).

6.4.3 EMG and Force Platform Data Processing

EMG data were rectified and filtered using a bidirectional (zero lag) 8th order Butterworth bandpass filter (10-500 Hz). The first and last seconds of EMG data for each trial were removed and 12 seconds of the balance tests were analysed. To enable the normalisation of the EMG signals, amplitude was normalised to the data collected during the 10-metre walking trial at the self-selected comfortable speed (Cronin, Kumpulainen, Joutjärvi, Finni, & Piitulainen, 2015). All EMG data were reported as a percentage of root mean square (RMS) values obtained in the walking trial, allowing data to be compared between pre- and post-intervention measurements. To assess total EMG activity over the course of a phase, the area under the normalised RMS EMG curve (RMS-iEMG) relative to phase duration is reported. RMS-iEMG controls for potential differences in the EMG signal between participants and pre-post comparisons as set out in (Yaghoubi et al., 2018). The variability of data around the mean value of muscle activity (%RMS-iEMG) was calculated, also as stated in Yaghoubi et al. (2018).

The mean of COP data was measured from each time series. The COP data were filtered with a fourth-order 10 Hz low-pass zero-lag Butterworth filter. COP area and COP speed in both the anterior-posterior and medial-lateral directions were measured for each single leg balance trail. The COP area was estimated by fitting an ellipse that encompassed 95% of the total COP data (Duarte & Freitas, 2010; Freitas et al., 2005). The COP speed was calculated by dividing the COP resultant displacement by the total 14 second period of the trial in each direction (A-P and M-L). The mean of three trials of quiet standing for 14 seconds in the pre- and post-conditions was measured for each participant.

The EMG data processing was performed using Matlab R2015b (Mathworks Inc., Natick, MA, USA) and MRXP Master Edition, version 1.08.17 (Noraxon USA Inc., Scottsdale, AZ). The GRF data processing was performed using BioAnalysis (AMT, Inc., Watertown, MA, USA).

6.4.4 Statistical Analysis

Data was summarized using descriptive statistics. The Shapiro-Wilk test was used to test the normality of data across all dependent variables (SPSS Statistics version 22 software, IBM Crop, New York, USA). Data conformed to normal distribution. To compare the effects of shoe wear on strength, ROM, muscle activity, COP area and COP speed, pre- and post- 10 weeks of shoe wear intervention was used to determine differences between the three muscles measured. Due to the variability of the participants' characteristics, the height and weight were considered as covariates for balance tests.

Paired sample t-test was used to compare pre- and post-tests for percentage fatigue and the level of significance was set at $p \leq 0.05$ and t-values with degrees of freedom denoted conventionally as *t(df)*. Cohen's *d* statistic (Cohen, 1988) was calculated to determine the size of the effect of 10 weeks of wearing a shoe after more than 2 years boot-wear on plantarflexion and dorsiflexion peak torque. Cohen's cut-offs for effect sizes are, 0.20 small, 0.50 medium, and 0.80 large (Cohen, 1992).

6.5 Results

Paired analysis shows range of motion for both inversion ($t(64) = -8.3$, $p < .001$) and eversion ($t(64) = 8.4$, $p < 0.001$) were significantly increased by 27% and 39% respectively (Figure 6.2). There were significant improvements in plantar ($t(64) = -9.9$, $p > 0.001$) and dorsiflexor ($t(64) = -10.54$, $p < 0.001$) strength at 60^{O}/sec (Figure 6.3). The effect size for plantarflexion ($d = 0.9$) and for dorsiflexion ($d = 0.85$) at 60˚/sec were both found to be large effect sizes. Only plantarflexion strength-endurance (120^{O}/sec) was significantly increased ($t(64) = -7.13$, $p < 0.001$) (Figure 6.4).

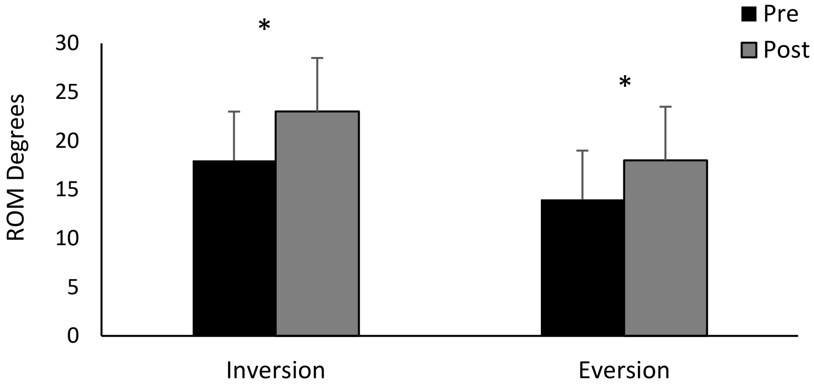


Figure 6.2. Pre and post range of motion. * Indicates significant difference pre and post (*p* < .001).

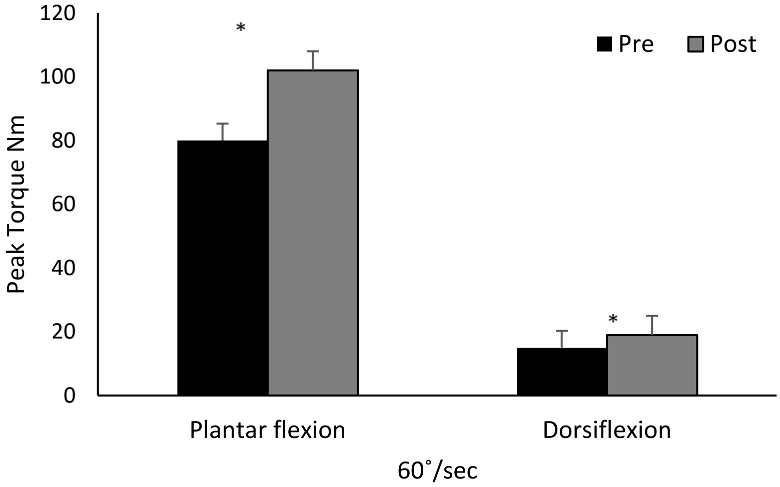


Figure 6.3. Strength pre/post peak torque at 60˚/sec. *Denotes significant difference pre and post (p < .001).

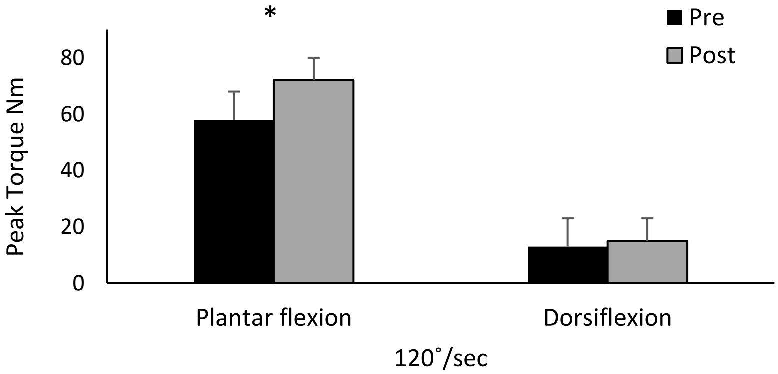


Figure 6.4. Strength endurance pre/post peak torque at 120˚/sec. *Denotes significant difference pre and post (p < .001).

Average WF of the plantar flexors measured at 120°/s significantly decreased from 34.9% (± 11.3) to 26.3% (± 10.1) from pre- to post-shoe wearing ($p < 0.001$), with a mean fatigue index decrease of 8.7% (± 7.3). The average fatigue index of the dorsiflexors at 120°/s was 43.2% (± 12.4) pre-, and 38.9% (± 11.7) post-training (Figure 6.5).

The results of COP area and speed in A-P and M-L directions (Figure 6.6A and B) were significantly decreased post- 10 weeks shoe wear in comparison to pre-test ($t(64) = 12.33$, $p < 0.001$). COP speed in A-P direction ($t(64) = 5.9$, $p < 0.001$) was significantly larger than M-L direction ($t(64) = 2.9$, $p = 0.004$) in both pre- and post-balance tests as seen in Fig. 6.6B. There was a significant decrease in gastrocnemius medialis and lateralis electrical activities ($p < 0.001$) (Figure 6.7) and variability (Figure 6.8) (GAS-M: $p = 0.019$; GAS-L: $p = 0.001$) at post-intervention compared to pre-intervention for the postural control balance test. In contrast, no difference was observed in TA muscle activation ($p = 0.367$) and variability ($p = 0.151$) between pre and post 10-week shoe wearing. Furthermore, TA activation was significantly greater than GAS-M and GAS-L in both pre- and post-balance testing ($p < 0.001$) (Figure 6.7).

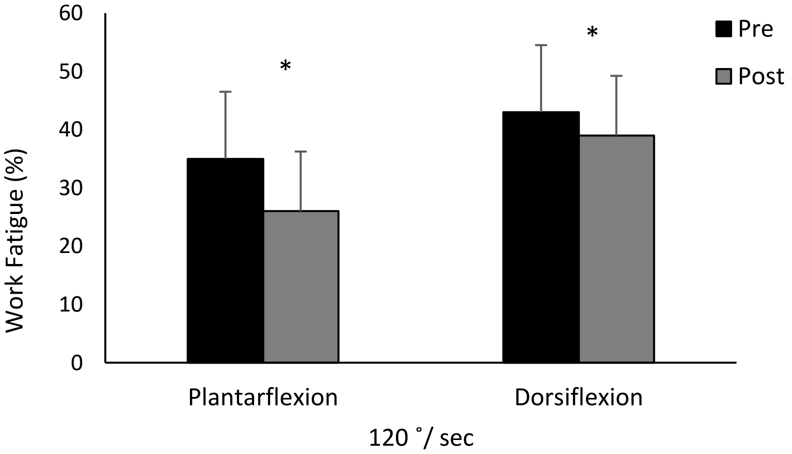


Figure 6.5. Pre and post work fatigue at 120˚/sec. *Denotes significant difference pre and post (p < 0.001).

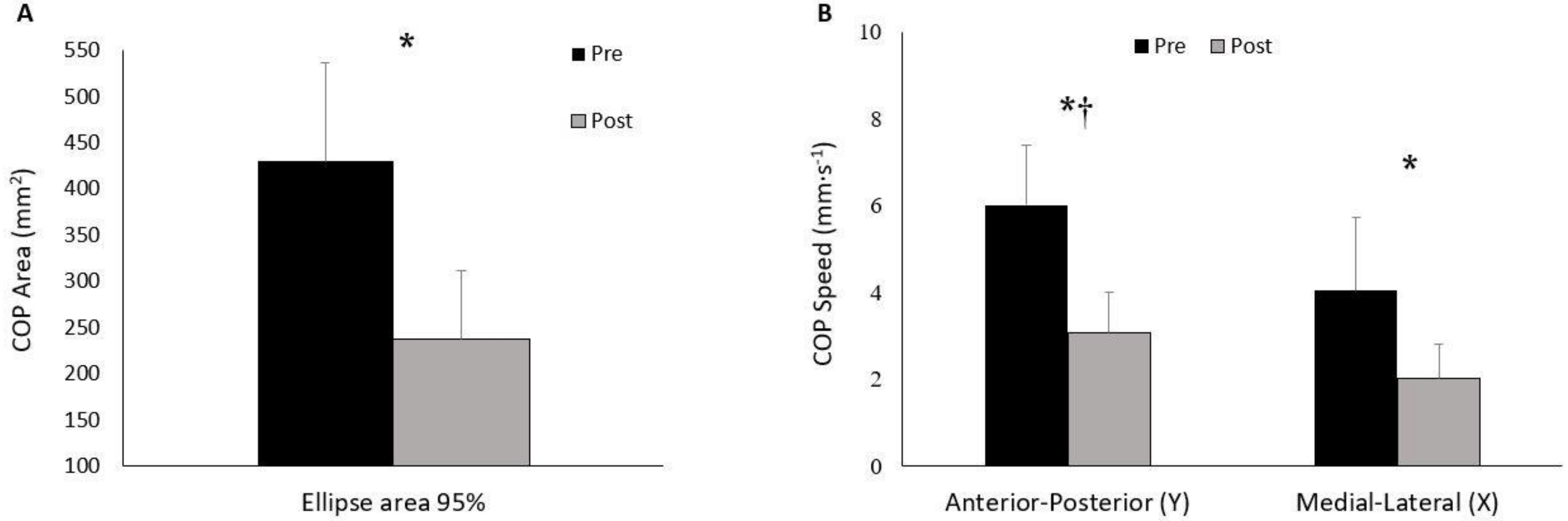


Figure 6.6. (A) Centre of pressure as 95% of ellipse area (B) Centre of pressure sway speed in each direction (Anterior-Posterior and Medial-Lateral). * indicates significant differences between pre-post ($p < 0.001$). †indicates significant differences between directions ($p < 0.001$).

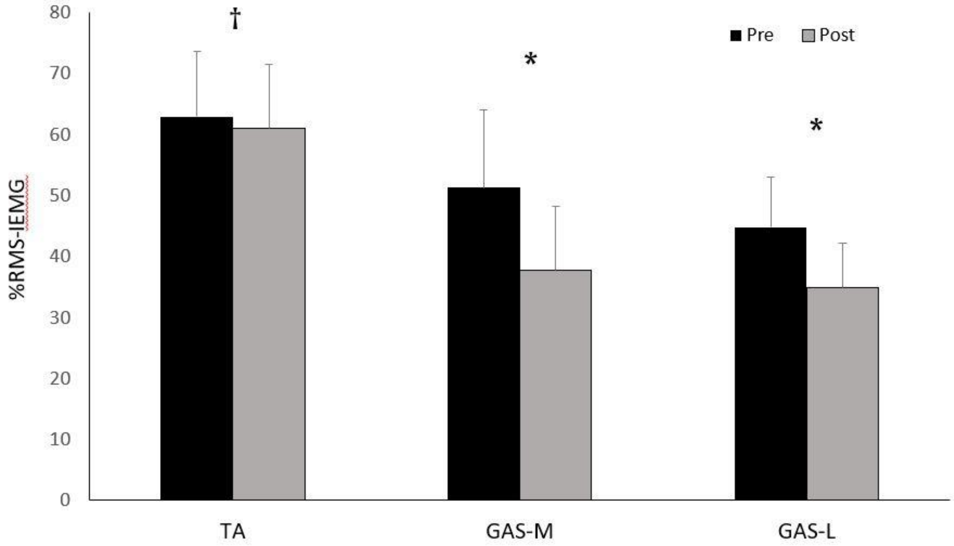


Figure 6.7. %EMG activation pattern of tibialis anterior (TA), gastrocnemius medialis (GAS-M) and gastrocnemius lateralis (GAS-L) at pre and post-shoe wear, eyes closed quiet standing balance test. * indicates significant differences between pre-post (*p* < 0.05). † indicates significant differences between TA and both gastrocnemius muscles (*p* < 0.001).

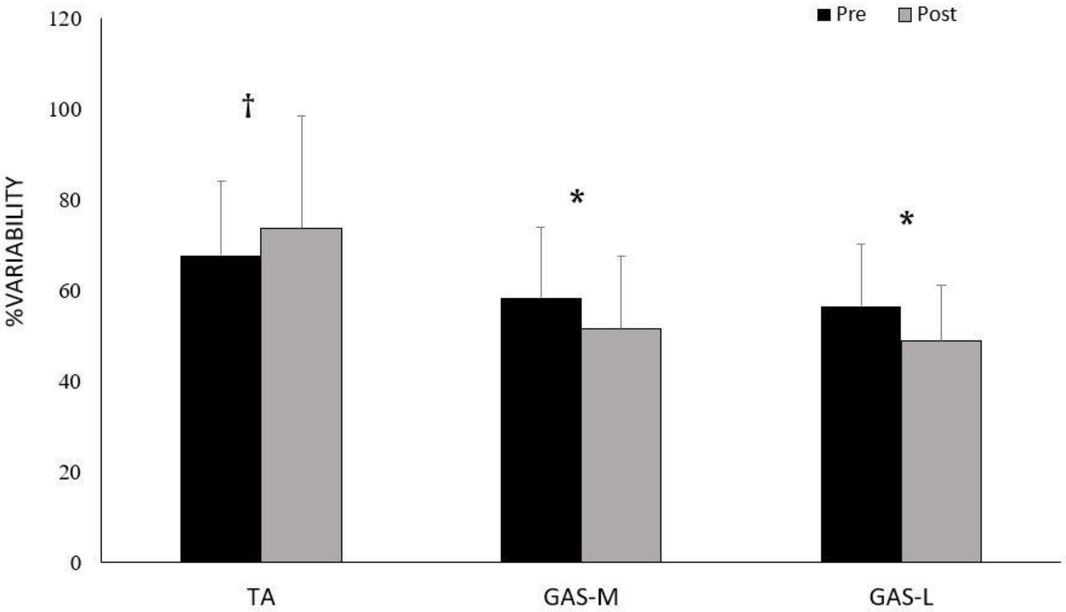


Figure 6.8. %EMG variability of tibialis anterior (TA), gastrocnemius medialis (GAS-M) and gastrocnemius lateralis (GAS-L) at pre and post-shoe wear, eyes closed quiet standing balance test. * indicates significant differences between pre-post (*p* < 0.05). † indicates significant differences between TA and both gastrocnemius muscles (*p* < 0.001).

6.6 Discussion

This study is unique in that it shows the effect of different footwear over a period of time which allows adaptations to the footwear to take place. Range of motion, strength, and strength-endurance were all significantly increased after habitual boot wearing military personnel changed to wearing flexible shoes for 10 weeks. Furthermore, individuals achieved significantly better overall postural balance control while activating the ankle muscles less, which reduced the muscle fatigue.

Some studies have concluded that boot footwear makes the ankle more stable, and that changing to lower cut (below malleolus) flexible shoes means the ankle is more unstable (Chander et al., 2015; Fu et al., 2014). However, it appears that the boot over time actually makes the ankle joint inherently more unstable and weakens the surrounding muscles so that an acute change of footwear to more flexible training shoes seems disadvantageous and increases injury risk. When time is allowed for adaptations in the more flexible shoe, then the ankle joint appears to become more stable.

The muscle adaptations occurring by reverting to a shoe for 10 weeks increased the strength of tibilais anterior and gastrocnemius muscles, which is likely linked to the larger ankle ranges of motion as evidenced by both the increase strength and ROM results (Figures 6.2 and 6.3). The muscle-tendon complex can now generate optimal strength over a greater range. To achieve this, muscle fibres may have been added in series in response to mechano-stretching of the muscle (Goldspink, 1999), particularly the passive elements like Titin which have been intimated as having a role in skeletal muscle remodelling (Herzog, 2018; Krüger & Kötter, 2016). A further benefit, maintaining strength over the larger range of motion, particularly in inversion-eversion, is a reduced risk for ankle sprain and strain type injuries.

The increase in strength endurance maybe due to fibre type specificity whereby type I fibres predominate (Ogborn & Schoenfeld, 2014), but this is really only true with light resistance training and there was no difference in training regime in the change from boots to shoes. Other theories such as enhanced capilliarisation (Iaia et al., 2011) and/or better bicarbonate buffering (Sahlin, 2014) have been postulated, but again these are training dependent. It may in fact be a contribution by all these mechanisms combined if the shoe enabled the wearer to utilise their muscles differently. The mechanism(s) for the significant increase in strength endurance remain to be elucidated.

It would be reasonable to assume the increase in strength would be due to increased muscle activation. There may well be larger or more fibres present, however, the level of activation to maintain postural control was significantly reduced (Figure 6.7). Therefore, either not as many fibres were activated or they were stimulated to a lesser degree, nevertheless the overall outcome would be lower levels of fatigue. The reduction in muscle activation may, in part, be due to the lightness of the shoe in comparison to the boot. For example, the heavier boot mass requires more muscle activity during gait, which can also increase fatigue as found by Garner et al. (2013) in firefighters wearing heavier boots. This may also be the case on quiet standing as tested in this study.

The variability of the mean activation was significantly reduced in the gastrocnemius muscles (Figure 6.8) and was significantly less than the tibialis anterior muscle while maintaining a stable centre of pressure (Figure 6.6A). This reduced variation is reflected in the decreased centre of pressure speed (Figure 6.6B), whereby the muscles are not working as hard to maintain the postural control and there are less excursions to the outer reaches of the muscle range of motion. The adaptation of boot wearing had either diminished the proprioceptive ability of the sensors such as muscle spindles for muscle stretch and Golgi tendon bodies for reduced range of motion at the ankle joint. The reinstated range of motion appears to have increased the proprioceptive feedback of these sensors to increase stability and therefore requires less muscle activity to maintain that stability. Rose et al. (2011) and Ramanathan et al. (2011) postulated that the thick soles may mask sensory input, but the testing done pre- and post-intervention in this study was carried out in bare feet. The authors in this current study agree with (Robbins et al., 1992) who stated that foot position awareness was a function of age and footwear.

Interestingly You et al. (2004) carried out a study with an application of circumferential applied pressure (CAP) [band around the leg above the ankle, but not restricting the ankle per se]. Based on the premise that ankle braces, taping, and adaptive shoes or military boots are widely used to address chronic ankle instability. The assumption was that the CAP intervention might improve ankle stability through increased proprioceptive acuity and stiffness in the ankle. They did find that the CAP increased proprioceptive acuity and demonstrated trends toward increased active stiffness in the ankle, and concluded this was the reason for the improved postural stability with boot-wear. However, the effects tended to be limited to individuals with low proprioceptive acuity, and they recruited university students who were probably not habitual boot wearers.

Lack of information regarding variables such as injuries and weight during the 12-month period before retesting occurred could be considered limitations to this study. However, bearing in mind the homogeneity of the cohort and the length of time the shoe was worn, the individual's percentage changes were not expected to make any significant differences for the group means. Further work would take into consideration the effects of these variables.

6.7 Conclusion

In conclusion, shoe wearing for 10 weeks does reverse some of the disadvantageous musculoskeletal adaptations of habitual boot wearing. The increase in range of motion and strength enhanced postural stability probably by augmented proprioceptive feedback. The decreased reliance on muscles for stability means a decrease in muscle fatigue, and combined these changes may reduce the incidence of ankle injuries. Shoe wearing as an alternate to boot wearing when in garrison (i.e. in military camp) appears to be a viable intervention to attenuate the high number of lower limb injuries reported in the military.

6.8 References

Andersen, K. A., Grimshaw, P. N., Kelso, R. M., & Bentley, D. J. (2016). Musculoskeletal Lower Limb Injury Risk in Army Populations. *Sports Medicine - Open, 2*(1), 22. doi:10.1186/s40798-016-0046-z

Arndt, A., Westblad, P., Ekenman, I., & Lundberg, A. (2003). A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait Posture., 18*. doi:10.1016/s0966-6362(02)00191-1

Böhm, H., & Hösl, M. (2010). Effect of boot shaft stiffness on stability joint energy and muscular co-contraction during walking on uneven surface. *Journal of Biomechanics, 43*(13), 2467-2472. doi:https://doi.org/10.1016/j.jbiomech.2010.05.029

Bosquet, L., Maquet, D., Forthomme, B., Nowak, N., Lehance, C., & Croisier, J. L. (2010). *Effect of the Lengthening of the Protocol on the Reliability of Muscle Fatigue Indicators* (Vol. 31).

Brenton-Rule, A., Bassett, S., Walsh, A., & Rome, K. (2011). The evaluation of walking footwear on postural stability in healthy older adults: an exploratory study. *Clinical Biomechanics, 26*(8), 885-887.

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science, 6*(1), 59-66. doi:10.1080/19424280.2013.834979

Chander, H., Wade, C., & Garner, J. C. (2015). The influence of occupational footwear on dynamic balance perturbations. *Footwear Science, 7*(2), 115-126.

Cikajlo, I., & Matjačić, Z. (2007). The influence of boot stiffness on gait kinematics and kinetics during stance phase. *Ergonomics, 50*(12), 2171-2182. doi:10.1080/00140130701582104

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. *Hillsdale, Lawrence Erlbaume*(ed 2).

Cohen, J. (1992). A power primer. *Psychological bulletin, 112*(1), 155.

Coombes, J., & Skinner, T. (2014). ESSA's Student Manual for Health, Exercise and Sport Assessment. Chatsworth, NAW, Australia: Mosby.

Cronin, N. J., Kumpulainen, S., Joutjärvi, T., Finni, T., & Piitulainen, H. (2015). Spatial variability of muscle activity during human walking: The effects of different EMG normalization approaches. *Neuroscience, 300*, 19-28. doi:https://doi.org/10.1016/j.neuroscience.2015.05.003

Davidson, P. L., Chalmers, D. J., Wilson, B. D., & McBride, D. (2008). Lower limb injuries in New Zealand Defence Force personnel: descriptive epidemiology. *Aust N Z J Public Health, 32*(2), 167-173. doi:10.1111/j.1753-6405.2008.00195.x

Dobson, J. A., Riddiford-Harland, D. L., & Steele, J. R. (2015). Effects of wearing gumboots and leather lace-up boots on lower limb muscle activity when walking on simulated underground coal mine surfaces. *Applied ergonomics, 49*, 34-40.

Duarte, M., & Freitas, S. M. S. F. (2010). Revision of posturography based on force plate for balance evaluation. *Brazilian Journal of Physical Therapy, 14*, 183-192.

Edwards, R. H. (1981). Human muscle function and fatigue. *Human muscle fatigue: physiological mechanisms*, 1-18.

Freitas, S. M. S. F., Prado, J. M., & Duarte, M. (2005). The use of a safety harness does not affect body sway during quiet standing. *Clinical Biomechanics, 20*(3), 336-339. doi:https://doi.org/10.1016/j.clinbiomech.2004.12.002

Fu, W., Fang, Y., Liu, Y., & Hou, J. (2014). The effect of high-top and low-top shoes on ankle inversion kinematics and muscle activation in landing on a tilted surface. *Journal of Foot and Ankle Research, 7*(1), 14. doi:10.1186/1757-1146-7-14

Garner, J. C., Wade, C., Garten, R., Chander, H., & Acevedo, E. (2013). The influence of firefighter boot type on balance. *International Journal of Industrial Ergonomics, 43*(1), 77-81. doi:https://doi.org/10.1016/j.ergon.2012.11.002

Goldspink, G. (1999). Changes in muscle mass and phenotype and the expression of autocrine and systemic growth factors by muscle in response to stretch and overload. *The Journal of Anatomy, 194*(3), 323-334.

Hamill, J., & Bensel, C. K. (1996). *Biomechanical analysis of military boots: phase III* (Natick/TR-96/013). Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.934.5109&rep=rep1&type=pdf

Herzog, W. (2018). The multiple roles of titin in muscle contraction and force production. *Biophysical reviews, 10*(4), 1187-1199.

Holmbäck, A. M., & Lexell, J. (2007). Reproducibility of isokinetic ankle dorsiflexor strength and fatigue measurements in healthy older subjects. *Isokinetics & Exercise Science, 15*(4), 263-270.

Hosoda, M., Yoshimura, O., Takayanagi, K., Kobayashi, R., Minematsu, A., Nakayama, A., . . . Wilson, C. K. (1997). The effect of various footwear types and materials, and of fixing of the ankles by footwear, on upright posture control. *Journal of physical therapy science, 9*(1), 47-51.

Iaia, F. M., Perez-Gomez, J., Thomassen, M., Nordsborg, N. B., Hellsten, Y., & Bangsbo, J. (2011). Relationship between performance at different exercise intensities and skeletal muscle characteristics. *Journal of Applied Physiology, 110*(6), 1555-1563.

Jancova, J. (2008). Measuring the balance control system--review. *Acta Medica (Hradec Kralove), 51*(3), 129-137.

Kaufman, K. R., Brodine, S., & Shaffer, R. (2000). Military training-related injuries: surveillance, research, and prevention. *Am J Prev Med, 18*(3 Suppl), 54-63.

Krüger, M., & Kötter, S. (2016). Titin, a central mediator for hypertrophic signaling, exercise-induced mechanosignaling and skeletal muscle remodeling. *Frontiers in physiology, 7*, 76.

Lima, B. N., Lucareli, P. R., Gomes, W. A., Silva, J. J., Bley, A. S., Hartigan, E. H., & Marchetti, P. H. (2014). The acute effects of unilateral ankle plantar flexors static-stretching on postural sway and gastrocnemius muscle activity during single-leg balance tasks. *Journal of sports science & medicine, 13*(3), 564.

Maulder, P., & Cronin, J. (2005). Horizontal and vertical jump assessment: reliability, symmetry, discriminative and predictive ability. *Physical Therapy in Sport, 6*(2), 74-82. doi:https://doi.org/10.1016/j.ptsp.2005.01.001

Neely, F. G. (1998). Biomechanical risk factors for exercise-related lower limb injuries. *Sports Medicine, 26*(6), 395-413.

Ogborn, D., & Schoenfeld, B. J. (2014). The role of fiber types in muscle hypertrophy: implications for loading strategies. *Strength & Conditioning Journal, 36*(2), 20-25.

Park, H., Trejo, H., Miles, M., Bauer, A., Kim, S., & Stull, J. (2015). Impact of firefighter gear on lower body range of motion. *International Journal of Clothing Science and Technology, 27*(2), 315-334.

Poulis, S., & Soames, R. W. (2003). Plantarflexion/dorsiflexion strength and isokinetic range of motion following injury to the ankle lateral collateral ligament. *Isokinetics & Exercise Science, 11*(2), 117.

Ramanathan, A., Parish, E., Arnold, G., Drew, T., Wang, W., & Abboud, R. (2011). The influence of shoe sole's varying thickness on lower limb muscle activity. *Foot and Ankle Surgery, 17*(4), 218-223.

Riddell, D. (1990). Changes in the incidence of medical conditions at the Commando Training Centre, Royal Marines. *Journal of the Royal Naval Medical Service, 76*(2), 105-107.

Riemann, B. L., & Schmitz, R. (2012). The relationship between various modes of single leg postural control assessment. *International journal of sports physical therapy, 7*(3), 257-266.

Robbins, S., Gouw, G. J., & McClaran, J. (1992). Shoe sole thickness and hardness influence balance in older men. *Journal of the American Geriatrics Society, 40*(11), 1089-1094.

Rose, W., Bowser, B., McGrath, R., Salerno, J., Wallace, J., & Davis, I. (2011). *Effect of footwear on balance.* Paper presented at the American Society of Biomechanics Annual Meeting. Long Beach, CA.

Sahlin, K. (2014). Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Medicine, 44*(2), 167-173.

Schulze, C., Lindner, T., Schulz, K., Finze, S., Kundt, G., Mittelmeier, W., & Bader, R. (2011). The Influence in Airforce Soldiers Through Wearing Certain Types of Army-Issue Footwear on Muscle Activity in the Lower Extremities. *Open Orthop J, 5*, 302-306. doi:10.2174/1874325001105010302

Schulze, C., Lindner, T., Woitge, S., Schulz, K., Finze, S., Mittelmeier, W., & Bader, R. (2014). Influence of footwear and equipment on stride length and range of motion of ankle, knee and hip joint. *Acta Bioeng Biomech, 16*(4), 45-51.

Simeonov, P., Hsiao, H., Powers, J., Ammons, D., Amendola, A., Kau, T.-Y., & Cantis, D. (2008). Footwear effects on walking balance at elevation. *Ergonomics, 51*(12), 1885-1905.

Sinclair, J., & Taylor, P. J. (2014). Influence of New Military Athletic Footwear on the Kinetics and Kinematics of Running in Relation to Army Boots. *The Journal of Strength & Conditioning Research, 28*(10), 2900-2908. doi:10.1519/jsc.0000000000000477

Yaghoubi, M., Lark, S. D., Page, W. H., Fink, P. W., & Shultz, S. P. (2018). Lower extremity muscle function of front row rugby union scrummaging. *Sports biomechanics*, 1-13.

Yang, H.-R., Kim, M.-K., & Yoo, K.-T. (2015). The effects of the length of rain boots on balance during treadmill walking. *Journal of physical therapy science, 27*(10), 3261-3266.

You, S. H., Granata, K. P., & Bunker, L. K. (2004). Effects of circumferential ankle pressure on ankle proprioception, stiffness, and postural stability: a preliminary investigation. *journal of orthopaedic & sports physical therapy, 34*(8), 449-460.

Chapter 7: Discussion

7.1 Overall Discussion

This is a unique study, charting the adaptations of chronic boot-wear and its consequences followed by the reversal of the adaptations and the implications for injury risk.

Chapter 3 outlined the trend of injuries in the NZ army over 11 years, and the vulnerability of the ankle joint to injury. The particular types of injuries included medial-tibial stress syndrome (MTSS) and inversion excursions, and these occurred mostly while running. Notably, the running was during physical training, whilst wearing a flexible trainer type shoe. While some studies state that wearing the training shoe (or barefoot) is less stable footwear than the military boot (Chander, Garner, & Wade, 2014; Chander, Wade, & Garner, 2015; Hamill & Bensel, 1992), it was highlighted that these were conducted as one-off measures and did not take into account any physiological maladaptation that would occur by wearing military boots over a prolonged period of time. It was thought that the boot was supplying the stability as seen in previous studies, but in fact had made the ankle joint inherently unstable when the boot was not worn. This led to an investigation on the aetiology of ankle injuries and in particular, the role adaptations of prolonged boot wearing played. Figures 4.1 – 4.4 and 5.3 - 5.5 display the inter-relationships of the changes that habitual boot wearing causes, which are discussed below.

The first stage in the investigation of aetiology of boot wearing was the effects of long-term biomechanical restrictions and is outlined in chapter 4. It was necessary to measure the effect in non-habitual boot wearing individuals, and hence new recruits were selected for this trial. This allowed for robust paired analysis (pre- and post- 1-year boot-wear) which eliminated individual variation in the comparisons. The height and stiffness of the boot shaft covering the malleolus restricted movement around the ankle joint, and over time reduced the habitual range of motion (ROM) for inversion-eversion, and plantarflexion-dorsiflexion. Motor performance was compromised by this decrease in ROM, which can be attributed to a decrease in muscle fibre length when wearing the boot (Figure 7.1).

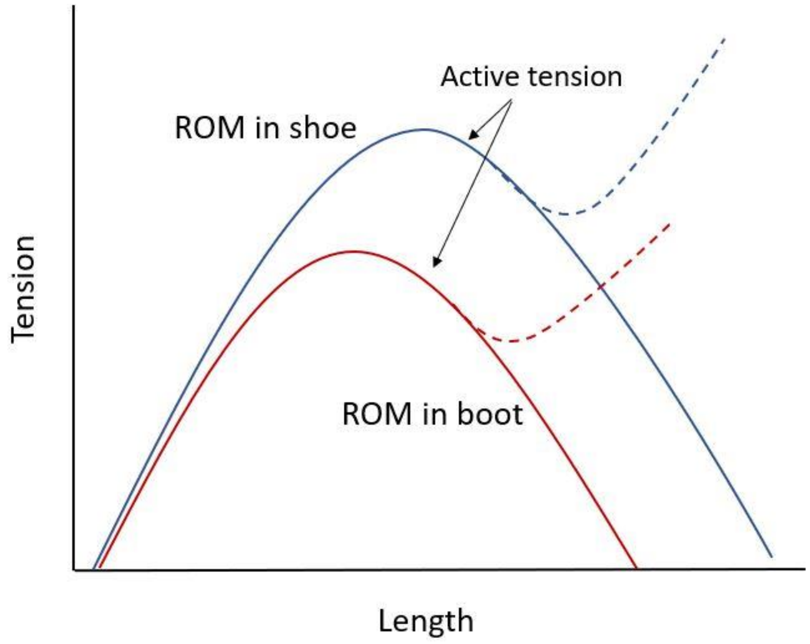


Figure 7.1. Diagram representing changes in the length tension curve as a result of decrease in ROM

The second stage of the investigation of the aetiology of boot wearing focused on the activation of the lower limb muscles during static balance after having worn the military boot > 2 years. The thickness of the boot sole played a role in filtering and dispersing sensory information from the ground surface to the plantar tactile receptors, and over time negatively affected balance and stability.

The decreased ROM reduced the functional range over which peak torque could be developed and it is speculated that this led to a detraining effect or adaptation over time. One of the features of detraining is a change in fibre type profile, with the percentage of type I and II fibres playing significant roles in reactive balance as quick movements become necessary when adjusting to unexpected perturbations. When Miller, Heath, Dickinson, and Bressel (2015) investigated the relationship between muscle fibre type and reactive balance, they found those with lower type II fibres were at a greater risk of falling when reactive balance was critical. However, in this study the muscles were not only activated more (possibly as more fibres were activated), but the speed of sway about the COP also increased (Figures 5.3 A and B). This indicated the muscles were moving significantly faster to correct sway about the COP which would suggest a shift towards more type II muscle fibres. This agrees with findings of Scott, Stevens, and Binder–Macleod (2001), whereby a decreased use of skeletal muscle can lead to a conversion of muscle fibre types in the slow oxidative to fast oxidative fibres, which accounts for increased fatigue.

If the ROM was due to less numbers or smaller muscle fibres in series, then it would account for the decreased peak torque (as measured at 60^o/s) that was recorded from the plantarflexor muscles (Figure 4.1), which supply the push-off power during activities involving the lower limbs. The combined reduction in ROM and plantarflexor strength means less force is developed over a smaller range. This has implications for highly repetitious training such as long marches and runs whereby there would be earlier onset of fatigue in the muscles surrounding the ankle joint. The fatigue of the plantarflexors significantly increases after 1-year of boot-wear (Figure 4.2). This raises the risk of more chronic injuries such as medial-tibial stress syndrome.

The combination of a smaller ROM and less strength also reduces whole body stability. The excursion to the outer limits of the reduced ROM leads to a larger sway pattern around the centre of pressure (COP) as the muscles are constantly activated to maintain balance and postural control. This is in accordance with Nardone, Tarantola, Giordano, and Schieppati (1997) who stated that the high intensity workloads military personnel are exposed to are often the cause of neuromuscular fatigue causing postural and balance discrepancies. It is possible that the ability of the muscle proprioceptors to relay joint position of the limbs to the central nervous system diminishes due to localised muscular fatigue.

The increased activation of the medial and lateral gastrocnemius muscles is shown in chapter 5 (Figure 5.4), along with the enlarged area of sway about the centre of pressure (Figure 5.3 A and B). The speed of movement about the COP also intimates the lack of resistance to movement which is indicative of a lack of movement control. The lack of postural stability, reduced ROM and strength contribute to the risk of more catastrophic injuries of sprains and tears of ankle or foot ligaments and tendons. It is worth noting that the gastrocnemius muscles are very much involved with the inversion-eversion act for stabilisation, and inversion injuries are the primary cause of acute ankle sprains. Wearing the boot for 1-year has negatively affected balance when the boot is removed (i.e. barefoot or wearing flexible trainers for physical training), indicating physiological maladaptions.

Having established the negative effects of chronic boot-wear, the question arises '*Could these changes be reversed*?' The final experimental chapter used the same type of measures (ROM, strength, COP, and fatigue) pre- and post-shoe wear for 10 weeks on an adapted boot-wearing cohort. The soldiers recruited in this study had been enlisted for a minimum of 2 years and had worn the boots issued during this time. The period of 10 weeks for shoe wear was chosen as it has been established that neuromuscular changes in training can occur in as little as 6 weeks in young healthy individuals (Moritani, 1979). The outcomes of this intervention were an increase in ROM which increased the range over which peak torque could be developed, and indeed the plantarflexor and dorsiflexor strength was significantly increased through wearing shoes. Although the muscles produced greater strength, there was less electrical activity to achieve it and this resulted in lower levels of muscular fatigue. This infers a lower risk of chronic lower limb injury. Without multiple muscle biopsies it was not possible to confirm a shift in muscle fibre type due to the shoe wearing as a cause. Greater muscle strength and the range over which it is developed means more functional potential push-off power by the plantarflexors during dynamic activities, and also more stability.

The sway pattern about the COP after adapting to wearing shoes reverses the instability caused by boot wearing. This has major implications for reducing acute injury risk of the lower limbs. The increase in stability is a function of proprioceptive integrity and sensitivity. The sole of the shoes were thinner than those of the boots, which could lead to greater proprioceptive information being processed at a higher level, resulting in enhanced stability and less sway. Alternatively, the increased function could also enhance proprioceptive feedback from greater stimulation of muscle spindles and golgi-tendon bodies.

This theory was to be tested with the original experimental design of four groups; two boot-wearing and two shoe-wearing groups, and one group of each foot wear would undergo specific proprioceptive training. However due participants not doing the proprioceptive training we could not discern if the shoe increased proprioception per se, or it was due to the ability to carry out proprioception training over a full ankle functional ROM. This has still to be determined.

7.2 Conclusion

The magnitude of the reported *t*-values (chapters 3 – 5) indicate significant changes in ROM, lower limb muscle strength, balance and muscle activity pre- and post-testing. Likewise, there are large t-values for the shoe intervention trial. Therefore, the research hypothesis that long term military boot wear and a transition to wearing a shoe for 10 weeks has significant influences on lower limb function can be accepted, thus rejecting the null hypothesis that no changes would be manifested.

Habitual boot-wear causes maladaptations to structures and movement around the ankle join, which are probably a combination of muscle morphology and physical restrictions. The result of these changes is to weaken the ankle and cause instability if the boot is not constantly worn. However, these negative adaptations can be reversed with habitually wearing more flexible low-cut footwear.

7.3 Impact of Research

This research impacts both the scientific body of knowledge and its practical applications. The fundamental thinking of the military boot as a means for providing support and inherent stability is radically altered. It has demonstrated that boot-wear over a period of time means the ankle is unstable and more prone to injury when the boot is removed.

Notwithstanding the long term maladaptations of long-term military boot-wear, it would still provide external stability during time of deployment and working in uneven and hostile terrain. Based on the incontrovertible conclusion, that long-term boot wear is a leading cause of ankle and lower limb injury, the NZDF have developed a comprehensive shoe-wearing policy (appendix 6). Furthermore, presentations of this work at international forums have garnered particular global interest from other defence forces who have the same problems regarding lower limb injuries. This puts New Zealand at the forefront globally for reducing lower limb injuries in Defence Forces globally.

A reduction in injury rate will not only increase in the number of personnel ready for deployment, but also allows the NZDF to save money and is a game changer in the number of service personnel who can be deployed.

Based on the results of this research, the overall outcome has been the development of a 'Shoe Wearing' policy by the NZDF, and a positive shift towards shoe wearing while on base (Appendix 5 and 6). While on military manoeuvres boots must still be worn. Anecdotally, those who wear shoes most of the time have reported "I can run again; I have passed my RFL (Required Fitness Level assessment) again; Why didn't we (the NZDF) do this ages ago."

7.4 Future Research

Future research is already underway to compare the injury statistics from chapter 1 of this study to a period when the shoe policy was implemented. This will provide proof of the injury incidence linked to footwear.

This thesis has increased the knowledge of the effects of footwear on lower limb injuries in military populations, which has exposed areas that require further research. These include:

1. Investigating whether balance can be further enhanced by balance and proprioceptive training.
2. The trialling of a combat boot with a more flexible sole and shaft.
3. Collaboration with coalition partners to study the effect of habitual boot-wear on female military personnel due to the small numbers in the NZDF.

7.5 References

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science, 6*(1), 59-66. doi:10.1080/19424280.2013.834979

Chander, H., Wade, C., & Garner, J. C. (2015). The influence of occupational footwear on dynamic balance perturbations. *Footwear Science, 7*(2), 115-126.

Hamill, J., & Bensel, C. K. (1992). *Biomechanical Analysis of Military Boots. Phase 1. Materials Testing of Military and Commercial Footwear*. Retrieved from: appa.dtic.mil/dtic/tr/fulltext/u2/a257293.pdf

Miller, A. I., Heath, E. M., Dickinson, J. M., & Bressel, E. (2015). Relationship between muscle fiber type and reactive balance: a preliminary study. *Journal of motor behavior, 47*(6), 497-502.

Moritani, T. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American journal of physical medicine, 58*(3), 115-130.

Nardone, A., Tarantola, J., Giordano, A., & Schieppati, M. (1997). Fatigue effects on body balance. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control, 105*(4), 309-320.

Scott, W., Stevens, J., & Binder–Macleod, S. A. (2001). Human Skeletal Muscle Fiber Type Classifications. *Physical Therapy, 81*(11), 1810-1816. doi:10.1093/ptj/81.11.1810

Appendices

Appendix 1: Information Sheet

COLLEGE OF HEALTH

SCHOOL OF SPORT AND EXERCISE

TeKura Hangarau o Kai-oranga-a-tangata

Private Box 756

Wellington

JOINT OPERATIONAL HEALTH GROUP

Trentham Camp

Private Bag 905

Upper Hutt

New Zealand

Lower Limb Injury Prevention in the NZ Army

Information Sheet

Researchers Introduction

The following researchers will be involved with this research project investigating the mechanisms of lower limb musculoskeletal injuries in the New Zealand Army:

Major Jacques Rousseau who is the main researcher and is an Exercise Physiologist with the New Zealand Army. He is completing this research as part of a Doctoral degree.

Dr. Sally Lark who is a senior lecturer and Exercise Physiologist at Massey University Wellington.

Associate Professor Hugh Morton, a biostatistician at Massey University with 30 years teaching and research experience in this topic area.

Lieutenant Colonel (Dr) Andrew Dunn, a senior medical officer in the New Zealand Defence Force.

Project Description and Invitation

You are invited to participate in this study investigating the causes of lower limb musculoskeletal injuries in the New Zealand Army.

The purpose of this study is to investigate whether the natural structures of the foot are weakened by long-term footwear, in particular the military boot, which in turn leads to the reliance of footwear to support the foot. This reliance on footwear to support the foot is not the same as the support provided by a well-functioning foot.

Before agreeing to participate in this research study, it is important that you read the following explanation of this study. This information sheet describes the purpose, procedures, benefits, risks, discomforts and precautions of the programme.

Also described is your right to withdraw from the study at any time. No guarantees or assurances can be made as to the results of the study.

Participant Identification and Recruitment

Two groups of army personnel will be recruited. These are:

1. New recruits, who will have completed a fitness test to enter the army but will not have been subjected to continual wearing of army boots during training, and
2. Army personnel enlisted longer than 12 months. This means participants of both groups will be approximately the same, with the same gender proportion.

Participants will complete an anonymous questionnaire about training regimes (recreational and sport participation) and lifestyle. In addition height, weight, age, and percentage body fat will be measured and recorded.

Participants should report any information regarding his/her individual health status that may affect the safety of any of the tests. Any unusual feeling or discomfort associated during the tests should be immediately disclosed to the study investigators.

The possibility of discomfort (if any) would be when shaving small areas of the lower limb for EMG electrode placing. Any risk of infection will be combated by using single use disposable razors and cleaning the area with swabs before and after shaving.

Participants will not be paid to participate in this research project nor will they be charged for participating in the research programme. Participation or non-participation will have no impact on current or future employment.

Project Procedures

You will be asked to complete a questionnaire about your training/sport and injuries, Then the following measurements will be conducted on each participant to determine lower limb musculoskeletal function:

- Electromyography (EMG) recordings will be done on the lower legs with and without boots to determine muscle activation. Electromyography will require recording electrodes to be placed on the skin in order to measure muscle activation. This will require very small areas of your legs to be shaved where the 4 cm electrodes will be placed. This will take approximately 15 minutes to set up and 5 minutes of recording.
- Balance will be determined by the use of a force plate which is a metal plate that measures body mass movements. You stand on the plate quietly with either your boots on or off, and your eyes open or closed. This takes approximately 5 minutes.
- We will measure your hip, knee and ankle joint range of motion. You will be either lying down or seated and the investigator will use hand held instruments called an inclinometer and a goniometer. They place them on your leg or foot and move your leg in a particular motion i.e. flex the knee. This should take approximately 15 minutes to complete.
- Your lower limb muscle strength will be measured using an Isokinetic Chair. You will be strapped into a chair specially designed to isolate certain muscle movements to measure strength. You will be asked to extend or flex your leg or foot against a constant resistance set by the researcher. This should take approximately 45 minutes.

In the unlikely event of a physical injury as a result of your participation in this study, you will be covered by ACC under the Injury Prevention, Rehabilitation and Compensation Act. ACC cover is not automatic and your case will need to be assessed by ACC according to the provisions of the 2002 Injury Prevention Rehabilitation and Compensation Act. If your claim is accepted by ACC, you still might not get any compensation. This depends on a number of factors such as whether you are an earner or non-earner. ACC usually provides only partial reimbursement of costs and expenses and there may be no lump sum compensation payable. There is no cover for mental injury unless it is a result of physical injury. If you have ACC cover, generally this will affect your right to sue the investigators.

If you have any questions about ACC, contact your Medical Treatment Centre (MTC) or the investigator.

Data Management

Data will be analysed using a statistical analysis package. The collated and analysed data will in no way be traceable to the names of the original participants; all information gathered from the study will remain confidential. Individual participants will have their data, obtained during the research study, individually stored in a locked cabinet in a secure office. Individual data will be known only to the participant and the researchers. No participants will be named in the final summaries/reports which will feature only group data and results.

Participants Rights

Participation in this study is voluntary. You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- Decline to answer any particular question;
- Withdraw from the study at any time and not give reason without prejudice from the New Zealand Army.
- Ask any questions about the study at any time during participation;
- Provide information on the understanding that your name will not be used unless you give permission to the researcher;
- Be given access to a summary of the project findings when it is concluded.

Questions

Any questions concerning the research project can be directed to:

Jacques Rousseau:	(04) 527 5721
Dr. Sally Lark:	(04) 801 5799 ext 62503

Agreement

Your signature below indicates that you have received, read and understand this information sheet.

______________________________________ ____________________
Signature of Participant Date

____
Participant name (printed)

______________________________________ ____________________
Signature of Researcher Date

Appendix 2: Individual Participation Form

COLLEGE OF HEALTH
SCHOOL OF SPORT AND EXERCISE
TeKura Hangarau o Kai-oranga-a-tangata
Private Box 756
Wellington

ARMY HEALTH SERVICES
Trentham Camp
Private Bag 905
Upper Hutt
New Zealand

LOWER LIMB INJURY PREVENTION IN THE NZ ARMY

PARTICIPATION FORM

This is to confirm ___________________________________ is a participant in this study and is required to wear Salomon Sensemantra shoes for a period of eight weeks. The shoes are to be worn as a "garrison shoe" in place of normal boots.

For any further information please feel free to contact MAJ Rousseau.

Major Jacques Rousseau (MPhil (Exercise Science))
Joint Operational Health Group
Performance Health Team Clinical Exercise Physiologist
Trentham Military Camp, Upper Hutt, New Zealand
New Zealand Defence Force
T [redacted]

Appendix 3: Individual Consent Form

COLLEGE OF HEALTH
SCHOOL OF SPORT AND EXERCISE
TeKura Hangarau o Kai-oranga-a-tangata
Private Box 756
Wellington

ARMY HEALTH SERVICES
Trentham Camp
Private Bag 905
Upper Hutt
New Zealand

LOWER LIMB INJURY PREVENTION IN THE NZ ARMY

PARTICIPANT CONSENT FORM - INDIVIDUAL

I have read the Information Sheet and have had the details of the study explained to me.

My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name - printed ....

Appendix 4: Screening Questionnaire

MASSEY UNIVERSITY

NZ ARMY
NGATI TUMATAUENGA

LOWER LIMB INJURY PREVENTION IN THE NZ ARMY

Injury and Training Questionnaire

Surname……………………………………………………………..

First Name……………………………………………………………

Date…………………………………………………………………..

Contact telephone number…………………………………………

Address………………………………………………………………

Date of Birth (dd/mm/yr)…………………………………………….

Circle appropriate choice: Male / Female

Which ethnic group do you belong to? Choose one or more of the following:

European descent
Maori
Samoan
Cook Island Maori
Tongan
Niuean
Chinese
Indian
Other such as Dutch, Japanese, Tokelauan. Please state:

………………………………….

Musculoskeletal Injury History

1	Have you had any previous lower limb musculoskeletal injuries prior to enlisting in the army (e.g. Ankle sprain, hamstring strain, fractured bone etc)? If yes please answer questions 2, 3, 4 & 5	**Y/N**
2	Tick the box representing your previous lower limb musculoskeletal injurie/s. If you tick “other” please name the injury site in the space provided below. a. Foot ☐ b. Ankle ☐ c. Shin ☐ d. Knee ☐ e. Hip ☐ f. Other ☐ Other ………………………………………………………………………………	
3	What was the cause of the injury (e.g. rolled ankle during a rugby game)?	

4	Following a musculoskeletal injury, did you undergo a rehabilitation programme?	**Y/N**
5	If you did not receive treatment please state the reason/s why	
6	Do you have an injury currently?	**Y/N**
7	Tick the box representing your current musculoskeletal injury/s. If you tick “other” please name the injury site in the space provided below. ☐ a. Foot ☐ b. Ankle ☐ c. Shin ☐ d. Knee ☐ e. Hip ☐ f. Other Other …………………………………………………………………………………	
8	Are you currently suffering from a head cold or ear infection?	**Y/N**
9	Are you undergoing a rehabilitation programme for your current injury?	**Y/N**
10	If not state the reason/s why	
11	Do you suffer from lower back pain?	**Y/N**
12	Do you consider well designed physical training programmes as an important part of preventing injuries?	**Y/N**
13	Do you smoke?	**Y/N**
14	If currently smoking, how many cigarettes per day?	

Physical activity and training:

15	Do you participate in any type of sport or physical activity	**Y/N**
16	At what level do / did you participate in, i.e., recreational, representative, NZDF, regional, national, or international. List the sport and the level below.	

Sport	Level

17	How often do you participate in each activity? List number of times each week and time spent playing below.	
Sport / physical activity	Number of times per week	Minutes each time

Thank you for your participation

Appendix 5: Garrison Shoe Approved for Introduction

UNCLASSIFIED

DEFENCE LOGISTICS COMMAND
Logistics Command (Land)
MINUTE

LC(L)10001/5/CLO

14th July 18

AGS (Attention: ACA(D))

For Information:
HQ NZDF
HQ JFNZ
HQ DLC
LCC
SOCC
JSCC

INTRODUCTION INTO SERVICE APPROVAL: GARRISON SHOE

Reference:
A. May 2018 AMB Minutes

1. At the May 18 AMB, LC(L) presented a submission on behalf of the Army Clothing Board for introduction of a Garrison Shoe into NZ Army due to the health and injury avoidance benefits presented. AMB was in favour of introduction and requested TRADOC and 1 (NZ) Bde provide impact statements for the introduction of a Garrison Shoe, noting recommended wear recommendations presented at the AMB of:

   a. Worn in the garrison environment only and with loads not exceeding 25kg;

   b. Not worn on parade due to lack of cushioning for drill movements;

   c. Alternate with combat boots before field training;

   d. Worn after field training, military exercises and pack marches as a recovery shoe; and

   e. Not to replace Safety Boots.

2. Feedback from both Formations recommended the introduction of the Garrison Shoe with issue approval level of "CO discretion". This approval level is consistent with other boot types and TRADOC requesting the Garrison Shoe not be issued for recruit training. Both TRADOC and 1(NZ) Bde further recommended retention of the Garrison Boot.

3. It is therefore recommended that ACA(D):

   a. **Note** TRADOC and 1 (NZ) Bde feedback requested by May 18 AMB;

   b. **Approve** the introduction of Garrison Shoe to NZ Army at CO discretion and wear recommendations.

UNCLASSIFIED

(1) Upon approval:

   (a) NZ P23 Scale 200 will be updated to reflect that the Garrison Shoe can be issued to Army personnel at CO discretion;

   (b) The Army Boot Catalogue will have the Garrison Shoe included; and;

   (c) An article will be released in next publication of Soldier's Five.

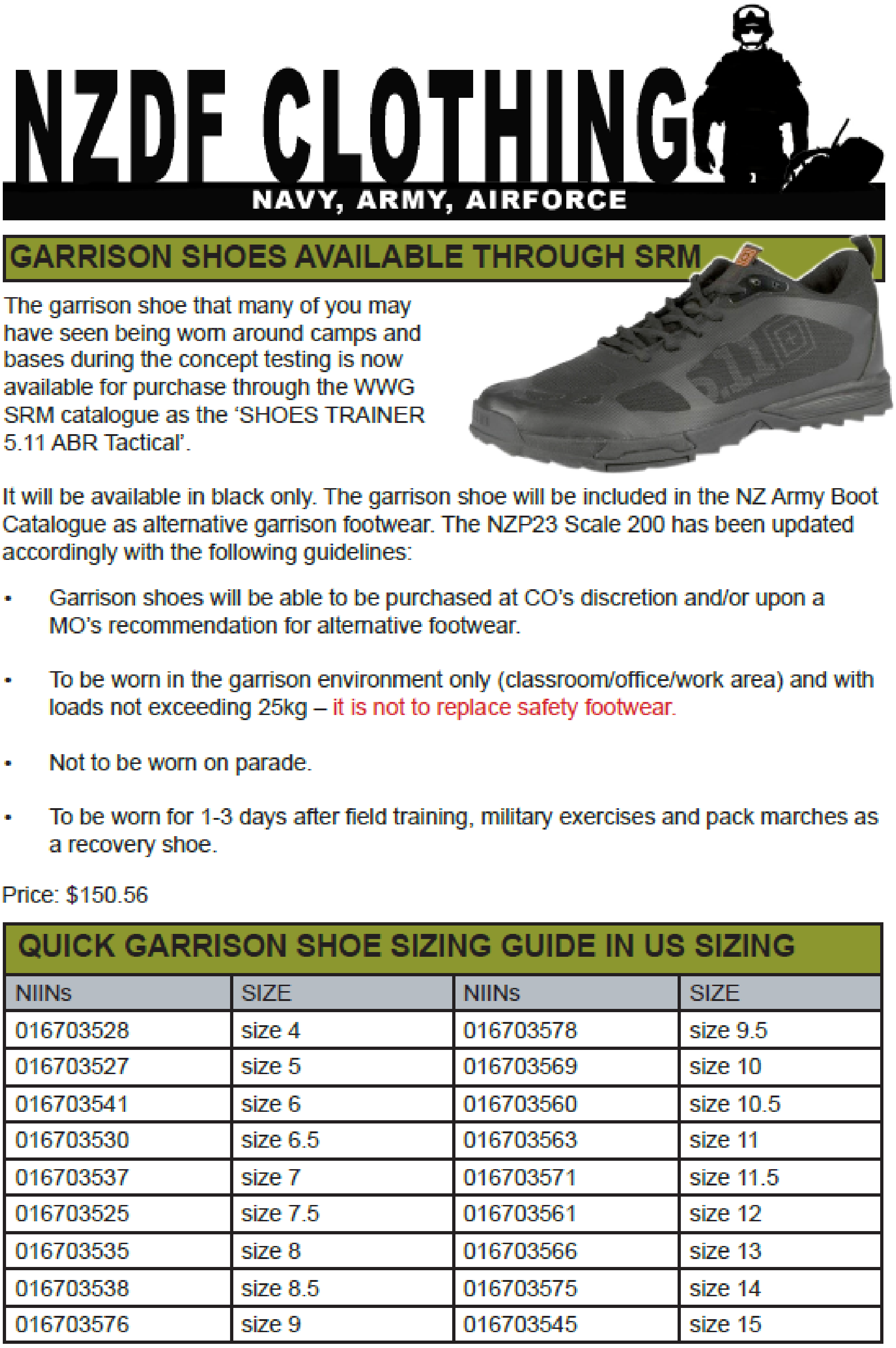
4. DLEM LC(L) POC for all NZDF Clothing matters is Mrs Mary Roberts DTelN 343 – 5177.

S.K. PIERCY
COL
LC(L)

[✓ APPROVED] / ~~NOT APPROVED~~

H.J. COOPER
COL
ACA (D)

Appendix 6: Garrison Shoe Guide



NZDF CLOTHING

NAVY, ARMY, AIRFORCE

GARRISON SHOES AVAILABLE THROUGH SRM

The garrison shoe that many of you may have seen being worn around camps and bases during the concept testing is now available for purchase through the WWG SRM catalogue as the 'SHOES TRAINER 5.11 ABR Tactical'.

It will be available in black only. The garrison shoe will be included in the NZ Army Boot Catalogue as alternative garrison footwear. The NZP23 Scale 200 has been updated accordingly with the following guidelines:

- Garrison shoes will be able to be purchased at CO's discretion and/or upon a MO's recommendation for alternative footwear.
- To be worn in the garrison environment only (classroom/office/work area) and with loads not exceeding 25kg – it is not to replace safety footwear.
- Not to be worn on parade.
- To be worn for 1-3 days after field training, military exercises and pack marches as a recovery shoe.

Price: $150.56

QUICK GARRISON SHOE SIZING GUIDE IN US SIZING

NIINs	SIZE	NIINs	SIZE
016703528	size 4	016703578	size 9.5
016703527	size 5	016703569	size 10
016703541	size 6	016703560	size 10.5
016703530	size 6.5	016703563	size 11
016703537	size 7	016703571	size 11.5
016703525	size 7.5	016703561	size 12
016703535	size 8	016703566	size 13
016703538	size 8.5	016703575	size 14
016703576	size 9	016703545	size 15

Appendix 7: List of Potential Journals for Publication

Title	Target Journal	Impact Factor
Incidences and Causative Factors of Lower Limb Injuries in the New Zealand Army	Australia and New Zealand Journal of Public Health	-
Changes in Lower Limb Strength and Ankle Joint Range of Movement after One Year of Military Boot-Wear	Journal of the Royal Army Medical Corps Journal of Sports Sciences	0.883 1.2
Changes in Balance and Lower Limb Muscle Activity after One Year of Military Boot-Wear	Military Medicine Injury Prevention	1.19 2.4
Can Ten Weeks of Shoe Wear Reverse Years of Neuromuscular Adaptation Due to Military Boot-Wear?	Military Medicine Injury Prevention	1.19 2.4