Sex-Specific Biomechanical and Neuromuscular Adaptations to a Targeted Physical Training Program for Military Load Carriage

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Abstract

Tactical occupations within military organisations require soldiers to routinely undertake physically demanding tasks such as load carriage (i.e., carrying load externally fixed on the body). Carried loads are typically comprises essential equipment military personnel require during training and operational tasks, and therefore cannot be easily reduced without compromising operational capabilities. Recurrent exposure to excessive external loads adversely impacts on soldiers' physical capabilities (i.e., mobility, task sustainment, and strength), and are highly associated with increased risks of musculoskeletal injury and/or impaired performance. Importantly, the capacity for soldiers to tolerate external loading can be improved through physical training to help mitigate potential performance implications and injury risk. However, current physical training sessions for military personnel are not tailored to meet specific occupational task demands, or individuals' physical capacity. This issue is of relevance for females who are now eligible to apply for combat-related roles in most countries, meaning they will be required to complete the same physical training and job-specific tasks as males. As females typically have lower physical capabilities compared to males, they may be at a disadvantage in these physically demanding roles. Identifying and understanding sex-specific responses to load carriage tasks and associated physical training will inform the optimisation of training programs that better prepare both males and females for operational readiness. Therefore, the purpose of this thesis was to quantify the neuromuscular, physical, and biomechanical adaptations to load carriage over time, and in response to an evidence-based physical training program.

The first research paper, Chapter 3, examines the implementation of a 10-week physical training program which was designed using findings from previous research to target the neuromuscular demands of load carriage in a male civilian population. Current approaches in the military do not tailor training to match load carriage task demands, even though this method has been shown to improve individuals' physical capacities and mitigate associated injury risks. Fifteen male civilians completed a load carriage task equivalent to the minimum Australian Army All Corps physical employment standard (i.e., walking for 5 km at 5.5 km·h^{-1}, wearing a 23 kg torso-borne vest) before and after 10 weeks of training. Measures of physical capacities (i.e., maximal jumps, push-ups, sit-ups, and beep test) were conducted before, during, and after the 10 weeks of training to identify neuromuscular adaptions, as

evidenced by improvements in performance. Psychophysical responses were assessed during the load carriage task before and after training, which showed reductions in task perceptions, indicating an improved task tolerance as a direct result of training. These positive findings could serve as an alternative approach to training soldiers in roles that regularly undertake load carriage tasks. The manuscript highlighting physical and psychophysical performance improvements was published as Wills, J. A., Saxby, D. J., Glassbrook, D. J., & Doyle, T. L. A. (2019). Load Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males. *Journal of Strength and Conditioning Research, 33*(9), 2338-2343.

The second research paper, Chapter 4, examines the same 10-week physical training program completed by a female civilian population. These results were comparatively analysed to the male data presented in chapter 3 to examine if sex-specific responses exist between males and females in response to the same physical training. Since the opening of combat-related roles, females have seemingly been placed at a disadvantage due to inherent differences in physical capacities (e.g., strength) compared to males, despite undertaking the same training. Favourable main effects of training were found for both sexes, however, males outperformed females in all tests other than sit-ups. Surprisingly, females' push-up performance improved at mid- and post-testing, compared to the start; while male improvements were only realised at the end of the training period. Male cardiovascular responses as per beep test scores improved after training, but females did not. Irrespective of overall positive responses in performance, sex-specific differences were still evident after completing the same physical training, suggesting that females should be trained differently to males in order to optimise performance on load carriage tasks and physical conditioning in general. The manuscript describing these results has been submitted as Wills, J. A., Saxby, D. J., Glassbrook, D. J., & Doyle, T. L. A. (2019). Sex-Specific Physical Performance Adaptive Responses are Elicited after 10 weeks of Load Carriage Conditioning, *Journal of Science and Medicine in Sport*.

The third research paper, Chapter 5, investigates lower limb biomechanical adaptations during a load carriage task in a male civilian population. Load carriage tasks are known to alter lower limb biomechanics. However, limited research has examined time-course changes of loaded walking or detailed changes in external joint-level mechanics (i.e., joint moments, power, and work) in response to a physical training program for load carriage. Whole-body marker kinematics and ground reaction forces were acquired in over-ground walking trials before and after the 5 km load carriage task. Subsequently, individual scaled anatomic models were created in OpenSim and experimental data were used to calculate inverse kinematics and inverse dynamics to determine lower limb joint angles, net joint moments, powers, and work, respectively. Primary mechanical changes were observed at the knee and ankle ($p < 0.05$). Knee moments were maintained for longer after training compared to before. Positive power contribution shifted distally after training, increasing at the 5 km measure from 39.9% to 43.6% at the ankle joint ($p < 0.05$). Findings suggests that 10 weeks of periodised training may reduce injury risk through favourable ankle and knee joint adaptations and can enable individuals to sustain performance during a load carriage task. The manuscript detailing these results was accepted as Wills, J. A., Saxby, D. J., Lenton, G. K., & Doyle, T. L. A. (2019). Ankle and Knee Moment and Power Adaptations are Elicited through Load Carriage Conditioning in Males. *Journal of Biomechanics, 97*.

The fourth research paper, Chapter 6, is a continuation of research conducted in Chapter 5 and comparatively analysed male and female lower limb biomechanical data. This study aimed to identify and quantify potential sex-specific differences over the duration of a standardised load carriage marching task, and in response to the same 10 weeks of training. Training resulted in females generating significantly greater hip power during loaded walking compared to males, whereas ankle joint power contributions increased for both sexes. Over the duration of the 5 km march, most mechanical adaptive changes were observed in females. Findings strongly indicate sex-specific differences and highlights how physical training should be tailored to the requirements of each sex in order to maximise the benefits of training. The manuscript describing these results has been submitted as Wills, J. A., Saxby, D. J., Lenton, G. K., & Doyle, T. L. A. (2019). Lower Limb Biomechanical Responses during a Standardised Load Carriage Task are Sex-Specific. *Journal of Biomechanics*.

The fifth research paper, Chapter 7, examined female-only physiological and psychophysical responses during the 5 km load carriage task before and after the 10-week training program. Reductions in maximal oxygen uptake ($\dot{V}O_2$) requirements during the load carriage task after training ($p < 0.05$) suggests participants improved their mechanical efficiency through neural and muscular responses to the strength aspect of training. Furthermore, a shift towards fat utilisation was observed after training, with other physiological responses demonstrating an increased ability to sustain the metabolic demands of the load carriage task. Results indicate the 10 weeks of training reduced the physiological demands of the load carriage task, and improved task tolerance. The manuscript describing these findings has been submitted as Wills, J. A., Drain, J., Fuller, J. T., & Doyle, T. L. A. (2019). Physiological Responses of Female Load Carriage Improves after 10 weeks of Training, *Medicine and Science in Sports and Exercise*.

In conclusion, physical training that targets the specific neuromuscular demands of load carriage tasks helps to enhance individuals' physical capacities and load carriage performance, whilst potentially mitigating injury risks. The data from this thesis provides important insights into sex-specific neuromuscular, psychophysical, physiological, and biomechanical responses to physical training targeting load carriage. Importantly, these world-first findings provide evidence that can be used to inform future physical training programs that meet the specific requirements of each sex and load carriage tasks.

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Statement of Originality

I certify that the work in this thesis entitled "Sex-Specific Biomechanical and Neuromuscular Adaptations to a Targeted Physical Training Program for Military Load Carriage" has not been previously submitted for a degree nor has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University. I also certify that the thesis is an original piece of research and has been written by me. Any help and assistance that I have received in my research and the preparation of this thesis have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in this thesis.

The research presented in this thesis was approved by the Macquarie University Human Research Ethics Committee, reference numbers:

Human Ethics Approval (2017): 5201700406

Rapid and targeted training to reduce injury and improve performance during load carriage undertaken during physically demanding occupations

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Sex-specific adaptive responses to a load carriage specific training program

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List of Publications

The following publications were produced from this research;

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Wills, J. A., Saxby, D. J., Glassbrook, D. J., & Doyle, T. L. A. Sex-Specific Physical Performance Adaptive Responses are Elicited after 10 weeks of Load Carriage Conditioning, *Journal of Science & Medicine in Sport* (In review).

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Wills, J. A., Saxby, D. J., Lenton, G. K., & Doyle, T. L. A. Doyle. Lower Limb Biomechanical Responses during a Standardised Load Carriage Task are Sex-Specific. *Journal of Biomechanics* (In review).

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Wills, J. A., Saxby, D. J., Glassbrook, D. J., & Doyle, T. L. A. A Targeted Load Carriage Training Program Elicits Positive Adaptations After 10 weeks. International Society of Biomechanics in Sport Conference, Auckland, New Zealand, 2018. International level meeting, Oral presentation.

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List of Abbreviations

3D	Three-dimensional
ANOVA	Analysis of Variance
RMANOVA	Repeated Measures Analysis of Variance
COM	Centre of Mass
DOF	Degrees of Freedom
GRF	Ground Reaction Force
ID	Inverse Dynamics
IK	Inverse Kinematics
MSI	Musculoskeletal Injuries
ROM	Range of Motion
RPE	Ratings of Perceived Exertion
HR	Heart Rate

Chapter 1: Introduction

1.1. Load Carriage and Soldier Capability

Load carriage is a critical element of a soldier's military career and is a basic requirement during training and military operations. External load characteristics (i.e., configuration, distribution, fit, form, and load magnitude) often impact on the ability of a soldier to carry required loads comprising of essential equipment. This includes but is not limited to, clothing, basic protection (e.g., body armour and helmet), combat equipment (e.g., weapons systems, ammunition, and webbing), communication equipment (e.g., radio) and sustainment stores (Drain, Orr, Attwells, & Billing, 2012). Loads carried are determined by operational tasks requirements and environment hostility, meaning the total load carried often exceeds 20 kg (Dean, 2004). In training and low threat environments, soldiers wear basic protective equipment in the form of a body armour vest. However, in hostile environments, additional protection is needed via inserting ballistic plates into the front, back, and side vest pockets of standard body armour. While these additions are necessary for personal protection, soldier task performance may be impaired as the increased external load restricts movement and contributes to general pain and/or discomfort. Maintaining mobility is crucial to effective soldiering; however, current load carriage requirements often do not prioritise mobility and the carried load often exceeds an individual's capability contributing to injury risk.

A historical perspective of military load carriage reveals that absolute loads carried by the war fighter have substantially increased by around 3-fold in the past 150 years (Knapik, Reynolds, & Harman, 2004). Although the "rule of thumb" within the literature recommends limiting carried loads to ~33 % body weight, loads carried are generally assigned based on operational demands rather than what is deemed physiologically acceptable. Although advancements in technology have reduced the mass of some carried items, the requirement of soldiers to carry increasing amounts of necessary equipment has offset the benefits of lighter individual components (Drain et al., 2012). The encumbrance of heavy load on soldering was highlighted in most recent conflicts where total loads carried were reported to average ≥ 45 kg (Seay, 2015). Such heavy load carriage leads to substantial reductions in soldiering performance and increased risk of musculoskeletal injury, negatively impacting overall mission success. Heavy external load carriage can further impair soldier preparedness, especially during physical training (Nindl et al., 2013a). Soldiers physical preparedness is integral to mission success in order to achieve and execute core functions whilst completing operational tasks. During training, load carriage tasks are undertaken in combination with high volume and intensity in-field activities, leaving soldiers at risk of 'load bearing' musculoskeletal overuse injuries (Birrell & Haslam, 2010; Seay, Fellin, Sauer, Frykman, & Bensel, 2014).

Basic training aims to develop a soldier's physical capabilities (Knapik et al., 2005) for military-specific tasks. Specifically, muscular strength and aerobic fitness are key physiological characteristics essential to combat-related occupational roles (Sharma, Greeves, Byers, Bennett, & Spears, 2015) and are primarily trained through endurance running, resistance training, in-field activities, and loaded marching (Blacker, Wilkinson, Bilzon, & Rayson, 2008). Although there are many beneficial effects of physical training, poor exercise programming combined with demanding tasks and high training volumes can lead to detriments in both physical capacity and task-specific performance (Brushøj et al., 2008; Groeller et al., 2015). For example, if recruits are unaccustomed to undertaking vigorous exercise (e.g., loaded marching, running, resistance-based training, etc.), the failure to adapt to the increased training volume and loads combined with repetitive mechanical loading increases the risk of injury (Sharma et al., 2015).

The simplest solution to reduce injury risks would be to decrease the external loads carried by soldiers (Dean, 2004). However, as loads are allocated based on their necessity in relation to operational demands in order to achieve and execute core tasks, this is not an adequate solution. A more viable approach is to reduce the gap between task demands and soldier's physical capacity (Friedl et al., 2015) by using appropriate loading schemes within physical training that are specific to occupational demands. This ensures soldiers are physically prepared to adequately perform occupational roles both individually and as a unit during field operations (Szivak & Kraemer, 2015). To date, research has designed and implemented various training interventions aimed at improving soldiering performance and reducing musculoskeletal injury risk during training, with few reporting positive responses (Brushøj et al., 2008; Knapik et al., 2002). Interestingly, of those interventions that focussed on targeting specific injury mechanisms, training successfully elicited improvements in performance outcomes (Coppack, Etherington, & Wills, 2011) compared to those interventions that focussed on implementing general conditioning (Brushøj et al., 2008). As musculoskeletal injury rates remain consistently and unacceptably high for military personnel, it is imperative to understand load carriage task demands so that effective, evidence-based physical training regimes that target injury mechanisms can be developed and implemented (Sharma et al., 2015).

1.1.1. The Female Combat Soldier

Although combat-related roles have been open to women since 2014 (Department of Defence, 2014), and remain open in the armies of developed nations, inherent differences in physical capacities between men and women (i.e., strength, power, and aerobic fitness) (Nindl, Jones, Van Arsdale, & Kraemer, 2016) still influence the successful execution of crucial combat tasks (e.g., load carriage). As females typically have lower physical capabilities compared to males (Nindl et al., 2016), they are at a disadvantage in physically demanding combat-related roles (Kraemer et al., 2001; Kraemer et al., 2004). Furthermore, females are twice as likely as males to sustain an injury in a military setting (Friedl et al., 2015; Jones et al., 2017; Knapik et al., 2001; Krupenevich, Rider, Domire, & DeVita, 2015; Nindl, 2015; Nindl, Williams, Deuster, Butler, & Jones, 2013b; Silder, Delp, & Besier, 2013a). The integration into these combat-focused occupational roles is critical particularly as recent Australian government mandates pledge to increase female participation in these typically male-dominated defence roles. However, to successfully execute this task, female physical capabilities, challenges, and specific responses to physical training and load carriage tasks are required to be thoroughly investigated and understood. Military organisations can then make informed decisions on how to effectively prepare females to meet the physical demands required to successfully fulfil the requirements of these physically demanding roles (Friedl et al., 2015).

1.1.2. Impact on Soldier Capability

1.1.2.1. Injury Risk Factors and Incidence in the Military

Musculoskeletal injuries (MSI) are the biggest medical threat to readiness of both active-duty and reserve soldiers (Nindl et al., 2013a), and are the most frequently claimed conditions through the through Military Rehabilitation and Compensation Act (Department of Veterans' Affairs, 2014). Claims are primarily made of injuries including joint sprains and strains, disorders of muscle, tendon, and other soft tissues, joint inflammation, and associated disorders (Department of Veterans' Affairs, 2014; Popovich, Gardner, Potter, Knapik, & Jones, 2000). Soldiers who sustain an MSI are usually placed on restricted duties over varying time periods whilst recovering, equating to ~25 million restricted duty days across military organisations globally (Ruscio et al., 2010). Of those injured, many require additional time consuming costly rehabilitation services to restore readiness, placing substantial financial burdens on military organisations through direct and indirect costs (Sherrard, Lenné, Cassell, Stokes, & Ozanne-Smith, 2004). In 2014-2015 Australia spent AUD$102.2 million on personnel incapacitated through injury, representing a 25.5 % annual increase compared to the AUD$81.4 million spent in the previous year (Department of Veterans' Affairs, 2014). In the United States, MSI sustained by military personnel result in ~2.2 million medical encounters annually (Nindl et al., 2013a), with > 55 % of these incidences attributing to overuse injuries within active-duty soldiers (Jones, Canham-Chervak, Canada, Mitchener, & Moore, 1993). Further data has identified that over USD$3 billion dollars in general health care and salary costs are associated with soldiers who are unable to deploy as a result of injury (Nindl et al., 2013a), accounting for ~USD$349.9 million in disability-related rehabilitation costs (Department of Veterans' Affairs, 2014). Discharge compensation has substantial long-term effects on military organisations, with indirect costs associated with decreased work capacity, recruitment, and replacement of discharged soldiers. There is a clear need to develop strategies to minimise and mitigate MSI risks, and to enable optimal soldier function and capability.

1.1.3. Mechanical Loading as a Risk Factor of Injury

The most frequent injuries experienced within the military population are lower limb MSI including: patellofemoral pain, medial tibial stress syndrome, stress fractures, Achilles tendinopathy, and plantar fasciitis (Rosendal, Langberg, Skov-Jensen, & Kjær, 2003; Wang, Frame, Ozimek, Leib, & Dugan, 2012). Injury incidences primarily occur during basic training (Sharma et al., 2015) or during in-field operations (~23 %) (Cohen et al., 2010), and result in lost training days (Rhon, Golden, Trevino, & Hatler, 2017) and increased medical costs (Popovich et al., 2000). For example, Pope, Herbert, Kirwan, and Graham (2000). found that of 1357 Australian army recruits completing 12 weeks of basic training, ~20 % sustained a lower limb injury. Within Australia specifically, MSI reporting is generally poor, however, vast amounts of international data reporting MSI estimate that general incidence rates range between 0.8-59 %, depending on the injury type (Cohen et al., 2010; Popovich et al., 2000; Sharma et al., 2015; Van Tiggelen et al., 2004).

A key determinant of lower limb MSI is mechanical loading, specifically the repetitive loading of tissues and/or joints primarily associated with physical training and occupation-specific tasks (e.g., marching and running) (Jones, Perrotta, Canham-Chervak, Nee, & Brundage, 2000; Popovich et al., 2000; Wang et al., 2012). Joint anthropometrics, external ground reaction forces, internal joint forces (Besier et al., 2011), and the specific phase of the gait cycle all influence the magnitude of mechanical loading experienced during load carriage tasks (Besier et al., 2011). Repetitive applied loading leads to excessive internal tissue stresses and strains (Xu et al., 2016). Increases in training intensity, volume, type, and frequency heightens the amount of internal mechanical loading experienced by soldiers (Jones et al., 2000). More specifically, increases in ground reaction forces (GRFs) and internal loading rates from high volumes of physical activity are cited as primary causal factors for MSI (Jones et al., 1993; Knapik et al., 2004; Xu et al., 2016). These factors combined with heavy loads carried increase peak mechanical loading of lower limb joints.

Reductions in peak mechanical loading may be achieved through re-engineering tasks to decrease demands, achieved through decreasing the total weight carried by soldiers, and/or conditioning soldiers to tolerate heavy loads. Current standards for fitness and mandatory equipment for combat-related occupations mean that decreasing total loads carried by soldiers is not viable. The implementation of targeted conditioning programmes however, may improve load carrying ability of soldiers and protect them from injury by increasing their ability to control and attenuate load (Hoffman, Chapnik, Shamis, Givon, & Davidson, 1999). Many studies have attempted to decrease the gap between task demands and the physical capacities of soldiers with little success in load carriage tasks (Sharma et al., 2015).

A critical limitation of previous studies that aimed to improve performance and reduce injury risks is that they lack an evidence-base for the development and implementation of the physical training program used. Evidence-based training enables improved efficiency of training with faster results and fewer injuries. Additionally, few studies have examined the magnitudes of lower limb joint loading encountered by soldiers when carrying military relevant loads. Despite this, research investigating the biomechanics of external load carriage helps to explain potential mechanisms related to the high incidences of MSI reported in soldiers.

1.2. Biomechanics of Load Carriage

It is well documented that external load carriage alters human biomechanics and can result in adaptive changes in order to meet the demands of the task. The lower limbs are the most commonly reported injured area in military personnel (Department of Defence, 2000). Consequently, research has predominately focused on lower limb biomechanics and potential overuse injury mechanisms associated with load carriage tasks. Specifically, adaptive responses to spatial-temporal, kinematic (motion-focused), and kinetics (force-focused) have been examined during load carriage under varying conditions to further understand biomechanical responses, explore potential injury mechanisms, and to determine condition-based task demands. The primary goal of biomechanical adaptations in response to load carriage are to control the additional external load and to conserve or minimise energy costs.

1.2.1. Kinematics

Kinematics is the subdivision of mechanics focussed on describing the motion of an object, without the consideration of forces that cause the associated movement. Methods for data acquisition has evolved over the years, with specific motion capture technology allowing for the collection of movement data using accurate, high-sampling cameras. Within the load carriage literature, studies mainly report lower limb (e.g., hip, knee, and ankle joints) kinematic adaptations in response load carriage throughout the gait cycle (Attwells, Birrell, Hooper, & Mansfield, 2006; Birrell & Haslam, 2009; Harman, Han, Frykman, & Pandorf, 2000; Knapik, Harman, & Reynolds, 1996; Majumdar, Pal, & Majumdar, 2010; Polcyn et al., 2002). Changes to gait kinematics during level walking load carriage have been investigated under varying conditions; participants walking at different speeds (fixed or self-paced) (Harman et al., 2000; LaFiandra, Wagenaar, Holt, & Obusek, 2003; Lenton et al., 2019), with different magnitudes of loads (Attwells et al., 2006; Birrell & Haslam, 2009), or load distribution (Birrell & Haslam, 2010; Majumdar et al., 2010). External factors such as the those previously mentioned are known to influence lower limb kinematic responses, meaning variations in methodologies may contribute towards the inconsistencies of results reported within the load carriage literature.

1.2.1.1. Spatial-Temporal

Alterations in spatial-temporal variables are consistently reported and are known to occur as a result of carrying additional load (Birrell & Haslam, 2009; Harman et al., 2000). Responses whilst under load tend to differ depending on phase of the gait cycle, which can be divided into two primary phases: the stance phase (i.e., the period of time the foot is in contact with the ground), and the swing phase (i.e., the period of time the foot is not in contact with the ground). Common responses observed during the stance phase are increases in stance time (express as a % of the entire gait cycle) and the amount of time spent in double limb support (time of both limbs spent in contact with the ground) (Birrell & Haslam, 2009; Harman et al., 2000; Mullins et al., 2015). These increases serve to facilitate stability during gait and may decrease lower limb internal loading (Birrell & Haslam, 2009; Kinoshita, 1985; Polcyn et al., 2002). During the swing phase, studies generally report decreases in step length and step rate (LaFiandra et al., 2003; Polcyn et al., 2002), which are suggested to modulate additional unnecessary stresses placed upon the body (Kinoshita, 1985).

1.2.1.2. Trunk Forward Lean

As gait stability is compromised with external load (Hsiang & Chang, 2002), forward trunk lean serves to counteract the additional torque generated at the hips and pelvis (Polcyn et al., 2002; Ren, Jones, & Howard, 2005). Ultimately this facilitates the restoration of centre of mass (COM) centralisation within the base of support (Attwells et al., 2006; Birrell & Haslam, 2009; Harman et al., 2000; Knapik et al., 2004) to optimise mechanical efficiency. Increased trunk flexion is assisted through anterior pelvic rotations to counterbalance posterior torque generated by the external load to counterbalance the displaced COM (Attwells et al., 2006; Harman, Han, & Frykman, 2001). Loads as light as 8-10 kg have elicited up to ~5° increases in trunk forward lean (Attwells et al., 2006), with additional changes observed as load proportionally increases (e.g., ≥ 30 kg donned loads) (Harman et al., 2000; LaFiandra et al., 2003; Majumdar et al., 2010; Polcyn et al., 2002; Seay et al., 2014; Simpson, Munro, & Steele, 2012b). Some research has postulated that this adaptive response to external load carriage can increases the stress placed on internal structures such as connective tissues and muscles in the lower back (Bobet & Norman, 1984), however, limited research has confirmed these findings. When carrying external load, the distribution of weight alters trunk forward lean responses. For example, reductions in trunk forward lean are observed when load is more evenly distributed (i.e., equal anterior and posterior loading) around an individual's COM, with maximum lean values equating to ~1 % (Seay et al., 2014). As COM displacement is reduced, an upright posture is adopted, similar to that shown during unloaded walking (Kinoshita, 1985; Park et al., 2014b). Regardless of the extent of these changes, the magnitude of external load carried appears to be the governing mechanism behind trunk forward lean adaptations.

1.2.1.3. Hip Angle

The hip angle is defined as the relative position of the pelvis with respect to the thigh. Research to date has predominately reported changes in sagittal plane lower limb kinematics in response to load carriage tasks. Hip flexion responses are similar to those observed in trunk forward lean, as loads ≥ 30 kg demonstrated greater increases in peak hip flexion angles (up to 11º) (Harman et al., 2000) compared to loads ≤ 30 kg loads (up to 5º) (Birrell & Haslam, 2009; Park et al., 2014b; Seay et al., 2014). Changes in peak hip extension have been observed, typically aligning with spatial-temporal responses whereby individuals spend an extended time in the stance phase of the gait cycle (Harman et al., 2000; LaFiandra et al., 2003; Silder et al., 2013a).

Birrell and Haslam (2009) notably found increases in adduction/abduction and rotation of the hip and pelvis tilt during stance when carrying a 32 kg load. These and loads as light as 18 kg have been shown to elicit greater step width values in comparison to loads < 18 kg. Such changes in step width are associated with increases in peak hip adduction at heel strike and greater external hip rotation (Birrell & Haslam, 2009; Park et al., 2014a). Such changes in hip biomechanics accommodate a wider step width due to the additional load being carried (Birrell & Haslam, 2009; Park et al., 2014b; Seay et al., 2014). Stiffening of the hips and trunk has further been observed, likely acting as a protective mechanism to stabilise the spine and resist pelvic rotation (Holt, Wagenaar, LaFiandra, Kubo, & Obusek, 2003). However, decreases in pelvic rotation combined with increased pelvic tilt during loaded conditions have been associated with increased injury risk (LaFiandra et al., 2003), suggesting that compensatory mechanistic responses may not always be beneficial.

1.2.1.4. Knee Angle

Generally, findings at the knee joint are inconsistent throughout the literature. Knee angle is defined as the posterior angle between the thigh and the shank (lower leg); expressed as degrees of flexion (i.e., lower flexion values indicate greater knee extension). Most studies observe increases in knee flexion as a function of load mass (Attwells et al., 2006; Harman et al., 2000; Silder et al., 2013a; Simpson, Munro, & Steele, 2012a), which is a compensatory mechanism that acts to aid shock absorption and facilitate a smooth transfer of the system weight through the foot to the ground (Birrell & Haslam, 2009). Furthermore, this response promotes stability during loaded walking by lowering the body's COM to reduce excursions that contribute towards excessive energy costs (Harman et al., 2000). Findings reported for knee joint range of motion (ROM) conflict with some studies as significant increases in knee joint ROM with the addition of load have been observed (Attwells et al., 2006), while other studies report little or no changes to a 55 kg external load (Birrell & Haslam, 2009; Harman et al., 2000; Seay et al., 2014). Indeed, it is important to highlight that differences in load configurations and walking speeds between studies may contribute towards these equivocal findings in the literature, especially as loads carried and march speeds are determined by occupational requirements rather than soldier's total body mass or preferred walking speed. Therefore, future research should attempt to use specific study protocols that permit the generalisation of results to the population of interest through well matched experimental conditions.

1.2.1.5. Ankle Angle

Similar to the knee joint, inconsistencies in the literature have been shown at the ankle joint. Ankle angle is defined as the angle between the shank (lower leg) and the foot. Similarly to the knee joint, some studies have found no changes in peak ankle dorsiflexion (Harman et al., 2000; Holt et al., 2003; Quesada, Mengelkoch, Hale, & Simon, 2000), while others have found increases in peak angles during stance (Attwells et al., 2006) and immediately prior to foot contact (Silder et al., 2013a). Variations in study methodologies and specific research protocols may account for the general inconsistencies of findings for lower limb kinematics detailed within the literature. For example, some studies have allowed participants to assume a self-selected speed while performing loaded walking tasks (Attwells et al., 2006), whereas others assigned fixed speeds (Huang & Kuo, 2014; Silder et al., 2013a) to limit the effects of speed on gait parameters. Load distributions varied between studies which further elicited different gait responses. Loads carried in some studies are relative (i.e., normalised to participant's body weight) (Quesada et al., 2000; Seay et al., 2014; Silder et al., 2013a), whereas other studies used absolute loads (Attwells et al., 2006; Birrell & Haslam, 2009; Krupenevich et al., 2015). Moreover, participants' experience of carrying load varies considerably between studies, ranging from novice individuals (Silder et al., 2013a) to experienced military personnel (Harman et al., 2000). As such, the application of findings to the soldier population to date have been limited and requires further investigation in order to draw effective conclusions.

1.2.2. Kinetics

Kinetics is the subdivision of mechanics focused on the forces acting upon, or within a system that causes motion. GRFs are contact forces that arise due to interactions between the body and ground. When the foot contacts the ground, the resultant GRF vector provides information regarding the magnitude and direction of the combined force exerted by the individual (i.e., person, plus external load). Ground-embedded force platforms or force-instrumented treadmills have the capability to measure GRFs effects during load carriage and allow for the analysis of multiple strides throughout the gait cycle. Measuring GRFs is important as it is an key contributor to determining lower limb overuse MSI risk status during load carriage tasks (Birrell & Haslam, 2010; Quesada et al., 2000).

1.2.2.1. Ground Reaction Forces

The GRFs are composed of medio-lateral, vertical, and anterior-posterior orthogonal components, with the resultant GRF representing the combined force of the individual and system load. Compared to unloaded walking, loaded walking significantly increases peak breaking and vertical GRF loading rates (Wang et al., 2012), where the magnitude of the vertical and anterior-posterior GRF increases proportionally to the magnitude of the load carried (Birrell, Hooper, & Haslam, 2007; Harman et al., 2000; Kinoshita, 1985; Knapik et al., 1996; Polcyn et al., 2002; Seay et al., 2014; Tilbury-Davis & Hooper, 1999). However, these increases are not similarly distributed across stance, with early (i.e., loading response) and late (i.e., push-off) stance phases revealing the largest GRFs changes. Certain kinetic variables appear to be more sensitive to change when certain load distributions are carried during level-walking. For example, anteriorly displaced load increase the weight placed over the striking foot during initial ground contact, which increases total joint contact forces (Hsiang & Chang, 2002). Conversely, posteriorly displaced load reduces vertical force magnitudes at toe-off (Birrell & Haslam, 2010). Even distribution of load reduces peak forward trunk lean angles (Attwells et al., 2006; Kraemer et al., 2004) and COM displacements (Harman et al., 2000) in comparison to loads that are unevenly distributed (e.g., more load posteriorly or anteriorly donned) (Birrell & Haslam, 2009). Some research has found that evenly distributed loads decrease the magnitude of anterior-posterior GRFs during heel strike, and increase the magnitude of anterior-posterior GRFs at toe-off (Birrell & Haslam, 2010), while other studies showed no changes in any GRFs (Harman et al., 2000). As loaded walking is known to significantly increase the magnitude of peak GRFs (Wang et al., 2012) experienced by soldiers', investigating the roles of lower limb joints and muscles could provide important information which elucidates to MSI injury mechanisms during load carriage. Furthermore, this information could be key in informing effective strategies to reduce the burden of MSIs associated with carrying external loads.

1.2.2.2. Joint Moments during Load Carriage

About the sagittal plane and during walking, joint moments arise primarily due to muscle forces that control and accelerate our body (Seay et al., 2014). These moments increase in response to increased load magnitudes carried during walking (Huang & Kuo, 2014; Wang, Frame, Ozimek, Leib, & Dugan, 2013). Joint moments are the closest measure of neuromuscular stressors that can be calculated without the need to compute muscular forces. Although there are mechanical quantities that are in part dependent on muscle forces (i.e., joint contact forces and pressures, articular tissue stresses/strains), joint moments are relevant because they might be directly related to the injury mechanism (Seay et al., 2014), calculating physiological valid, and physically plausible muscle forces during dynamic motor tasks is highly non-trivial. Inverse dynamics (ID) and Inverse Kinematics (IK) equations are used to calculate net joint moments by combining the measured GRF and body segment kinematics, and the associated segment masses and lengths (Sartori, Gizzia, Lloyd, & Farina, 2013).

Sagittal plane joint moments are commonly reported within load carriage literature as gait propulsion and primary joint motion is executed in the sagittal plane. During early stance, peak hip extensor, knee extensor, and ankle dorsiflexion moments increase to counteract COM excursions associated with carrying external load (Seay et al., 2014; Wang et al., 2013), and reduce potential energy costs associated with excessive COM excursions (Holt et al., 2003). Interestingly, these biomechanics (as detailed above) may increase the requirements for eccentric muscular contractions and induce premature muscular fatigue (Quesada et al., 2000). For example, increased demands for hip extensor moments are experienced during loaded walking as hip flexion moments increase as a result of increase in magnitude of GRFs (Wang et al., 2013). Hip extensors may therefore experience increased mechanical stress and be unable to meet the demands of a loaded walking task. Indeed, forward trunk lean is used as a compensatory strategy during running to reduce hip flexion and knee extension moments (Teng & Powers, 2014, 2016), meaning it could be postulated that a similar pattern may be adopted during loaded walking. These findings further suggest that there is an increased demand placed on proximal joints in the kinetic chain during these tasks (i.e., hip and knee compared to ankle).

During late stance, an increased reliance on the lower limb musculature helps to generate forward momentum, but seemingly only when heavy external loads are carried (Harman et al., 2000). Interestingly, loads ranging from 15 to 22 kg appear to have minimal effects on hip joint flexion moment changes (Seay et al., 2014; Silder et al., 2013a; Wang et al., 2013), in comparison to loads ≥ 30kg, which have been shown to elicit substantial increases in peak hip joint moments during late stance (Harman et al., 2000). Similarly, external peak knee flexion moments increase when simulated combat loads incremental increase from 15 kg up to 55 kg in comparison to lighter loads of < 15 kg (Seay et al., 2014; Wang et al., 2013). Increased external knee flexion moments combined with consistent knee flexion at heel strike likely pre-stretches the knee extensors, which in turn increases the quadriceps extension moment arm, and results in an increased knee extensor moment for any given muscle activation (Wang et al., 2013). If true, this may help explain the high incidence of knee injuries within military personnel, as such biomechanics are indicative of a greater reliance on knee extensor musculature to support the body in response to the external loads carried. Furthermore, individuals who lack knee extensor strength are known to be at a greater risk of lower limb MSI, as quadriceps muscle activity significantly increases during the loading-response phase of gait (Park et al., 2014a; Silder et al., 2013a; Simpson, Munro, & Steele, 2011a). Therefore, it appears that minimising joint moments elicited in response to load carriage tasks in early stance may in turn help reduce MSI injury risks. Silder et al. (2013a) found increases in peak plantar flexion moments and gastrocnemius forces (deemed as coordinated musculature adjustments) help to maintain forward progression throughout the duration of a load carriage task. Although, the application of this finding may be redundant given military personnel are required to wear military boots that restrict ankle joint motion, ultimately limiting the ankle joints contribution during walking (Sinclair, Taylor, & Atkins, 2015).

1.2.3. Female Gait Biomechanics during Load Carriage

Despite combat roles being open to females since 2014 (Department of Defence, 2014), limited research has investigated the effects of heavy load carriage on gait biomechanics in this population (Simpson et al., 2012a; Simpson et al., 2012b), whereas extensive research has been conducted within a male population (Attwells et al., 2006; Birrell & Haslam, 2010; Birrell et al., 2007; Harman et al., 2000; Quesada et al., 2000). In combat-related occupational roles, males and females are required to complete the same load carriage tasks regardless of sex, or individual physical capabilities (Knapik et al., 1997; Nindl, 2015). Yet, there are known physiological sex-differences that impair the successfulness of executing critical combat tasks, with potential implications for female in combat-related roles. Indeed, females are twice as likely to sustain a lower limb MSI compared to males during training and in combat-related occupations (Friedl et al., 2015; Jones et al., 2017; Knapik et al., 2001; Krupenevich et al., 2015; Nindl, 2015; Nindl et al., 2013b; Silder et al., 2013a). This high injury risk highlights the importance of attaining a deeper understanding of potential sex-differences during physically demanding tasks in military jobs so that risk mitigation strategies can be put in place.

Moderate to heavy load carriage alters lower limb gait patterns and joint loading responses within a male population (Attwells et al., 2006; Birrell & Haslam, 2009; Seay et al., 2014), with similar variations in female gait biomechanics demonstrated during load carriage during short (Simpson et al., 2012b) and long duration (Simpson et al., 2012a; Simpson, Munro, & Steele, 2011b) load carriage tasks. However, when males and females are comparatively analysed during loaded walking, limited sex-specific changes in lower limb gait mechanics have been reported (Krupenevich et al., 2015; Silder et al., 2013a). The contrasting findings demonstrated between Silder et al. (2013a) and Simpson et al. (2012a) are particularly interesting, especially as both studies prescribed similar relative external loads ranging between 10 % and 40 % of body weight. The lack of observed gait adaptations may be accounted for by the normalisation of the load carried, especially as absolute strength and load carriage ability is correlated with body mass (Pandorf et al., 2003; Patterson, Roberts, Lau, & Prigg, 2005; Zatsiorsky & Kraemer, 2006). Since those loads impose an equivalent burden on both groups, it is not surprising that neither neuromuscular recruitment nor walking mechanics differed between sexes. Thus the accommodation of these equivalent relative loads resulted in similar changes in gait, although this would have not been anticipated if the same fixed (absolute) heavy loads were used (Haisman, 1988; Knapik et al., 2004).

Investigating the effects of load relative to body mass may provide further understanding of the influence of stature or general differences in individual's anthropometry between sexes (Krupenevich et al., 2015; Silder et al., 2013a). However, Krupenevich et al. (2015) found that walking at 1.5 $m \cdot s_{-1}$ with a standardised load of 22 kg load resulted in no evident sex-specific differences in lower limb biomechanics. Nevertheless, such findings suggest that females do not adjust their gait biomechanics to compensate for their smaller statures and lower absolute strength compared to males (Krupenevich et al., 2015); possibly accounting for the higher injury rates observed in female military recruits. Findings by Simpson et al. (2012a) have shown that load carriage tasks > 2 km evoke a greater change in biomechanics compared to shorter tasks in females, which means further investigations that examine the role of task during with sex-specific responses may be required. Moreover, previous investigations have also been limited to sagittal plane kinematics, thus neglecting the potential for changes in the coordination of the biomechanics of all three lower limb joints.

Loverro, Hasselquist, and Lewis (2019) recently examined potential effects of sex on frontal plane hip and knee biomechanics as previous studies have mainly investigated the effects of sex in the sagittal plane. Examining effects of sex on frontal plane biomechanics is potentially relevant for research into MSI, because at least at the knee, frontal plane moments are associated with degenerative disease severity and progression (Miyazaki et al., 2002) Carrying standardised medium (15 kg) and heavy (27 kg) loads over a short walking trial (2 minutes) resulted in males and females using different gait strategies. For example, peak hip adduction angles increased for females, but not males, and was the only sex-difference found when carrying the same standardised load. In contrast to Krupenevich et al. (2015) and Silder et al. (2013a), normalising loads to body mass elicited alterations to load in females at the hip, with kinematic changes noted in females at the knee and in males at the hip. These specific adaptive gait strategies used in response to heavy carried load may have implications for hip and knee injury risks when carrying military-relevant loads (Loverro et al., 2019).

1.3. Physiological Impact of Load Carriage

1.3.1. Physiological Responses during Load Carriage

The physiology of load carriage has been extensively investigated as various physical task factors (i.e., load magnitude, load distribution, walking speed, task distance and duration) impact on soldiering performance when walking while carrying external load. During training, soldiers regularly undertake load carriage tasks at low to moderate walking speeds (3 km.h^{-1} to 6 km.h^{-1}), over distances of 5 km to 20 km, with loads ranging from ~20 kg up to > 60 kg. However, the substantial physical and physiological stressors experienced by the load carrier are known to negatively influence their load carrying capacity through impairments in physiological, physical, and perceptual responses (Drain et al., 2012).

A key physiological consequence of load carriage is that the energy cost (energy expenditure) of walking increases progressively different load magnitudes and walking speeds (Bastien, Willems, Schepens, & Heglund, 2005; Epstein, Rosenblum, Burstein, & Sawka, 1988; Goldman & Iampietro, 1962; Pandolf, Givoni, & Goldman, 1977). Numerous studies (Epstein, Yanovich, Moran, & Heled, 2013; Legg & Mahanty, 1985; Li et al., 2019; Quesada et al., 2000; Ricciardi, Deuster, & Talbot, 2008) have established a linear increase in energy cost when loads of 30 kg to ~60 kg are carried, with similar findings reported for walking speeds ranging between 5 km.h^{-1} - 6 km.h^{-1}. These findings have highlighted an evident weight-load threshold at which load carriage performance is degraded. Epstein et al. (1988) suggested that maximal load carriage efficiency (as determined by energy expenditure) is achieved at 4.5 km.h^{-1} - 5.0 km.h^{-1} walking speed with a load weighing 40-50 % of body mass (e.g. 32 kg to 40 kg for an 80 kg soldier). However, more recent research by Christie and Scott (2005) recommends that the individual threshold of load and speed for acceptable load on the individual is achieved at 35 kg at 3.5 km.h^{-1} and 20 kg at 4.5 km.h^{-1}. However, the applicability of these 'optimal' thresholds may not be achievable given the loads, walking speeds, and distances of load carriage tasks can be substantially higher in many real-world military scenarios (e.g., Australian PES standards, United States PES standards, United Kingdom PES standards) (Christie & Scott, 2005).

The duration of load carriage tasks can vary substantially, ranging from minutes to hours, or possibly conducted over consecutive days. Increases in the energy cost of load carriage have been shown by most studies during prolonged task durations (i.e., > 120 minutes) carrying moderate to heavy loads (i.e., ≥ 30kg) (Blacker, Fallowfield, Bilzon, & Willems, 2009a; Epstein et al., 1988; Patton, Kaszuba, Mello, & Reynolds, 1990). Furthermore, increases in cardiovascular demands (also referred to as cardiovascular drift) reflected by variables including $\dot{V}O_2$ uptake (oxygen uptake) and HR have been observed under equivalent task conditions (Epstein et al., 1988; Mullins et al., 2015; Pandorf et al., 2003; Patton et al., 1990). Interestingly, Patton et al. (1990) observed increases of 3.8 % and 8.4 % in $\dot{V}O_2$ uptake over a 120-minute walking task, carrying 31.5 kg and 49.4 kg, respectively. Similar increases in $\dot{V}O_2$ responses have further been reported when carrying lighter loads (22 kg and 25 kg), at varying walking speeds (Blacker et al., 2009a; Mullins et al., 2015). Over time, such changes may be indicative of accelerated fatigue induce by load carriage which leads to reductions in neuromuscular function, as evident by simultaneous increases in $\dot{V}O_2$ requirements. In order to prevent premature fatigue and prolong task sustainment (ability to maintain a given intensity over time) it is recommended that tasks are performed ≤ 50 % of an individuals $\dot{V}O_{2max}$ (Åstrand, Kaare, Hans, & Sigmund, 2003). For example, Epstein et al. (1988) reported that cardiovascular drift occurred at a workload that elicited an aerobic output of 52 % $\dot{V}O_{2max}$, but not at 46 % $\dot{V}O_{2max}$. These findings suggest that controlling the given intensity of a loaded march to limit soldiers from exceeding ~45 % of their $\dot{V}O_{2max}$ may effectively delay the onset of fatigue during more prolonged tasks.

Interestingly, more recent research has identified that energy expenditure is not the sole determinant of load carriage task demands: both metabolic and musculoskeletal factors appear to be important (Pandolf, 1978). Task vigilance (Mahoney, Hirsch, Hasselquist, & Lieberman, 2007), decision making ability (May, Tomporowski, & Ferrara, 2009), mental alertness (Johnson, Knapik, & Merullo, 1995), and perceptions of task demands have been associated with reductions in performance and/or task sustainment as a consequence of carrying external load (Drain et al., 2012; Hasselquist et al., 2013).

1.3.1.1. Psychophysical Impact on Soldiers Performance

As previously mentioned, a broad amount of research examining physiological responses during low to moderate intensity load carriage has indicated there are multiple limiting factors potentially contributing towards detrimental performance during prolonged load carriage tasks (Blacker et al., 2009a; Epstein et al., 1988; Patton et al., 1990). Localised discomfort and muscular fatigue induced by the load itself is known to cause pain at different contact points of the upper body (e.g., shoulders) (Lenton et al., 2018). This combined with prolonged physical exertion, can impact RPE and HR responses (Birrell et al., 2007; Simpson et al., 2012a), potentially limiting overall task performance.

Research demonstrates the highest overall RPE values are generally elicited during heavy load carriage (≥ 30 kg), irrespective of speed (Pimental & Pandolf, 1979). Consequently, tasks are perceived to be more intense and can negatively impact an individual's capability to sufficiently sustain load carriage performance irrespective of having the physiological capacity to do so (Drain et al., 2012). Supporting this notion, Patton et al. (1990) reported the effects of the external load carried during a 12 km march negatively influenced RPE responses (linearly increased throughout the task) in comparison to the measures physiological variables (i.e., $\dot{V}O_2$ uptake remaining similar). These findings indicate that psychophysical responses during load carriage can significantly impact on the load carriage capacity of individuals, hence future research should focus on implementing strategies to build soldiers cognitive resilience and physical capacity (Nindl et al., 2018).

1.3.2. Female-Specific Physiological Responses during Load Carriage

Physiological responses during prolonged load carriage tasks to date have mainly been established in a male population, with limited research available in a female population. Lidstone et al. (2017) investigated female responses when walking with an operational load of 55 % body mass for one hour at 5.4 km.h^{-1} significantly increased $\dot{V}O_2$ (maximal oxygen consumption), HR, and RPE measures. Interestingly, lighter loads of 20 % of body mass appear to elicit similar physiological responses over an 8 km self-paced distance, with larger responses elicited in variables as load magnitudes incrementally increased (up to 40 % body mass) (Simpson et al., 2011b). These similarities through measures such as increased $\dot{V}O_2$ requirements may occur due to an increased demand placed upon the cardiovascular system as load carriage distance progresses. This combined with a decreases in neuromuscular function (Lidstone et al., 2017) or movement efficiency (Kraemer et al., 2001) may further contribute to the greater physiological demands required during prolonged load carriage tasks.

Studies investigating female responses during load carriage typically normalise loads as a percentage of body mass. However, this method makes the application of findings to a military setting difficult (Drain et al., 2012), as loads are primarily determined by occupation and/or task requirements rather than individuals' physical characteristics (i.e., height, mass, age, sex, or strength) (Nindl, 2015). Yet, surprisingly, only one study to date (Phillips 2016) has investigated and examined female physiological responses during a prolonged load carriage task using an absolute load (walking with a 25 kg torso-borne load for 45 minutes at 1.5 $m \cdot s^{-1}$). Phillips, Stickland, and Petersen (2016) reported increases in ventilatory responses (minute inspiration and expiration), perceived exertion (RPE responses), and breathing discomfort increase. Although responses were similar to those of a male population, the changes observed were greater than those previously detailed in males, supporting previous claims that females work at a higher relative intensity than males during heavy load carriage tasks (Blacker, Wilkinson, & Rayson, 2009b; O'Leary, Saunders, McGuire, & Izard, 2018; Patterson et al., 2005). Though this may inevitably result in a greater energy expenditure cost for females, studies have identified that this is not the sole determining variable of load carriage task demands, with both metabolic and musculoskeletal factors being important (Pandolf, 1978). Furthermore, external load has been shown to influence factors such as discomfort or pain (Park et al., 2013), and respiratory mechanics (Phillips et al., 2016) in female-specific cohorts completing physically demanding load carriage tasks, which may impact psychophysical responses (Simpson et al., 2011b).

1.3.2.1. Female-Specific Psychophysical Responses during Training and Load Carriage

Recent load carriage literature has highlighted that external load influences both physical (i.e., discomfort or pain) (Park et al., 2013) and physiological (i.e., respiratory mechanics) (Phillips et al., 2016) factors. Experiencing increases in physical and physiological factors can impair load carriage capacity and/or sustainment (defined as the capacity of an individual to maintain a given work intensity) (Drain et al., 2012). These impairments can manifest in numerous forms, however, a key determining factor highlighted by research is the manifestation of impaired physical performance through heightened perceptual responses (i.e., RPE) (Simpson et al., 2011b). An effective strategy to mitigate these effects is through implementing targeted physical training to not only improve individuals physical capacity, but to also build task resilience by repeated load carriage task exposure (Harman et al., 2008a; Kraemer et al., 2001; Kraemer et al., 2004). Conditioning individuals in this way has the ability to enhance the performance capacity of female military personnel (Nindl et al., 2018).

1.4. Physical Training of Load Carriage

The burden of mandatory load carriage tasks in military roles place large physical demands on soldiers and is highly associated with being a primary cause of musculoskeletal overuse injuries (Brushøj et al., 2008). To address this ongoing issue, training is implemented from the onset of military enrolment to develop individuals' physical capacity (Knapik et al., 2005) in order to meet specific occupational demands. Physical preparation begins with basic training which typically ranges between 6 to 14 weeks (depending on the country of service) and aims to transform civilian personnel into physically prepared soldiers. However, as civilians generally begin training at various states of physical readiness for exercise (e.g., untrained or recreationally active), the failure to adapt to increasing musculoskeletal demands and physiological stresses experienced during training can impair performance and place them at elevated risk of injury (Groeller et al., 2015). Specifically, the accelerated exposure to high training volumes combined with demanding tasks and poor exercise programming is known to impair performance and increase injury (Brushøj et al., 2008).

1.4.1. Neuromuscular Demands and Physical Characteristics of Load Carriage

Roy, Knapik, Ritland, Murphy, and Sharp (2012) previously determined that MSI sustained during deployment were likely related to discrepancies between the soldiers' physical capabilities and task demands. Emerging evidence suggests that an effective strategy to manage and reduce this risk is to focus physical training towards known injury sites and associated mechanisms by using evidence-based interventions (Coppack et al., 2011; Friedl et al., 2015; Sharma, Weston, Batterham, & Spears, 2014). Adopting this approach could act as a viable solution for addressing the discrepancy between the demands of military tasks (i.e., load carriage) and the physical capabilities of individuals. Within the military setting, this could be achieved by tuning physical training programs to be more specific towards occupational demands (i.e., the implementation of individualised training or training related to job-specific requirements) and could ultimately translate into enhanced task performance.

Muscular strength and aerobic fitness are key physiological characteristics required to successfully meet the specific demands of load carriage tasks (Friedl et al., 2015).

Investigations into the most effective training modality for these characteristics have varied substantially within available research. For example, the most common modes of physical training examined to date include aerobic training, interval training, resistance training, load carriage related exercises, or a combination of those mentioned. Progressive resistance training can elicit neuromuscular and cardiovascular adaptations and subsequent muscle hypertrophy (Friedl et al., 2015) that results in improved occupational load carriage performance (Haff et al., 2005; Harman et al., 2008b; Kraemer et al., 2001; Kraemer et al., 2004; Santtila, Häkkinen, Nindl, & Kyröläinen, 2012; Williams & Rayson, 2006; Williams, Rayson, & Jones, 1999). On the other hand, concurrent training methods (i.e., combined strength and aerobic training) have been extensively investigated as this mode appears to elicit the most beneficial overall performance improvements (Brushøj et al., 2008; Häkkinen et al., 2003). However, these studies did not adopt a periodised, progressive approach to training which is known to reduce the cumulative demands of repetitive tasks completed within a military setting (e.g., physical training and load carriage), and can limit performance detriments experienced by soldiers (Szivak & Kraemer, 2015; Williams, Rayson, & Jones, 2002). Therefore, implementing a periodised physical training program targeting the known demands of load carriage tasks could effectively facilitate physical performance improvements.

1.4.2. Physical Training Modalities

Resistance training improves muscle strength through neural adaptations and subsequent muscle hypertrophy (Friedl et al., 2015). Adaptations in response to progressive resistance training are easily attainable in untrained military recruits (Häkkinen et al., 2003). Harman et al. (2008a) observed that 8 weeks of progressive resistance training significantly improved general physical fitness tests (i.e., push-ups, sit-ups, and maximal jumps) and timed load carriage performance over a 3.2 km distance. Similarly, Kraemer et al. (2004) reported improvements in push-up performance and time to completion for a 2-mile loaded run in individuals that completed a 12-week training regime. However, in both studies, resistance-based training was performed in combination with other training modalities (i.e., running, agility-based training, and load carriage tasks). Indeed, concurrent training (e.g., strength and aerobic training combined) has been shown to be effective in improving general fitness performance (Williams & Rayson, 2006) and timed criterion load carriage tasks (Blacker et al., 2009a; Harman et al., 2008a; Harman et al., 2008b; Knapik, 1997; Kraemer et al., 2001).

However, a major limitation of this research is that typically the training programs have not used an evidence-based approach to program design (i.e., periodisation).

Interestingly, only a few studies have investigated the independent effects of resistance training on load carriage performance (Hendrickson et al., 2010; Kraemer, Vogel, Patton, Dziados, & Reynolds, 1987). Hendrickson et al. (2010) demonstrated significant improvements in load carriage run time to completion (3.2 km) while carrying a 32.7 kg load, upper body muscular endurance, and lower body strength (1RM squat), with Kraemer et al. (1987) reporting similar findings. However, a key limitation in these studies is that load carriage tasks are measure via timed run criterion tasks which heavily rely on a cardiorespiratory endurance aspect of fitness rather than strength or power. Consequently, it remains unclear as to whether resistance training alone could elicit similar improvements in load carriage performance.

1.4.3. Task-Specific Load Carriage Training

Similar to resistance training, carrying external load induces high levels of activation of type 2 motor units and results in positive neuromuscular adaptations (Friedl et al., 2015). Repeated task exposure enhances an individual's tolerance to physical stressors over time (Szivak & Kraemer, 2015) and is associated with eliciting the best performance outcomes in relation to load carriage (Knapik et al., 2004; Spiering et al., 2008; Williams, Rayson, & Jones, 2004). For instance, Harman et al. (2008a) found that including progressive load during an 8-week training program elicited greater improvements in load carriage performance (15 % reduction in completion time carrying 32 kg over a 3.2 km distance) compared to studies that did not (Williams et al., 1999). Conversely, Patterson et al. (2005) reported strength and aerobic capacity improvements, without changes in load carriage performance, after a 12-week training intervention that included resistance training, running and two load carriage marches. However, the limited load carriage march training may account for the lack of specific performance improvements and highlights the need for appropriate training volume in relation to specific tasks is essential to elicit desired outcomes. For example, the largest improvements in load carriage performance has been observed by studies that implemented specific and progressive load carriage tasks in training regimens, at a minimum, once weekly over programs lasting between 9 and 11 weeks in duration (Harman et al., 2008a; Williams et al., 1999). Doing so, provided an effective stimulus for key muscle groups that contribute to loaded walking and associated energy systems to respond over the intervention period. Ultimately, the improvement in load carriage performance is dependent upon the specificity of the training and evaluation mode (Williams & Rayson, 2006).

1.4.4. Female Physical Training for Load Carriage

In a recent review of conditioning programs used to improve female military task performance, it was concluded that a minimum of 6 months of training is required (Nindl et al., 2017), using task-specific exercises (i.e., load carriage). Additionally, greater emphasis should be placed on development of upper body strength and power to prepare women for combat-related occupations. However, training time restrictions within military organisations may be a barrier to the implementation of this recommendation. Some militaries, such as the Australian Defence Force, provide opportunities to complete additional pre-entry physical training programs to help integrate female personnel into physically demanding roles. Nevertheless, developing an effective training program that can minimise MSI risks and enhance task performance, while reducing time spent in training has the potential to reduce costs for military organisations and ensure faster deployment times.

Collectively, strength training is known to improve female physical performance overall (Kraemer et al., 2001; Nindl et al., 2016). However, findings to date demonstrate concurrent training implemented over a prolonged period (between 12 and 24 weeks) elicits the greatest improvements in physical and load carriage performance (Harman., Frykman, Palmer, & Reynolds, 1997; Nindl et al., 2017). Nindl et al. (2017) completed one of the most recent studies examining responses to physical training where the training program aimed to improve female performance thus minimising the performance gap between sexes. Pre-to-post-test comparisons identified that 24 weeks of a combination of resistance training, long-distance running, backpacking, and specialised drills results in elicited improvements in maximal strength (12 kg vs 20 kg), endurance (improving by between 9 and 34 repetitions after training), and improved time to completion of a 3.2 km load carriage task carrying 34 kg (completion times reduced by 3.7 - 8.6 minutes). Similarly, Harper, Knapik, and De Pontbriand (1997) reported improvements for the same load carriage timed task after conducting 24 weeks of combined resistance-based training, running, backpack hill rucks and generic drills. Indeed, such enhancements suggest periodising resistance training in the military, is vital to elicit adequate training adaptations in strength, power, and endurance that would markedly improve female performance. Though, the time frames in which these responses were shown are unrealistic in relation to military-specific timelines where standardised physical assessments and physical employment tests are completed (Australian Defence Force). Investigations into similar program designs are required to established if similar responses can be elicited in a reduced amount of time to align with military specific requirements.

1.5. Problem Statement

Military organisations rely heavily on physically fit, capable, and effective soldiers in order to successfully execute critical operational tasks in combat-related occupational roles. However, musculoskeletal injuries associated with mandatory load carriage tasks present a significant risk that threatens their overall functionality. Soldier injury results in diminished unit effectiveness, with severe long-term implications such as costly rehabilitation to restore physical readiness, a reduction in the numbers of soldiers ready for deployment, and substantial financial burdens for the organisation through direct and in-direct costs associated with injuries (Sherrard et al., 2004).

Simply reducing the external loads carried by soldiers would be the easiest solution, but not practical, especially as loads carried comprise essential equipment required to complete operational tasks that vary based on the threat of the environments. Therefore, the next, most viable solution is to reduce the gap between task demands and soldiers' physical capacity (Friedl et al., 2015). Recent evidence suggests using appropriate loading schemes within physical training that meet the specific occupational task demands (i.e., load carriage) could help adequately prepare military personnel for physical arduous roles (Coppack et al., 2011; Friedl et al., 2015; Sharma et al., 2014). Strength and aerobic fitness are key physiological components required to successfully meet load carriage task demands (Friedl et al., 2015), which can be trained through periodised resistance training.

As bans on females participation in combat-related occupations have been removed in the armies of developed nations, soldiers from mixed-sex platoons are required to complete the same physical training and physical employment standard tasks (Australian Defence Force). However, known differences in physical capacities between males and females (i.e., strength, power, and aerobic fitness) (Nindl et al., 2016) influence how well they perform crucial combat tasks (e.g., load carriage) (Brushøj et al., 2008; Groeller et al., 2015). These reduced capacities place females at a disadvantage compared to males, especially as loads carried in combat-related roles are often determined by occupational requirements regardless of sex, stature, or an individuals' physical capabilities (Knapik et al., 1997; Nindl, 2015).

Physical and neuromuscular adaptive responses to training have mainly been reported in males, with few studies focused on female-specific responses to physical training. Of the limited available research comparing sex-specific physical performance adaptations to training, it seems the same physical training stimulus may not elicit the same adaptive response for both sexes, and that females may require specific training to optimise their performance improvements (Varley-Campbell et al., 2018). Especially given studies consistently report that males generally outperform females in all tasks (Knapik et al., 2005; Yanovich et al., 2008), highlighting there is still an evident performance gap between sexes.

Biomechanical responses during load carriage completed under various conditions have been extensively reported within a male population, though few studies have investigated or reported the effects of external load carriage on mechanical joint work. Measuring such variables are important in understanding and determining the effects of load carriage on soldier performance and associated injury risks (Seay et al., 2014). Furthermore, it is still inconclusive how sex affects influences loaded gait biomechanics, as studies to date have shown equivocal findings (Krupenevich et al., 2015; Silder et al., 2013a). No research to date has explicitly examined sex-specific differences in physical, neuromuscular, and biomechanical adaptations in response to a physical training specifically designed for load carriage. Identifying and understanding potential differences in responses between males and females will provide an evidence-base to inform physical training in military organisations which has the potential to; 1) enable the development and implementation of tailored, sex-specific physical training programs for all serving military personnel, and 2) facilitate the successful integration of female soldiers into physically demanding combat roles.

The specific purposes of this thesis were to:

1. Design and implement an evidence-based physical training program to target the neuromuscular demands of load carriage tasks,
2. Examine neuromuscular and physical performance adaptations in response to a 10-week physical training program specific for load carriage in a male-only population,

3. Identify and quantify sex-specific neuromuscular and physical performance adaptations through comparatively analysing male and female data collected before, during, and after the same 10-week physical training program for load carriage,
4. Investigate lower limb biomechanical changes in a male-only population during a load carriage task, and in response to a 10-week physical training program,
5. Examine sex-specific lower limb biomechanical changes in response to the same 10-week physical training program during a standardised load carriage task, and
6. Investigate and characterise physiological and psychophysical responses during a standardised load carriage task in females, before and after 10 weeks of physical training.

The specific hypotheses of this thesis were:

1. Before training, knee joint moments will increase more over the 5 km load carriage marching task after training compared to before training,
2. After training, lower limb net joint powers will be maintained over the 5 km load carriage marching task after training compared to before training,
3. Improvements in physical performance tasks (i.e., strength, push-up and sit-up performance) will increase after training compared to before training,
4. Physical performance adaptations will be different between males and females,
5. Neuromuscular adaptations will be different between males and females,
6. Lower limb kinematic and kinetic responses will differ between males and females over the march duration and after training.

1.6. Thesis Objectives

To address these specific purposes a series of studies were designed and implemented, which resulted in five research papers. These individual studies are presented in this thesis as individual chapters.

Chapter 1. Provides a general introduction to the thesis topic, outlining the rationale for the research conducted and the evidence-based research used to design the targeted physical training program for load carriage used within this thesis.

Chapter 2. Details the methods used for data acquisition and processing for all studies included within this thesis. First, the chapter outlines an overview of the data collected, and associated analyses conducted for each study. General methods are subsequently detailed, with experimental chapters specifically detailing methods used within independent studies for physical performance and load carriage testing sessions.

Chapter 3. The first paper of this thesis provides findings that examined the physical performance adaptations of male civilian participants in response to a 10-week physical training program. Physical performance data were collected before, during, and after training. This chapter addresses the first and second specific purpose of this thesis and is published in the Journal of Strength and Conditioning Research (Wills, Saxby, Glassbrook, & Doyle, 2019a).

Chapter 4. The second paper in this thesis includes results from conducting direct comparisons of male and female neuromuscular and physical performance data. The implications of sex-specific adaptive responses were discussed, along with recommendations for the successful integration of females into combat-related roles. This chapter specifically addresses the first and third specific purposes of this thesis and has been submitted to the Journal of Science and Medicine in Sport (Wills, Saxby, Glassbrook, & Doyle, 2019).

Chapter 5. The third paper describes lower limb biomechanical changes in a male civilian population during load carriage, to understand the time-course implications of a prolonged load carriage task. Additionally, biomechanical changes in response to training were analysed to provide a greater understanding of external joint-level adaptations during load carriage. This chapter addresses the first and fourth specific purposes of this thesis and is published in the Journal of Biomechanics (Wills, Saxby, Lenton, & Doyle, 2019b).

Chapter 6. The fourth paper outlines sex-specific differences in adaptive gait during a load carriage task, expanding on the findings presented in chapter 5. Specifically, lower limb biomechanical variables were compared during a standardised load carriage task between male and female populations, before and after the same 10 weeks of physical training. This chapter addresses the first and fifth specific purposes of this thesis and has been submitted to the Journal of Biomechanics (Wills, Saxby, Lenton & Doyle, 2019).

Chapter 7. The fifth paper explores the physiological and psychophysical responses of females. Characterised variables provided a basis to discuss potential strategies that can further facilitate the integration of females into physically demanding combat-related roles. This chapter addresses the first and sixth specific purposes of this thesis and has been submitted to The Journal of Medicine and Science in Sports and Exercise (Wills, Drain, Fuller & Doyle, 2019).

Chapter 8. Findings from the five papers included within this thesis are summarised and discussed in relation to how these results can help improve load carriage performance for both males and females through implementing targeted physical training. Outcomes from chapters 3, 4, 5, 6, and 7 can be used to inform a future physical training programs for military personnel.

Chapter 2: Methods

2.1. Chapter Overview

The purpose of this chapter is to outline in detail the quantitative research design used to address the aims of this doctoral thesis research program. The five articles included in this thesis employed quantitative analysis methods (Table 1). The overall structure of the research design is first presented, followed by the specific methodology for data collection, interventions implemented, and the analyses conducted on all collected data.

Table 1. Methods and data included in articles.

Chapter	Data	Analysis
3	Original physical performance data were collected to determine neuromuscular responses before, mid-way, and after a 10-week physical training program. Psychophysical responses were also collected during a 5 km load carriage task completed before and after the 10 weeks of training.	Quantitative statistical analysis was completed on data collected in a civilian male population, representative of Army recruits (n=15). Specific analyses included a repeated-measures analysis of variances (ANOVA), one-way ANOVA, and paired t-tests to identify neuromuscular and psychophysical adaptive responses.
4	Original physical performance data collected for males and females to identify and compare sex-specific neuromuscular responses after 10 weeks of the same physical training. Psychophysical responses were also collected during a 5 km load carriage task completed before and after the 10 weeks of training.	Quantitative statistical analysis was used to identify and quantify potential sex-specific responses to the same physical training program, and during a standardised load carriage task. Male (n=13) and female (n=13) neuromuscular and psychophysical data were compared through conducting a mixed-design repeated-measures ANOVA and paired t-tests, respectively for performance outcome measures.
5	Original lower limb biomechanical data collected during a 5 km load carriage task completed before and after a 10-	Quantitative statistical analysis was completed using data collected from the same male participants (n=13) in Chapter

	week training program focused on strengthening the hip joint musculature. Lower limb three-dimensional and ground reaction force measures were acquired to assess joint-level responses.	3. Experimental data were inputted into a computational musculoskeletal model to calculate inverse kinematics and inverse dynamics, and was subsequently used to estimate joint angles, joint angular velocities, and moments.
6	Original lower limb biomechanical data collected for male and females during a 5 km load carriage task. Adaptive responses in gait mechanics were assessed before and after the same 10-week training program focused on strengthening the hip joint musculature.	Quantitative statistical analysis was used to identify and quantify potential sex-specific responses during a standardised load carriage task. Male (n=13) and female (n=12) civilian data were analysed using a two-way repeated measures ANOVA with sex as a between-subject factor and load as a within-subject factor.
7	Original experimental data collected in a female population during a 5 km load carriage task to assess physiological and physical performance responses before and after 10 weeks of physical training.	Quantitative statistical analysis was completed using data collected from civilian females (n=11), representative of Army recruits. Paired samples t-tests were conducted on performance variables to assess differences in physical performance before, mid-way, and after 10 weeks of training.

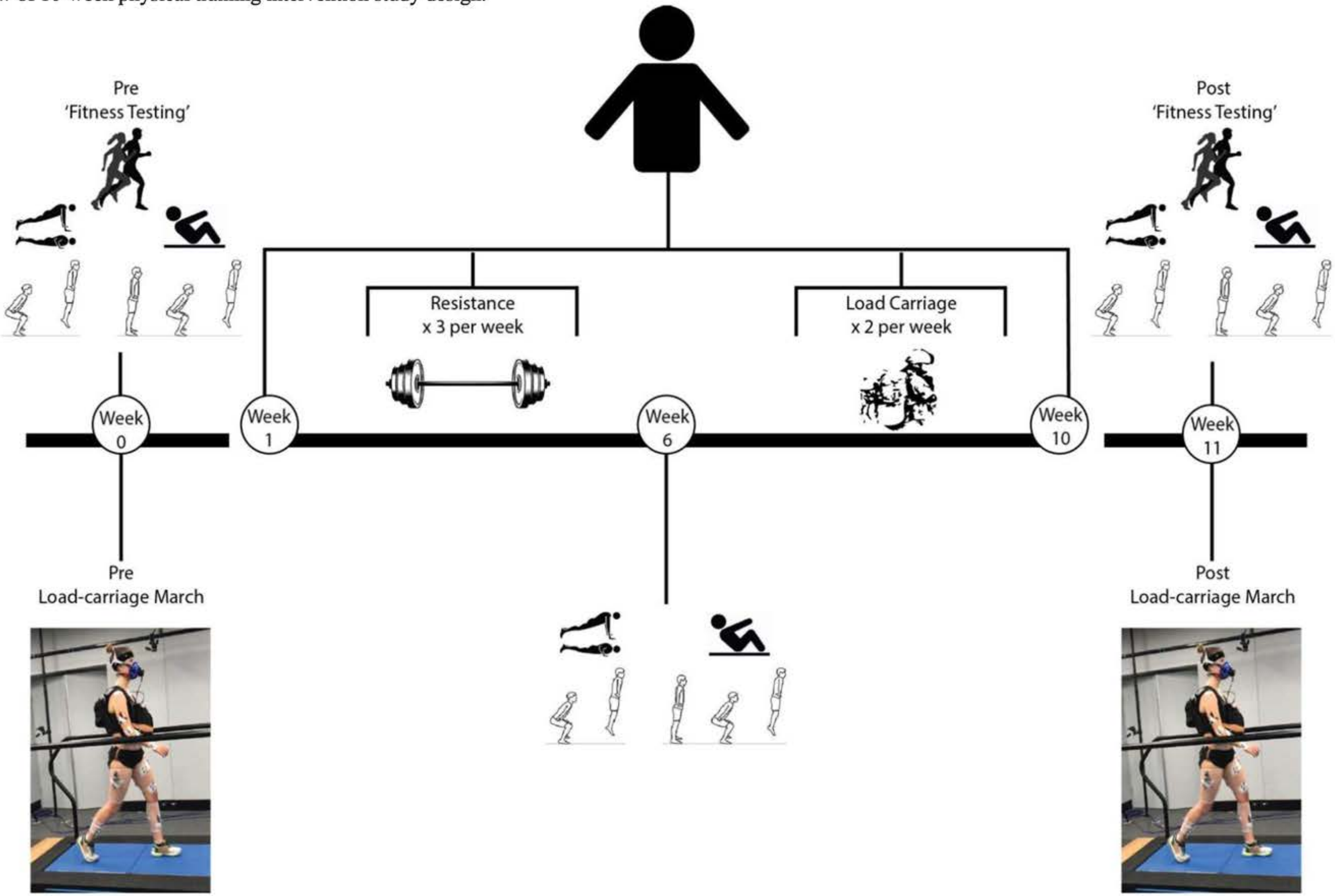
2.2. Methodological Approach

Prior to study enrolment, participants attended a single session ('fitness' testing) to assess study eligibility based on pre-defined inclusion criteria, which included matching or exceeding: a minimum of 70 sit-ups and 40 push-ups minimum of 21 push-ups for females) in 2 minutes each, or and a minimum of level 7.5 on the beep test. Additional inclusion criteria required a body mass of $\geq$ 73 kg for males (Mullins et al., 2015) and $\geq$ 55 kg for females (Lidstone et al., 2017). Participants who met or exceeded these criteria were deemed eligible for study participation and were invited to undertake additional testing procedures. Subsequent tests within the same session included neuromuscular performance measurements of maximal strength and power (including isometric mid-thigh pull, countermovement jumps, and squat jumps). Upon completion of all testing procedures, participants completed a five-minute load carriage walking task to become familiar with the donned weight (23 kg) to be carried on the torso during the main laboratory testing session. Procedures were conducted before, mid-way, and after (week 0, week 6, week 11, respectively) a 10-week physical training program intervention (Figure 2).

On a separate day to fitness testing, participants attended a laboratory testing session where they were required to complete a load carriage walking task (5 km march at 5.5 $km \cdot h^{-1}$) wearing 23 kg torso-borne weight (Figure 1). Prior to treadmill walking, static standing calibration and pointer trials were acquired to measure three-dimensional positions of markers, which were later used to define joint centres and track segments during dynamic tasks. Dynamic walking trials were conducted at the beginning (0 km) and at the end (5 km) of the load carriage task to acquire three-dimensional kinematic and kinetic data. Data were pre-processed using open-source custom biomechanical software (Mantoan et al., 2015) prior to data being applied to a generic, full-body OpenSim musculoskeletal model (created for each individual participant) (Rajagopal et al., 2016) which was scaled to determine lower limb inverse kinematics and inverse dynamics, respectively. Laboratory testing procedures were conducted before, and upon completion of a 10-week physical training program intervention, on a separate day to fitness testing procedures (Figure 2).

Figure 1. Weighted vest (IronEdge, Power Vest) used during the load carriage march.

Figure 2. Overview of 10-week physical training intervention study design.



2.2.1. Participants

Fifteen males (age 22.6 ± 1.5 years, height 1.82 ± 0.06 m, body mass 84.1 ± 6.9 kg) and thirteen females (age 21.3 ± 2.0 years, height 1.66 ± 0.08 m, body mass 64.2 ± 6.0 kg) were recruited to participate. All participants were recreationally active civilians and representative of a military recruit population. Prior to testing all twenty-eight participants were screened for pre-existing musculoskeletal injury or recent (< 6 months) acute or chronic injuries (verified via the adult pre-exercise screening tool using the Exercise Sports Science Australia (ESSA, see appendix 7) that were likely to impact walking or load carriage performance. Previous experience with load carriage was not required. Participants provided their written informed consent to the protocol. All research conducted was approved by Macquarie University Human Research Ethics Committee (Protocol numbers: 5201700406; 5201826834691).

2.2.2. Physical Performance Measures

2.2.2.1. Procedures

Inclusion criteria required participants to meet or exceed the current Basic Fitness Assessment (BFA) standards required of male (≤ 25 years old) and female soldiers (18-30 years old) in the Australian Army (Australian Defence Force) (Table 2). This ensured included participants were representative of Australian Army recruits to allow for generalisability of the research findings to this population. The ESSA pre-screening exercise tool was completed to screen participant suitability to identify pre-existing musculoskeletal injuries, which if disclosed would result in study exclusion to reduce injury risks.

Table 2. Australian Army Basic Fitness Assessment (BFA) standards required of male and female soldiers (adapted from Australian Defence Force).

	Male	**Female**	
Age	17-25	17-25	26-30
Push-ups	40	21	18
Sit-ups	70	70	65
Beep Test	7.5	7.5	7.5

The order of testing is outlined in Table 3 below. As all physical performance tests conducted were similar to common tasks (i.e., jumping, running, etc.) no familiarisation for procedures was provided. Upon completion of all testing procedures, participants undertook a 55-minute loaded walk carrying the weighted vest in the that was used in the subsequent main laboratory testing session in order to become familiar with the load carriage walking task procedure.

Table 3. Testing order of measured variables at pre, mid, and post-test time points.

	Pre-Test	**Mid-Test**	**Post-Test**
	Week 0	Week 6	Week 11
Fitness Testing			
1	CMJ	CMJ	CMJ
2	SJ	SJ	SJ
3	PU	IMTP*	PU
4	SU	PU	SU
5	Beep	SU	Beep
Laboratory			
1	IMTP*	**N/A**	IMTP*
2	HR	**N/A**	HR
3	RPE	**N/A**	RPE

CMJ, countermovement jump; **SJ**, squat jump; **PU**, push-ups; **SU**, sit-ups; **Beep**, beep test; **IMTP**, isometric mid-thigh pull; **HR**, heart rate; **RPE**, rating of perceived exertion.; **N/A**, not applicable as no data was collected.
* indicates data collected for a female-only population.

2.2.2.1.1. Push-ups

Push-up performance was determined by the maximal number of repetitions participants completed within two-minutes. The starting position required participants to establish a prone position with the feet shoulder width apart, the back straight, and arms in a locked-out position. A repetition was deemed successful and was counted when the participant descended from the start position until the elbows reached a 90° angle, and the upper arm was parallel with the ground, and returned to the start position (Australian Defence Force). Participants were able to take a rest throughout the two-minutes but were required to remain in the starting position during any rest period taken.

2.2.2.1.2. Sit-ups

Sit-up performance was determined by the maximal number of repetitions participants completed within two-minutes. Participants laid down in a prone position, with their knees flexed at a 90° angle, and feet flat on the floor. Anchored support at the feet was provided during the test and participants were required to keep their arms extended throughout. A repetition was counted when participants raised their body until the wrists reached the top of the knees and returned in a downward motion until the shoulder blades touched the floor. A repetition was not counted when participants broke contact between the hands and thighs, or when the shoulder blades did not reach floor contact during the downward motion of the sit-up (Australian Defence Force). Participants were able to take rest throughout the two-minute period whilst remaining laid down.

2.2.2.1.3. Jump Performance

Jump performance was measured using countermovement and squat jump to measure lower limb maximal power and lower limb strength (maximum force produced prior to take-off), respectively.

2.2.2.1.3.1. Countermovement Jump

Countermovement jumps (CMJ) were collected using a portable force plate (400-series, Fitness Technology, Adelaide, SA, Australia) with a linear position transducer attached to a lightweight wooden bar held across participants' shoulders. The lightweight wooden bar was placed across the shoulders to eliminate arm swing and to isolate the contribution of the lower body (Heishman et al., 2018). Consistent with previous research, participants stood still on the force plate for one second before the cue was given to jump (Owen, Watkins, Kilduff, Bevan, & Bennett, 2014), allowing for correct body mass measurement. Participants commenced the movement in an upright standing position, and performed a downward movement once cued by flexing at the knees and hips (self–selected depth), followed by immediately extending the knees and hips again to jump vertically upwards off the ground. Participants were instructed to execute the movement in one continuous motion to jump as high as possible. Each participant performed three maximum effort jumps, each separated by a one-minute rest. Force-time data for were collected using Ballistic Measurement System Software (Innervations, Perth, WA, Australia) and were analysed using the Advanced Jump Analysis Package (TLAD Solutions, Sydney, NSW, Australia). The maximum absolute peak power output value was extracted and used for statistical analysis of lower limb power (Cormack, Newton, McGuigan, & Doyle, 2008).The maximal absolute force output value was extracted and used for statistical analysis as a surrogate measure of lower limb strength.

2.2.2.1.3.2. Squat Jump

Squat jumps (SJ) were conducted similarly to countermovement jumps except participants were required to commence the movement in a semi-squat position. Participants were then instructed to hold the position for several seconds (3-5 seconds) before being provided a cue to perform the concentric phase of the jump, pushing away from the floor in one continuous motion to achieve maximal jump height. Each participant performed three maximum effort jumps, each separated by a one-minute rest. Force-time data were collected using Ballistic Measurement System Software (Innervations, Perth, WA, Australia) and were analysed using the Advanced Jump Analysis Package (TLAD Solutions, Sydney, NSW, Australia). The maximum absolute peak power output value was extracted and used for statistical analysis of lower limb power (Cormack et al., 2008). The maximal absolute force output value was extracted and used for statistical analysis as a surrogate measure of lower limb strength.

2.2.2.1.4. Isometric Mid-Thigh Pull

Isometric mid-thigh pull (IMTP) data collection was completed for the female population only. IMTP measures were conducted using a portable force plate (400-series, Fitness Technology, Adelaide, SA, Australia) and a Fitness Technology IMTP rack (FT700 Ballistic Measurement System, Fitness Technology, Adelaide, Australia) that allows the fixation of the bar at any height. Participants were instructed to stand on the force plate with the knees slightly bent at mid-thigh position (mid-point between the top of the patella and iliac crest, adjusted for each individual). The mid-thigh position is commonly used to measure maximal lower limb strength (Beckham et al., 2017; Haff et al., 2005) as it corresponds with the portion of weightlifting movements that are associated with producing peak forces (Haff et al., 1997). Knee and hip flexion angle ranges were maintained between 130-150° (measured using a goniometer) when determining bar height (Beckham et al., 2017; Comfort, Jones, McMahon, & Newton, 2015). Once the bar height was set it was recorded and maintained for the all conducted testing sessions. Participants' bar grip was assisted by weightlifting straps. Once in position, and data collection had commenced, participants were required to stand completely still for 1-2 seconds in order to acquire a minimum baseline measure. Participants were further instructed to use minimal pre-tension to ensure there was limited amounts of slack in the participants body prior to pull initiation (Beckham et al., 2017). Immediately following this, participants received a countdown to begin the test before receiving a cue to 'pull'. Additional external verbal cues including "push your feet through the floor" and "pull maximally up on the bar" were given to ensure maximal force production was achieved (Halperin, Williams, Martin, & Chapman, 2016). Each participant performed between 3-5 maximum efforts with one-two minutes rest between each repetition.

2.2.3. Physical Training Program Intervention

The physical training program was designed using an evidence-based approach. Previous research has identified that approximately 65 % of positive power is generated by the hip during load carriage walking, followed by the ankle (25 %), and knee (10 %). Shifting power production to proximal joints increases the work performed by the hip musculature and increase active work by hip-spanning muscles due to the muscle-tendon architecture (Neptune, McGowan, & Kautz, 2009). The shift towards a hip-dominated strategy during load carriage tasks reduces the reliance on knee musculature to produce positive work/power (Blacker, Fallowfield, Bilzon, & Willems, 2013; Teng & Powers, 2014, 2016). This strategy further assists in facilitating reductions in knee stress and loading, which is the most commonly injured site for army personnel (Department of Defence, 2000). Using this evidence-base, a physical training program was designed to strengthen the hip musculature to enhance load carriage performance.

Participants completed all physical training session at the Macquarie University Sport and Aquatic Centre. The 10-week training program was designed using a linear periodisation approach and consisted of up to three resistance-based (weight) training sessions and two weighted walking sessions (walking with a weighted vest to simulate load carriage specific tasks) per week. Table 4 outlines the resistance training program and Table 5 outlines the weighted walking training program. Weekly compliance of session completion and session data (i.e., weight lifted, repetitions and sets completed, and any additional notes required) was tracked and reported for each participant.

2.2.3.1. Resistance Training Sessions

The initial 2 weeks of resistance-based training sessions were used for familiarisation purposes and to progressively increase volume, ensuring technique instruction and assessment of individual abilities allowing for specific load prescription for each participant. Participants were supervised by a minimum level one Australian Strength and Conditioning Association (ASCA) Coach for all resistance-based training sessions throughout the 10-week program. Exercise resistance incrementally increased weekly if participants successfully completed the required number of repetitions and sets for individual exercises (Table 4). If participants were unable to perform the required repetitions, the number of repetitions performed was recorded and the resistance was adjusted accordingly.

2.2.3.2. Load Carriage Training Sessions

Participants complete load carriage conditioning training sessions were completed up to twice per week, depending upon the loading or de-loading phase of the program. Weighted walking sessions were self-directed on a separate day to the resistance training sessions, with load, distance, and speed incrementally increasing over the 10-week training program from 0 kg to 25 kg, 3 km to 6 km, and 4 $km \cdot h^{-1}$ to 6 $km \cdot h^{-1}$, respectively (Table 5).

Table 4. Evidence-based 10-week physical training program for resistance-based training sessions.

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
1	Squat	3	8-10	120	Deadlift	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Curls	3	8-10	120	Leg Curls	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Seated Row	3	8-10	120	Bench Pull	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Bench Press	3	8-10	120	Bench Press	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	20	0	Leg Raises	1	20	0	**NA**	**NA**	**NA**	**NA**
2	Squat	4	8-10	120	Deadlift	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Curls	4	8-10	120	Leg Curls	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Seated Row	4	8-10	120	Bench Pull	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Bench Press	4	8-10	120	Bench Press	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Face Pulls	4	8-10	120	Face Pulls	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	20	0	Leg Raises	1	20	0	**NA**	**NA**	**NA**	**NA**
3	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	30	120	Upright Rows	3	8-10	120	Hyperextensions	1	30	120
	Leg Raises	1	30	0	Crunches	1	30	0	Leg Raises	1	30	0

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
4	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	40	120	Upright Rows	3	8-10	120	Hyperextensions	1	40	120
	Leg Raises	1	40	0	Crunches	1	30	0	Leg Raises	1	40	0
5	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	50	120	Upright Rows	3	8-10	120	Hyperextensions	1	50	120
	Leg Raises	1	50	0	Crunches	1	50	0	Leg Raises	1	50	0
6	Hip Thrusts	3	5	120	Bench Pull	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Deadlift	3	5	120	Bench Press	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Curls	3	8-10	120	Face Pulls	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	KB Step-ups (alternating)	5	10	120	¾ Lat Pulldowns	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	50	120	Upright Rows	3	8-10	120	**NA**	**NA**	**NA**	**NA**

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
	Leg Raises	1	50	0	Crunches	1	50	0	**NA**	**NA**	**NA**	**NA**
7	Squats	5	5	120	Bent-over Rows	5	6-8	120	Deadlift	5	5	120
	Hip Thrusts	5	5	120	45-degree TRX Flyes	3	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	3	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	3	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0
8	Squats	5	5	120	Bent-over Rows	5	6-8	120	Squats	5	5	120
	Hip Thrusts	5	5	120	45-degree TRX Flyes	4	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	4	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	4	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	4	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	50	0	Bicycles	1	60 (s)	0	Roman Twists	1	50	0
9	Squats	5	5	120	Bent-over Rows	5	5	120	Squats	5	5	120
	Hip Thrusts	5	5	120	45-degree TRX Flyes	5	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	5	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	5	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	4	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	50	120

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
	Roman Twists	1	50	0	Bicycles	1	60 (s)	0	Roman Twists	1	50	0
10	Squats	3	5	120	Bent-over Rows	5	5	120	Squats	3	5	120
	Hip Thrusts	3	5	120	45-degree TRX Flyes	5	10	120	Hip Thrusts	3	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	3	10-15	120	Chin Ups	5	10 5**	120	Overhead Plates Walks	3	10-15	120
	Hyperextensions	1	40	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	40	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0

Reps, repetitions; **s**, seconds of recovery; **KB**, Kettlebell. **NA**, no session implemented; *Indicates 5 repetitions per leg were completed, **indicates the number of repetitions completed during the final set only.

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Table 5. Evidence-based 10-week physical training program for load carriage training sessions.

Week	Session	Acute Variables		
		Distance (km)	Speed (5.5 km·h-1)	Load (kg)
1	1	3	4	0
	2	0	0	0
2	1	4	4	0
	2	3	4	0
3	1	4	5	0
	2	4	4	5
4	1	5	5	5
	2	5	5	5
5	1	5	6	5
	2	0	0	0
6	1	5	6	10
	2	5	6	12.5
7	1	5	6	15
	2	5	6	17.5
8	1	6	6	20
	2	0	0	0
9	1	6	6	20
	2	5	6	25
10	1	6	6	25
	2	0	0	0

km, kilometres; **km·h-1**, kilometres per hour; **kg**, kilograms.

2.2.4. Biomechanical Measures

2.2.4.1. Procedures

All biomechanical testing procedures were completed at the Simulation Hub laboratory at Macquarie University. Participants completed a standardised treadmill walking task of 5 km at 5.5 km·h-1, wearing a 23 kg torso-borne vest before and after the 10-week training program. The load carriage task is equivalent to the Australian Army All Corps minimum employment standard (Australian Defence Force). For testing, participants were asked to wear black, non-reflective clothing and wore their own footwear (standard athletic trainers).

Prior to participant arrival the Vicon Nexus three-dimensional motion capture eight-camera system was calibrated to match an image error of ≤ 0.20. Camera calibration determines the capture volume to the system, enabling the production of accurate three-dimensional data.

During camera calibration, a 'calibration parameters' (.xcp) file was created, containing calibration settings and threshold data specified for the camera system. This data was subsequently used for subsequent data cleaning and processing within Nexus software.

2.2.4.1.1. Kinematic Measures

Upon arrival at the laboratory, spherical, 14 mm diameter retro-reflective markers, and marker clusters were placed on various anatomical locations of participants (Figure 3) to enable the collection of three-dimensional motion data. Markers were placed on the trunk, and bilaterally on the head, arms, legs, and feet (Table 6) of participants according to previously developed and validated marker set (Lenton, Doyle, Saxby, & Lloyd, 2017). A standing calibration trial was then captured with participants in a standardised base pose (i.e., an anatomically neutral pose) as demonstrated in Figure 3.

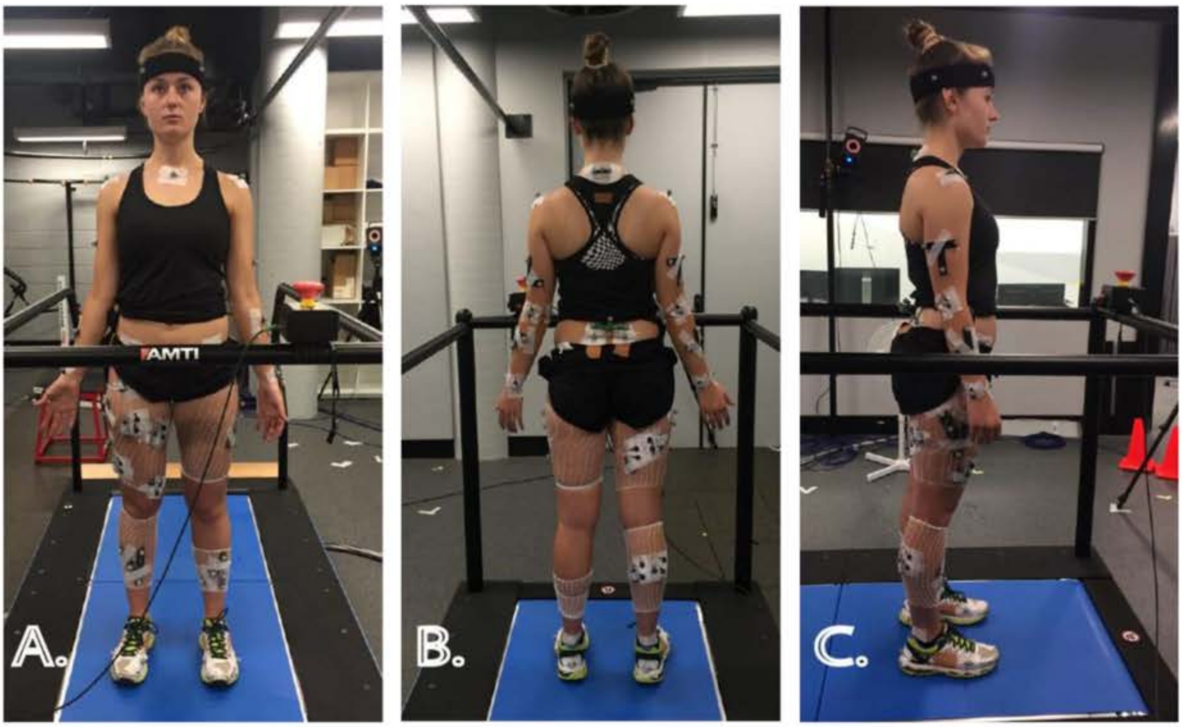

Figure 3. Anatomical position held during static and virtual marker trials is represented via: A.) Frontal view of anatomical position, B.) Posterior view of anatomical position, C.) Lateral view of anatomical position.

Table 6. Anatomical positions of markers used for three-dimensional motion capture (individual, clusters and virtual markers).

Anatomical Locations		Description	Identification
Head	L/R FHD	Front of the head	Marker
	L/R BHD	Back of the head	Marker
Upper body	L/R ACR	Single marker on the acromion process	Marker
	L/R UA1-4	Rigid cluster of 4 markers on the proximal upper extremity	Cluster
	L/R LEL	Lateral epicondyle of the humerus	Pointer
	L/R MEL	Medial epicondyle of the humerus	Pointer
	L/R FA1-3	Rigid cluster of 3 markers on the forearm	Cluster
	L/R WRR	Wrist radial side	Pointer
	L/R WRU	Wrist ulna side	Pointer
Thorax	NOTCH	Jugular notch on manubrium	Pointer
	C7 1-3	Rigid cluster of 3 markers attached to the C7 spinous process	Cluster
	T10	Spinous process of the 10_{th} Thoracic vertebra	Pointer
Pelvis	SAC1-4	Rigid cluster of 4 markers projecting from the sacrum	Cluster
	L/R ASI	Most prominent point of the anterior superior iliac spine	Pointer
	L/R PSI	Most prominent point of posterior superior iliac spine	Pointer
Lower body	L/R TH1-4	Rigid cluster of 4 markers on the thigh	Cluster
	L/R LFC	Lateral femoral epicondyles	Pointer
	L/R MFC	Medial femoral epicondyles	Pointer
	L/R TB1-4	Rigid cluster of 4 markers on the tibia	Cluster
	L/R LMAL	Lateral malleolus	Pointer
	L/R MMAL	Medial malleolus	Pointer
Feet	L/R CAL	Calcaneus	Marker
	L/R MTP1	Head of the 1_{st} metatarsal	Marker
	L/R MTP5	Head of the 5_{th} metatarsal	Marker

*L/R representative of left and right sides of the body respectively.

A second calibration trial was captured to define virtual marker positions using the tip of a 6-marker 'pointer' calibration wand of known dimensions (see Figure 4). Static standing calibration and pointer wand trials were used to define three-dimensional marker positions at 24 anatomic landmarks (Table 6, Figure 5) through using the wand's technical coordinate frame and a known offset between the handle and tip markers. Data were collected with the experimenter holding the wand with the tip placed on the allocated anatomical location for a minimum of one frame per landmark. Marker positions were later used to define joint centres and to track body segments during the load carriage dynamic walking task.

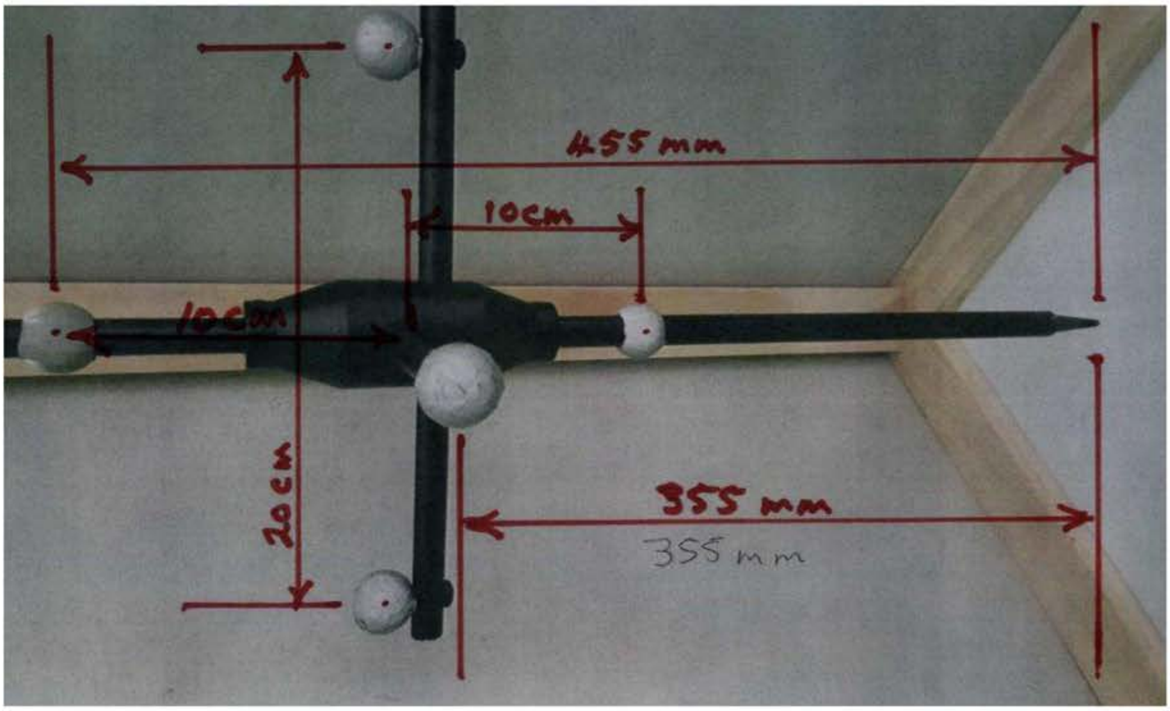

Figure 4. Six-marker 'pointer' calibration wand used for defining virtual marker locations during the static calibration trial (including known dimensions).

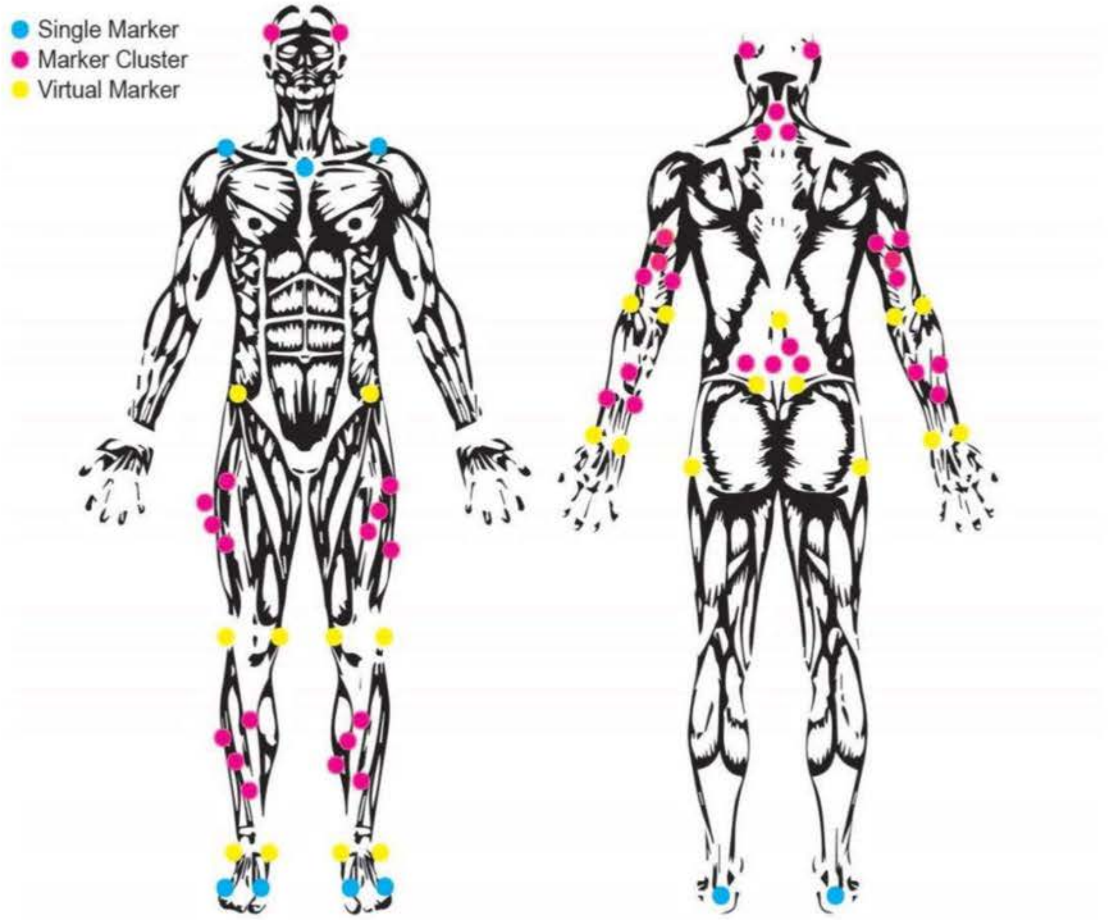

Figure 5. Schematic representation of marker placement. Pink markers represent markers on a cluster, blue markers are single markers, and yellow markers were defined using the pointer.

2.2.4.1.2. Kinetic Measures

During the load carriage task, marker trajectories (sampled at 100 Hz) and GRFs (sampled at 1000 Hz) data were concurrently and synchronously acquired. A limitation within this section of the protocol was that kinetic data (via GRFs) were collected differently between male and female populations. GRFs were collected using an in-ground force plate via overground walking trials (Type 9281E, Kistler, Germany) for the male population, whereas, GRFs for the female population were collected using a force-instrumented treadmill (AMTI, Watertown, MA, USA). This was due to acquisition of the instrumented treadmill after the male data collection period commenced. Riley, Paolini, Della Croce, Paylo, and Kerrigan (2007) identified only small differences in kinematic and kinetic parameters when overground and treadmill gait protocols were evaluated. However, the magnitude of differences found between protocols fall within variability ranges that are classified as accepted thresholds within normal gait parameters (Lee, Yoon, & Shin, 2017; Riley et al., 2007). Such findings suggest the mechanics of overground and treadmill-based protocols are adequately similar, demonstrating the equivalence kinematic and kinetic data quality for comparison between male and female populations within the current thesis.

2.2.4.1.2.1. Over-Ground Walking Protocol

Kinetic data collection for the male population required ten successful over-ground walking trials to be completed immediately before (pre-walk, 0 km), and immediately after (post-walk, 5 km) the 5 km load carriage walking task (< 3 minutes lapse between treadmill to over-ground transition). Prior to walking trials, participants were randomly allocated either their left or right limb to strike the in-ground force plates. To ensure this did not influence foot strike mechanics (e.g., targeting), participants were informed to take their initial step with the randomly allocated limb. During the trials, GRFs were collected using an in-ground force plate (Type 9281E, Kistler, Germany), sampling at 1000 Hz. Trials were deemed successful if the participant: (i) struck the force plate cleanly, (ii) struck the force plate with the randomly allocated left or right limb, and (iii) walked at a speed of 5.5 $km \cdot h^{-1} \pm 0.1$ %. Walking speed was monitored using a portable timing gate system (Kinematic Measurement System, Fitness Technology, Adelaide, SA, Australia).

2.2.4.1.2.2. Force-Instrumented Treadmill Walking Protocol

Kinetic data for the female population were collected by capturing 30 seconds of data (average of 10-30 gait cycles used for analysis) at the start (0 km) and the end (5 km) of the load carriage task, collecting GRFs via the treadmill embedded force plates (AMTI, Watertown, MA, USA). Walking speed during the load carriage task was fixed at 5.5 $km \cdot h^{-1}$ via the AMTI Treadmill Control Software (Version 3.1.2). Prior to testing, each participant was randomly allocated either their left or right limb in order to randomise individual gait cycles for post-data extraction and analysis, aligning with protocols used for the male population.

2.2.4.2. Data Analysis

Vicon Nexus (Vicon, Oxford, UK) was used to pre-process all raw three-dimensional motion capture data collected during load carriage overground and treadmill walking trial sessions. Pre-processing included cleaning data and gap filling missing marker trajectories using a cubic spline interpolation method. Raw marker trajectories from static and dynamic trials were reconstructed using a custom-built labelling template and were cleaned using Vicon Nexus (version 2.8.1). For dynamic trials, marker gaps (< 10 frames) were interpolated using cubic splines. Cleaned trials were then exported to Matlab (R2017b, The Mathworks, Math Works, USA) and processed using a custom implementation of biomechanical processing software (Mantoan et al., 2015).

2.2.4.3. Determination of Kinetic and Kinematic Variables

Lower limb joint centres were defined from static calibration trials using Harrington regression equations (Harrington, Zavatsky, Lawson, Yuan, & Theologis, 2007) at the hip, and the midpoint of the medial and lateral femoral condyles and malleoli at the knee and ankle, respectively. For over-ground walking trials, a single gait cycle per successful trial was determined using the vertical ground reaction force data of the foot in contact with the plate, with the detection threshold set to 20 N for both heel-strike and toe-off. Spatial-temporal and angular variables were determined using a velocity-based algorithm (Zeni, Richards, & Higginson, 2008). Gait events of heel strike and toe off were automatically detected using changes in the direction of velocity of heel and toe markers. Marker trajectories and GRFs were filtered using a 4th order zero-lag (Robertson & Dowling, 2003) Butterworth low-pass filter, with a 10 Hz cut off.

For males, results were derived from the average of 10 overground trials. For females, data were acquired during treadmill walking trials including marker positions and GRFs during a 30 second collection at the beginning and end of the 5 km load carriage walking task. Ensemble-averaged data for a minimum of 10 gait cycles (ranging between 10-30 gait cycles) from each 30 second collection were created for each participant. Aligned with the analysis of over-ground walking trials, marker trajectories and GRFs were filtered using a 4th order zero-lag (Robertson & Dowling, 2003) Butterworth low-pass filter, with a 10 Hz cut off. Marker position data for over-ground and treadmill walking trials were subsequently transformed from the laboratory coordinate system to the global coordinate system used within OpenSim (Delp et al., 2007).

2.2.4.4. Data Processing Workflow

An open-source MOtoNMS pipeline (Figure 6) was used to convert pre-processed GRFs and marker trajectories contained in exported C3D files to an OpenSim format (.c3d to .trc, and .mot respectively) via Matlab (R2017b, The Mathworks, Math Works, USA). Initial data post-processing steps required C3D files to be converted to Matlab format (.mat files) to enable future processing. The static interface pipeline outputted static acquisition (static.xml) and marker trajectory files (static.trc) for scaling use within OpenSim. Static files within this interface were modified to match the marker set specified for the current testing protocol and implemented the method used to determine hip, knee, and ankle joints (Harrington et al., 2007). Acquisition interface set-up files were adapted to match the desired laboratory set up (e.g., the number of force plates used and the motion capture system coordinate orientation) and the marker set used within all data collection trials. The laboratory orientation was defined such that the direction of walking aligned with the positive x-axis, the positive y-axis aligned with the medio-lateral direction, and the positive z-axis pointed vertically. GRFs and marker trajectory data were filtered using a 4th order low-pass Butterworth filter (10 Hz cut-off frequency), in addition to defining the analysis window from pre-determined gait events stored within C3D files. Once all data processing is completed, converted .trc, .mot and static.trc files were used as input files for the neuromuscular skeletal modelling in OpenSim (Figure 6).

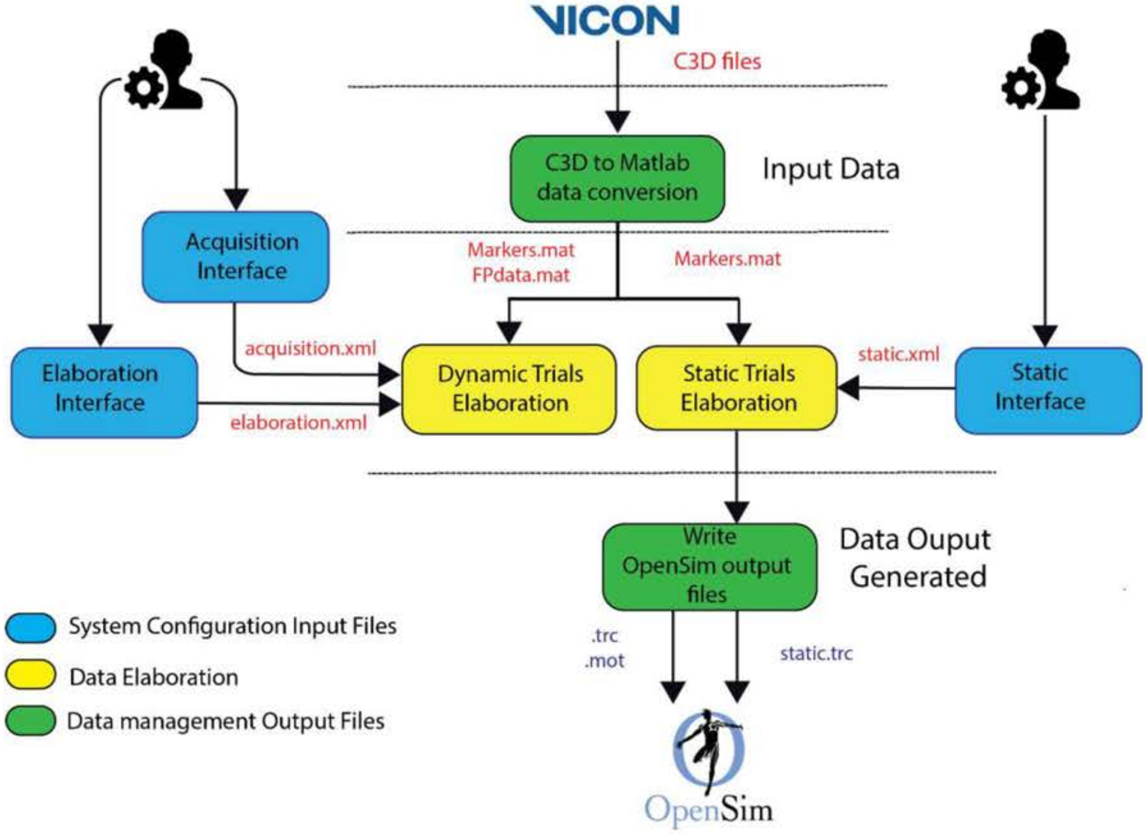

Figure 6. Adapted schematic of MOtoNMS pipeline used for processing and analysis of all experimental data (Mantoan et al., 2015).

2.2.4.5. Neuromusculoskeletal Modelling

OpenSim software was used to analyse all experimental data (Delp et al., 2007). A generic, full-body musculoskeletal model was created for each participant (Rajagopal et al., 2016), including 11 body segments with 29 degrees of freedom used to represent the arms, torso, pelvis, and the lower extremity. The model comprises three rotational degrees of freedom (DOF) for the hip, one DOF for the knee, and one DOF for the ankle. At the knee joint, abduction/adduction and internal/external rotations were prescribed as a function of knee flexion angle. Generic models were scaled using marker pairs on each body within the model to match the gross anatomy, mass, and inertia of each participant to obtain accurate kinematic and kinetic outputs from the model. Relative marker distances collected from experimental data were used to proportionally scale model bodies and muscle-tendon parameters (i.e., the shank segment was scaled via the lateral femoral epicondyle and lateral malleoli markers). Scaled models were then used to determine model kinematics and kinetics using inverse kinematics (Reinbolt et al., 2005) and inverse dynamics (Delp et al., 2007).

Peak joint angles, joint ROM, and joint angle waveforms were derived via inverse kinematics calculations through using the participant-specific model and experimental marker data. The inverse kinematics algorithm solved trunk, pelvis, hip, knee, and ankle joint angles through placing the participant-specific model within a configuration which closely matches (i.e., in a least-squares sense) the experimental data at each frame of motion recorded. Model kinematic and experimental GRFs data were used as inputs for the inverse dynamics algorithm where joint moment calculations in the sagittal, frontal, and transverse planes of the left and right hip, knee, and ankle joints were calculated.

From the inverse kinematics and inverse dynamics analyses, joint angular velocities and moments were used to determine hip, knee, and ankle joint powers, which were normalised to each participant's body mass ($W \cdot kg^{-1}$). Hip, knee, and ankle powers were calculated and represented by instantaneous joint power curves which were split into positive (energy generation) and negative (energy absorption) phases throughout the gait cycle (Winter, 1983). From these defined phases, positive and negative joint work ($J \cdot kg^{-1}$) were calculated through numerical integration of the instantaneous joint power curves. The sum of positive and negative hip, knee, and ankle joint work determined total positive (W_j^+) and negative (W_j^-) limb work. Individual joint contributions towards total positive work (W_{tot}^+) and total negative work (W_{tot}^-), throughout the gait cycle were identified through expressing W_j^+ and W_j^- as a percentage of W_{tot}^+ and W_{tot}^-, respectively.

2.2.5. Physiological Measures

2.2.5.1. Procedures

During the load carriage task, all participants were fitted with a heart rate (HR) monitor around the chest and a weighted vest (torso borne, evenly distributed) after static biomechanical trials were completed. Female participants were further fitted with a portable oxygen uptake ($\dot{V}O_2$) monitoring system to collect data associated with cardiovascular responses throughout the task. Prior to, and throughout the load carriage task, these measures, HR, and subjective measures of participants perceived exertion were collected.

2.2.5.1.1. Cardiovascular Measures

Data were collected using a portable oxygen uptake ($\dot{V}O_2$) monitoring system that wirelessly transferred live data via Bluetooth transmission (COSMED K5, COSMED, Italy). After a minimum of 20 minutes of the device warming up, the recommended manufacturer calibrations were performed (flowmeter, scrubber, reference gas calibration, and delay time). Flowmeter calibration involves injecting a known amount of air (3-litre calibration syringe) through the flowmeter in order to calculate and adjust inspector and expiratory gain factor values. Following this, the scrubber calibration was performed to detect the environmental air composition, and to zero the CO_2 analyser of the COSMED K5 system. The O_2 and CO_2 component analysers were calibrated using reference gases of known concentrations (16 % O_2, 5 % CO_2) to determine and calculate correction factors for each gas analyser, adjust dynamic ranges for O_2 values, and sensor outputs.

Prior to the load carriage walking task, participants were required to complete a delay calibration protocol as data were being collected via the breath-by-breath mode (BxB). Data were collected in this mode as it is more accurate in measuring metabolic data during low intensity exercise modalities (< 6 $km \cdot h^{-1}$) (Perez-Suarez et al., 2018). The BxB calibration protocol required participants to breath into the face mask maintaining a regular breathing rate (prompted by audible sounds created by the COSMED K5 system), to enable the time alignment of flow, O_2, and CO_2 sensors (delay = transport time + analyser response time).

The body-mounted elements of the system were included in the total external load carried and consisted of the COSMED K5 portable unit, a face mask (covering the mouth and nose), and a connecting sample and flow line. System elements were fitted immediately after the delay calibration, after which the participants commended their load carriage walking task. Data epochs were recorded every 5 minutes via COSMED OMNIA Software (Version 1.6.5) to enable collection of measures including oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER), and pulmonary ventilation ($\dot{V}_E$).

2.2.5.1.2. Rating of Perceived Exertion

The rating of perceived exertion (RPE) scale is a subjective measure that measures individual's perception of the intensity of exercise being undertaken. RPE was collected at 5-minute intervals during the load carriage treadmill walking task (0-55 minutes) using a

Borg scale (Borg, 1998) with a range of 6-20 (with 6 being no exertion at all, and 20 being maximum effort).

2.2.5.1.3. Heart Rate

HR responses were collected via using a chest mounted heart rate monitor (Polar, NSW, Australia) collected at 5-minute intervals during the load carriage treadmill walking task.

2.2.5.1.4. Beep Test

A multi-stage fitness test was used to determine estimated maximal oxygen uptake. Participants ran between two parallel lines set 20 m apart and were required to reach the lines prior to the subsequent beep. Participants were required to maintain the allocated speed as prescribed by the beeps until failure. The last successful completed shuttle within each stage was recorded and used to calculate estimated maximal oxygen uptake (Ramsbottom, Brewer, & Williams, 1988).

2.2.5.2. Data Processing

Cardiovascular data were collected within the COSMED OMNIA Software (Version 1.6.5) and raw data were exported to .csv files. An average steady state value was calculated for time points 15, 25, 35, 45 and 55 minutes by manually extracting steady state data and averaging BxB values. Data were averaged over a minimum of three minutes to compute the average $\dot{V}O_2$ (ml/kg/min and ml/min) and $\dot{V}CO_2$ (ml/min), RER $\left(\frac{VCO2}{VO2}\right)$, and VE $(([Volume\ of\ air\ collected\ /\ Collection\ time]\ x\ 60)\ x\ correction\ factor)$. HR values were collected continuously throughout the load carriage walk duration, with values extracted at 5-minute intervals for analysis. RPE values were aligned with HR and other cardiovascular measures at the selected time points to allow for specific data analysis included in Chapter 7 of this thesis only. RPE data was otherwise analysed as an independent measure at 5-minute intervals over the whole 55-minute load carriage task duration.

2.2.6. Statistical Analysis

All statistical analyses were conducted using IBM SPSS Statistics 25.0 software for Windows (IBM Corp Armonk, NY, USA), unless stated otherwise. Statistical significance main and interaction effects was set at $p < 0.05$. Statistical analyses conducted on all variables presented in this thesis were confirmed with an independent statistician from Macquarie University.

2.2.6.1. Sample Size and Statistical Power

The original recruitment target number of thirty participants (15 males, 15 females) was calculated using previously published data (Seay et al., 2014). A sample size of ten participants provided 83 % statistical power, which allowed the current study a buffer to accommodate for possible participant drop out. The actual sample size for the current project was twenty-eight participants (15 males, 13 females). For males, a sample size of 15 participants using representative force data for the countermovement jump provides 84 % statistical power. For biomechanical performance measures, a sample size of 13 male participants using representative knee joint moment data provides 98 % statistical power. For females, a sample size of 13 participants using representative force data for the countermovement jump provides 81 % statistical power. For biomechanical performance measures, a sample size of 13 participants using representative knee joint moment data provides 100 % statistical power. For cardiovascular measures, a sample size of 11 participants using $\dot{V}O_{2max}$ data provides 97 % statistical power.

2.2.6.2. Physical Performance Variables

2.2.6.2.1. Male-Only Data Analysis

A repeated-measures Analysis of Variance (ANOVA) was used to determine whether significant differences existed between pre, mid, and post-test (weeks 0, 6, and 11, respectively) measures for push-ups, sit-ups, CMJ, and SJ variables. Post-hoc paired t-tests with a Bonferroni correction were performed on all variables that demonstrated significant main effects of training. A one-way repeated measures analysis of variance, tested RPE and HR response variables were significant different between pre- and post-training measures. Post-hoc tests with Bonferroni corrections were used to calculated for mean differences for significant effects. A paired samples t-test was used to compare pre- and post-training means for estimated maximal oxygen uptake. The value of the Cohen's d statistic (Cohen, 1988), corrected for the biased estimate of the population effect size for small samples ($n < 25$) using Hedges's g (Hedges & Olkin, 1985). Effect sizes for all physical performance variables were calculated using difference in means (d) and were interpreted as trivial (0.0-0.1), small

(0.2-0.6), moderate (0.6-1.2), and large effects (≥ 1.2) (Hopkins, 2016). Statistical significance was set at $p < 0.05$.

2.2.6.2.2. Male-Female Data Comparisons

A mixed-design repeated-measures ANOVA with within-subject factor of training and a between-subject factor of sex were conducted for push-ups, sit-ups, CMJ, and SJ performance measures. Post-hoc paired t-tests with a Bonferroni correction comparison were performed when significant interactions or main effects were found for dependent variables between pre, mid, and post measures (week 0, week 6, week 11, respectively). Paired t-tests were conducted to compare pre- and post-training means for estimated maximal oxygen uptake (as determined by beep test scores). Statistical analysis for the IMTP performance measure was conducted for female data only. The value of the Cohen's d statistic (Cohen, 1988), corrected for the biased estimate of the population effect size for small samples ($n < 25$) using Hedges's g (Hedges & Olkin, 1985). Mean differences were computed for each significant main effect and post-hoc test to determine the effect size. Effect sizes for all physical performance variables were calculated using difference in means (d) and were interpreted as trivial (0.0-0.1), small (0.2-0.6), moderate (0.6-1.2), and large effects (≥ 1.2) (Hopkins, 2016).

2.2.6.3. Biomechanical Performance Variables

2.2.6.3.1. Male-Only Data Analysis

A two-way analysis of variance tested for significant interactions between, and main effects of training and distance marched when analysing male data independently. Normal distribution of data was confirmed using the Shapiro-Wilk test ($p < 0.05$). Pairwise comparisons post-hoc tests with Bonferroni corrections were performed on significant main and interaction effects to identify specific differences between training and distance marched measures. Effect sizes were calculated using the partial Eta squared (η_p^2), with small, medium, and large effects defined as η_p^2 between 0.01 and 0.06, 0.06 and 0.14, and greater than 0.14, respectively (Richardson, 2011). Statistical significance was set at $p < 0.05$.

2.2.6.3.2. Male-Female Data Comparisons

A two-way ANOVA repeated measures with sex as a between-subject factor and load as a within-subject factor was used to identify significant interactions between, and main effects training and distance marched. Non-normalized (spatial-temporal and three-dimensional joint kinematics) and normalized (joint moments, power, and work) variables were analysed across the gait cycle. Normal distribution of data was confirmed using the Shapiro-Wilk test. Bonferroni pairwise comparisons were used to detect differences between sexes when significant main and/or interaction effects of distance marched and training were found. Partial eta squared (η_p^2) effects sizes are reported for significant interaction and main effects. Small, medium and large effects were defined as 0.01, 0.06, and greater than 0.14 (Richardson, 2011). Statistical significance was set at $p < 0.05$.

2.2.6.4. Physiological Responses Variables

Data are summarized as mean ± 95% confidence intervals (95 %CI) unless otherwise stated. The normality of the data was confirmed using the Shapiro-Wilk test ($p > 0.05$). A two-way analysis of variance (ANOVA) was used to assess time (10-15, 20-25, 30-35, 40-45, 50-55 min) by training (pre, post) interactions. Tukey's multiple comparisons post-hoc test was used to detect specific differences. Statistical significance was set at the $p < 0.05$ level. All data were analysed using Microsoft Excel 2010 (Microsoft Corporation, WA, USA) and Graphpad Prism V7.0 (Graphpad Software Inc., CA, USA). RPE and HR response variables for male and female populations were analysed over the 5 km load carriage distance using a one-way ANOVA to test for significant differences between pre- and post-training measures (week 0 and week 11). Paired samples t-tests were conducted on estimated maximal oxygen uptake as determined by beep test scores. A RMANOVA was further completed to examine effects of sex (Chapter 4). Statistical significance was set at $p < 0.05$. Effect sizes were calculated using difference in means (d) and were interpreted as trivial, small, moderate, and large effects defined as d between 0.0-0.1, 0.2 and 0.6, 0.6 and 1.2, and > 1.2 (Hopkins, 2016).

Chapter 3: Load Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males

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This chapter has been re-formatted for this thesis, however all content (i.e., text, structure, tables, and figures) has remained as accepted for publication in The Journal of Strength and Conditioning Research as Wills, J. A., Saxby, D. J., Glassbrook, D. J., & Doyle, T. L. A (2019). Load Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males. *Journal of Strength and Conditioning Research, 33*, 2338-2343 (accepted 07/03/2019).

In this Chapter, I identified and characterised physical performance responses before, during, and after male civilian participants completed an evidence-based 10-week physical training program focussed on load carriage performance.

Load carriage and associated physical training is regularly conducted by military personnel throughout their career to ensure soldiers are physically prepared to complete occupational related tasks. However, the discrepancy between the demands of load carriage tasks and the physical capabilities of soldiers is believed to be a primary cause of musculoskeletal injury. Importantly, physical training can be implemented to reduce this discrepancy. Recent work has identified specific neuromuscular demands of load carriage, along with the primary joints and muscles that contribute towards walking with external load. These findings were used to design and implement a physical training program targeting the lower limbs (specifically the hip joint and associated musculature) to improve the capacity of individuals to carry load by optimising physical performance relative to task demands and mitigating injury risks.

The aim of this Chapter was to identify and characterise physical and psychophysical performance adaptations in response to a 10-week evidence-based training program for load carriage in a male-only population.

Load-Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males

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Abstract

Wills, JA, Saxby, DJ, Glassbrook, DJ, and Doyle, TLA. Load-carriage conditioning elicits task-specific physical and psychophysical improvements in males. *J Strength Cond Res* 33(9): 2338–2343, 2019—Load carriage is a requirement of many military roles and is commonly used as an assessment of soldier physical readiness. Loaded, compared with unloaded, walking tasks elicit increased physical demands, particularly around the hip joint, which can exceed the initial capacity of military personnel. This study aimed to identify and characterize physical performance responses to a lower-limb focused physical training program targeted toward load-carriage task demands. Fifteen healthy male civilians (22.6 ± 1.5 years, 1.82 ± 0.06 m, and 84.1 ± 6.9 kg) completed a 10-week physical training program consisting of resistance training and weighted walking. A load-carriage task representing the Australian Army All Corps minimum standard (5 km at 5.5 km·h^{-1}, wearing a 23-kg torso-borne vest) was completed before and on completion of the 10-week training program. Heart rate and rating of perceived exertion measures were collected throughout the load-carriage task. The performance measures of countermovement and squat jumps, push-ups, sit-ups, and beep test were performed before, mid-way, and on completion (weeks 0, 6, and 11) of the 10-week training program. Psychophysical performance, as measured by rating of perceived exertion, significantly decreased ($p < 0.05$) during the load-carriage task after training, demonstrating improvements in psychophysical responses. The training program resulted in significant increases in squat jump maximal force, push-ups, sit-ups ($p < 0.05$), and estimated maximal oxygen uptake ($p < 0.05$). Physical performance improvements and positive physiological adaptations to a load-carriage task were elicited in males after completing a 10-week training program. Military organizations could use this evidence-based training program to efficiently train soldiers to improve their load-carriage capacity.

Key Words: performance, neuromuscular, military, physical training, strength

Introduction

Load carriage is an occupational requirement for many military roles. To effectively complete occupational tasks, soldiers must have the physical capacity to meet the demands associated with their roles. Physical training is regularly implemented within military organizations to develop soldier's physical capacity (12). Although there are many positive effects of physical training, demanding tasks combined with poor exercise programming and high training volume can lead to detriments in both physical capacity and task-specific performance (3,8). Failure to adapt to increasing musculoskeletal demands and physiological stresses results in decreased soldier performance (3,8). Therefore, targeting the discrepancy between the demands of load carriage and physical capabilities of soldiers would benefit their occupational performance.

Physical training programs aim to facilitate the development of soldier's physical capabilities (12). Muscular strength, power, and aerobic fitness have been identified as key physiological characteristics required to successfully meet load-carriage task demands (7). Progressive resistance training can elicit neuromuscular and cardiovascular adaptations that result in improved occupational load-carriage performance (10,13,14,22,27,28). Harman et al. (10) observed that an 8-week resistance training program significantly improved general physical fitness tests (i.e., push-ups, sit-ups, and maximal jumps) and load-carriage performance. Moreover, including progressive load-carriage tasks throughout the 8-week training program resulted in greater improvements in load-carriage performance compared with studies that did not implement such training (28). Repeated task exposure through physical conditioning enhances an individual's tolerance to physical stressors over time (24). Concurrent training interventions (combined strength and aerobic training) appear to elicit load-carriage march performance improvements, whereas the evidence related to strength is equivocal (10,14). Reported training modalities do substantially vary within the literature; however, collectively, research demonstrates weight-based training elicits improvements in physical performance and positive physiological responses that are transferrable to load-carriage task performance.

Recent work by Lenton et al. (17) has characterized specific task demands of short-duration load-carriage tasks. Joint power

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Journal of Strength and Conditioning Research 33(9)/2338–2343

3.1. Abstract

Load carriage is a requirement of many military roles and is commonly used as an assessment of soldier physical readiness. Loaded, compared to unloaded, walking tasks elicit increased physical demands, particularly around the hip joint, which can exceed the initial capacity of military personnel. This study aimed to identify and characterise physical performance responses to a lower limb focussed physical training program targeted towards load carriage task demands. Fifteen healthy male civilians (22.6 ± 1.5 years, 1.82 ± 0.06 m, 84.1 ± 6.9 kg) completed a 10-week physical training program consisting of resistance training and weighted walking. A load carriage task representing the Australian Army All Corps minimum standard (5 km at 5.5 $km.h^{-1}$, wearing a 23 kg torso-borne vest) was completed before and upon completion of the 10-week training program. Heart rate and rating of perceived exertion measures were collected throughout the load carriage task. The performance measures of countermovement and squat jumps, push-ups, sit-ups, and beep test were performed before, mid-way, and upon completion (week 0, 6, and 11) of the 10-week training program. Psychophysical performance, as measured by rating of perceived exertion, significantly decreased ($p < 0.05$) during the load carriage task after training, demonstrating improvements in psychophysical responses. The training program resulted in significant increases in squat jump maximal force, push-ups, sit-ups ($p < 0.05$), and estimated maximal oxygen uptake ($p < 0.05$). Physical performance improvements and positive physiological adaptations to a load carriage task were elicited in males after completing a 10-week training program. Military organisations could use this evidence-based training program to efficiently train soldiers to improve their load carriage capacity.

3.2. Introduction

Load carriage is an occupational requirement for many military roles. To effectively complete occupational tasks, soldiers must have the physical capacity to meet the demands associated with their roles. Physical training is regularly implemented within military organisations to develop soldier's physical capacity (Knapik et al., 2005). Although there are many positive effects of physical training, demanding tasks combined with poor exercise programming and high training volume can lead to detriments in both physical capacity and task-specific performance (Brushøj et al., 2008; Groeller et al., 2015). Failure to adapt to increasing musculoskeletal demands and physiological stresses results in decreased soldier performance (Brushøj et al., 2008; Groeller et al., 2015). Therefore, targeting the discrepancy between the demands of load carriage and physical capabilities of soldiers would benefit their occupational performance.

Physical training programs aim to facilitate the development of soldiers' physical capabilities (Knapik et al., 2005). Muscular strength, power, and aerobic fitness have been identified as key physiological characteristics required to successfully meet load carriage task demands (Friedl et al., 2015). Progressive resistance training can elicit neuromuscular and cardiovascular adaptations that result in improved occupational load carriage performance (Harman et al., 2008b; Kraemer et al., 2001; Kraemer et al., 2004; Santtila et al., 2012; Williams & Rayson, 2006; Williams et al., 1999). Harman et al. (2008b) observed that an 8-week resistance training program significantly improved general physical fitness tests (i.e., push-ups, sit-ups, and maximal jumps) and load carriage performance. Moreover, including progressive load carriage tasks throughout the 8-week training program resulted in greater improvements in load carriage performance compared to studies that did not implement such training (Williams et al., 1999). Repeated task exposure through physical conditioning enhances an individual's tolerance to physical stressors over time (Szivak & Kraemer, 2015). Concurrent training interventions (combined strength and aerobic training) appear to elicit load carriage march performance improvements, whereas the evidence related to strength is equivocal (Harman et al., 2008b; Kraemer et al., 2004). Reported training modalities do substantially vary within the literature, however, collectively, research demonstrates weight-based training elicits improvements in physical performance and positive physiological responses that are transferrable to load carriage task performance.

Recent work by Lenton et al. (2017) has characterised specific task-demands of short-duration load carriage tasks. Joint power contribution shifted proximally up the kinetic chain from the ankle and knee to the hip when carrying loads of 15 kg and 30 kg compared to no load. Lenton et al. (2017) further identified the critical lower limb joint was the hip, contributing ~60 % power, followed by the ankle (~25 %), and then the knee (~15 %). Lenton and colleagues' study suggests the transfer of positive power may be load dependant, meaning physical training programs should be designed and implemented based upon physical requirements of specific load carriage tasks. Limited research to date has investigated physical performance adaptations in relation to physical training programs that target the specific neuromuscular demands of loaded walking tasks. Using an evidence-based approach, a physical training program targeting the hip joint musculature may improve a soldier's load carriage capacity.

The purpose of this study was to identify and characterise physical performance responses to an evidence-based 10-week training program focussed on load carriage performance. It was hypothesised that the physical training program would decrease rating of perceived exertion (RPE) and heart rate (HR) responses during a load carriage task. It was also hypothesised that lower limb maximal strength and general fitness performance would improve after training.

3.3. Methods

3.3.1. Experimental Approach to the Problem

Male civilians, representative of a recruit population, completed a 10-week load carriage specific training program. A load carriage task equivalent to the minimum physical employment standards requirement for Australian Army All Corps Standard (5 km at 5.5 $km.h^{-1}$, wearing a 23 kg torso-borne vest) was completed before and upon completion of 10-week training program. Physical performance measures were collected before, mid-way, and after (weeks 0, 6, and 11) the training program to examine physical and neuromuscular adaptations to the intervention.

3.3.2. Subjects

Fifteen healthy male civilians (22.6 ± 1.5 years, 1.82 ± 0.06 m, 84.1 ± 6.9 kg) participated and at the time of testing had no acute or chronic injuries. Previous experience with load carriage was not required, and no participants reported any previous experience. Participants meeting inclusion criteria were informed of experimental procedures and risks associated with participation. Participants gave their written informed consent to the protocol, which was approved by the Macquarie University Human Research Ethics Committee (protocol number: 5201700406).

3.3.3. Procedures

3.3.3.1. Physical Performance

3.3.3.1.1. Inclusion Criteria

Study inclusion criteria required participants to be ≤ 25 years, have a body mass ≥ 73 kg, and to meet or exceed a minimum of 70 sit-ups and 40 push ups in two minutes each, and a minimum of level 7.5 on the beep test (Australian Defence Force; Mullins et al., 2015).

Jump performance was measured using countermovement and squat jumps to measure lower limb maximal power and as a surrogate for lower limb strength (maximum force produced prior to take-off), respectively. As tests being conducted were common tasks (i.e., jumping, running, etc), no familiarisation was provided.

3.3.3.1.2. Countermovement and Squat Jump

Countermovement jumps (CMJ) were conducted on a portable force plate with a linear position transducer attached to a lightweight wooden bar held across participants' shoulders (400-series, Fitness Technology, Adelaide, SA, Australia). Participants were instructed to jump as high as possible in one continuous motion. Each participant performed three maximum effort jumps, each separated by a one-minute rest. Squat jumps (SJ) were conducted in a similar fashion to countermovement jumps except participants were instructed to commence in a semi-squat position and to hold the position for several seconds before being provided a cue to perform the concentric phase of the jump for maximal height. Each participant performed three successful maximum effort jumps, each separated by a one-minute rest. Force-time data for both countermovement and squat jumps were collected using Ballistic Measurement System Software (Innervations, Perth, WA, Australia) and were analysed using the Advanced Jump Analysis Package (TLAD Solutions, Sydney, NSW, Australia). The highest absolute peak power output value was extracted and used for statistical analysis of lower limb power (Cormack et al., 2008). The highest absolute maximal force output value was extracted from collected trials and used for statistical analysis as a surrogate measure of lower limb strength.

3.3.3.1.3. Push-ups

Push-up performance was determined by the maximal number of repetitions participants completed within two minutes. The starting position required participants feet to be shoulder width apart, keeping the back straight, and the arms in a locked-out position. A repetition was counted when the participant descended from the start position until the elbows reached a 90-degree angle, and upper arm parallel with the ground, and returned to the start position. Participants were able to take a rest throughout the two minutes but were required to remain in the start position during the rest.

3.3.3.1.4. Sit-ups

Sit-up performance was determined by the maximal number of repetitions participants completed within two minutes. Participants laid flat on the floor with their knees flexed at a 90-degree angle and feet flat on the floor. Anchored support at the feet was provided and participants were required to keep straight arms. A repetition was counted when participants raised their body until the wrists met the top of the knees (maintaining contact between the hands and thighs at all times) and returned in a downward motion until the shoulder blades touched the floor. Participants were able to take a rest throughout the two minutes.

3.3.3.1.5. Beep Test

A multi-stage fitness test was conducted to estimate maximal oxygen uptake. Participants ran between two parallel lines set 20 m apart and were required to reach the lines prior to the beep. Participants were required to maintain speed as prescribed by the beeps until failure. The last successful completed shuttle within each stage was recorded and was used to calculate estimated maximal oxygen uptake (Ramsbottom et al., 1988).

3.3.3.1.6. Rating of Perceived Exertion

Rating of perceived exertion (RPE) was collected at 5-minute intervals during the load carriage task using a Borg scale (Borg, 1998).

3.3.3.1.7. Heart Rate

Heart rate (HR) responses were collected at 5-minute intervals during the load carriage task using a heart rate monitor (Polar, NSW, Australia).

3.3.3.2. Load Carriage Task

On a separate day to inclusion criteria testing, participants completed a laboratory-based load carriage task which consisted of walking on a standard treadmill for 5 km at 5.5 km.h^{-1}, wearing a 23 kg torso-borne vest. Upon completion of the 10-week training program the load carriage task was repeated.

3.3.3.3. Physical Training Intervention

The 10-week physical training program consisted of resistance training and progressive load carriage tasks. Up to three resistance training sessions and two load carriage sessions were completed per week. The initial 2-weeks of the training program included general strength training to allow participants to become familiar with resistance training procedures and to allow for exercise technique corrections. Table 7 is an excerpt of the 10-week resistance training program which highlights changes in acute training variables (exercises, sets, repetitions and rest) (see Supplementary Table 1 for the full 10-week training program). Resistance training sessions were delivered by a level 1 minimum accredited Australian Strength and Conditioning coach, with resistance and progressions tailored to individual abilities. Exercise resistance incrementally increased weekly if participants successfully completed the required number of repetitions and sets for individual exercises. If participants were unable to perform the required repetitions the number performed was recorded and the resistance was adjusted accordingly. Exercise resistance, number of repetitions completed during individual sessions, and training compliance (resistance and load carriage tasks, respectively) were recorded throughout the 10-week training program.

Loaded carriage sessions were self-directed, and conducted on a treadmill, on a separate day to weight training sessions, with load incrementally increasing over the 10-week program ranging from 0 kg to 25 kg. Table 8 is an excerpt of the 10-week resistance training program which highlights changes in acute training variables (distance, speed, and load) in load carriage sessions (see Supplementary Table 2 for the full 10-week load carriage program).

3.3.4. Statistical Analyses

A repeated-measures ANOVA (RMANOVA) with a Bonferroni correction tested for significant differences between pre, mid, and post measures for CMJ, SJ, push-up, and sit-up variables. Post-hoc paired t-tests with a Bonferroni correction were performed on variables with significant main effects of time. Paired samples t-tests were conducted on estimated maximal oxygen uptake. A one-way ANOVA tested for significant differences between pre and post RPE and HR response variables. Statistical tests were conducted using IBM SPSS Statistics 25.0 software for Windows (IBM Corp Armonk, NY, USA), and significance was set at $p < 0.05$. Effect sizes were calculated using difference in means (d) and were interpreted as trivial (0.0-0.1), small (0.2-0.6), moderate (0.6-1.2), and large effects (≥ 1.2) (Hopkins, 2016). Results are presented as means ± standard deviations or effect size ± 95 % confidence intervals.

Table 7. Excerpt from 10-week training program highlighting key changes to acute variables within resistance training sessions.

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest	Exercise	Sets	Repetitions	Rest	Exercise	Sets	Repetitions	Rest (s)
1	Squat	3	8-10	120	Deadlift	3	8-10	120	ø	ø	ø	ø
	Leg Curls	3	8-10	120	Leg Curls	3	8-10	120	ø	ø	ø	ø
	Seated Row	3	8-10	120	Bench Pull	3	8-10	120	ø	ø	ø	ø
	Bench Press	3	8-10	120	Bench Press	3	8-10	120	ø	ø	ø	ø
	Hyperextensions	1	20	0	Leg Raises	1	20	0	ø	ø	ø	ø
Week 3	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	30	120	Upright Rows	3	8-10	120	Hyperextensions	1	30	120
	Leg Raises	1	30	0	Crunches	1	30	0	Leg Raises	1	30	0
Week 7	Squats	5	5	120	Bent-over Rows	5	6-8	120	Deadlift	5	5	120
	Hip Thrusts	5	5	120	45-degree TRX Flyes	3	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	3	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	3	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0
Week 10	Squats	3	5	120	Bent-over Rows	5	5	120	Squats	3	5	120
	Hip Thrusts	3	5	120	45-degree TRX Flyes	5	10	120	Hip Thrusts	3	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	3	10-15	120	Chin Ups	5	10	120	Overhead Plates Walks	3	10-15	120
	Hyperextensions	1	40	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	40	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0

Table 8. Excerpt from 10-week training program highlighting key changes of acute variables within highlighting key changes to acute variables within load carriage training sessions.

Week	Session	Acute Variables		
		Distance (km)	Speed (km.h-1)	Load (kg)
1	1	3	4	0
	2	0	0	0
3	1	4	5	0
	2	4	4	5
8	1	6	6	20
	2	0	0	0
10	1	6	6	25
	2	0	0	0

km, kilometres; **km.h-1**, kilometres per hour; **kg**, kilograms.

3.4. Results

3.4.1. Physical Training Compliance

Overall participant adherence to the 10-week training program were 97 %, with participants adhering to 99 % of total resistance training session and 94 % of loaded walking sessions. Four participants completed 100 % of sessions, with the remaining participants missing an average of two sessions out of forty-three due to re-scheduling issues or personal reasons.

3.4.2. Performance Measures

Table 9 presents the physical performance variable data at pre, mid, and post time points. Significant increases in SJ maximal force output were seen ($F[2, 28] = 3.805$, $p < 0.05$), with no significant differences shown for CMJ ($F[2,28] = 0.531$, $p>0.05$). Bonferroni post-hoc pairwise comparisons further revealed significant differences between pre-post SJ maximal force values (pre: 1957.98 ± 314.69 N vs post: 2081.94 ± 286.76 N, $p < 0.05$). Maximal power output values for both SJ ($F[1.303, 18.956] = 0.270$, $p > 0.05$) and CMJ ($F[1.845, 25.8251.85] = 1.847$, $p = 0.18$) variables did not reach statistical significance.

Significant improvements in push-ups ($F[2, 28] = 7.507$, $p < 0.05$) and sit-ups ($F[2, 28] = 4.149$, $p < 0.05$) were demonstrated. Bonferroni post-hoc pairwise comparisons further revealed significant differences between pre-post push-up repetitions (51 ± 8 vs 57 ± 13, 13 % increase; $p < 0.05$) but not for sit-up repetitions (76 ± 4 vs 81 ± 8, 7 % increase, $p > 0.05$).

Estimated maximal oxygen uptake as derived from beep test scores increased significantly after training ($t(14) = -4.271$, $p < 0.05$) from 42.9 $ml \cdot kg^{-1} \cdot min^{-1}$ to 45.2 $ml \cdot kg^{-1} \cdot min^{-1}$.

3.4.3. Psychophysical and Physiological Measures

Data from one participant have been excluded, as after testing concluded they reported they were not genuinely indicating their RPE, as such RPE results are based on n=14. Significant decreases were shown at 20 ($F[1, 26] = 5.534$, $p < 0.05$) and 35 ($F[1, 26] = 5.015$, $p < 0.05$) minutes during the post-training load carriage task compared to pre-training (see Figure 7). No significant differences were recorded for HR responses during the load carriage task ($p > 0.05$), however, HR decreased on average by nine beats as a result of the training program (see Supplementary Figure 1).

Table 9. Physical performance variable data at pre, mid and post collection intervals. Data are presented as mean (±standard deviation), CI (95% confidence interval), and effect sizes (mean differences). *significant differences pre-post values ($p < 0.05$).

Performance Measure	Variable	Pre(1)		Mid(2)		Post(3)		Effect Size		
		Mean(±SD)	**CI**	**Mean(±SD)**	**CI**	**Mean(±SD)**	**CI**	**1 vs 2**	**2 vs 3**	**1 vs 3**
SJ	Maximal Force (N)	1958(15)	1784, 2132	2024(302)	1857, 2192	2082(245)*	1945, 2217	0.22	0.21	0.44
	Maximal Power (W)	4172(729)	3768, 4576	4271(748)	3856, 4685	4270(887)	3779, 4762	0.13	0.00	0.12
CMJ	Maximal Force (N)	1899(182)	1798, 2000	1924(179)	4072, 2023	1930(214)	1811, 2049	0.14	0.01	0.16
	Maximal Power (W)	4291(718)	3894, 4836	4454(690)	4072, 4836	4362(635)	4011, 4714	0.23	-0.14	0.11
General Fitness Tests	Push-Ups(reps)	51(8)	46, 55	54(12)	48, 61	57(13)*	50, 65	0.38	0.23	0.60
	Sit-Ups(reps)	76(4)	73, 78	78(7)	74, 83	81(9)*	76, 86	0.43	0.33	0.74
	Estimated $\dot{V}O_2$	42.8(4.50)	**NA**	**NA**	**NA**	45(5)*	**NA**	**NA**	**NA**	0.48

SJ, squat jump; **CMJ**, countermovement jump; **N**, Newtons; **W,** Watts; **Reps,** Arbitrary units; **Estimated $\dot{V}O_2$**, maximal oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$); **NA**, no data to present.

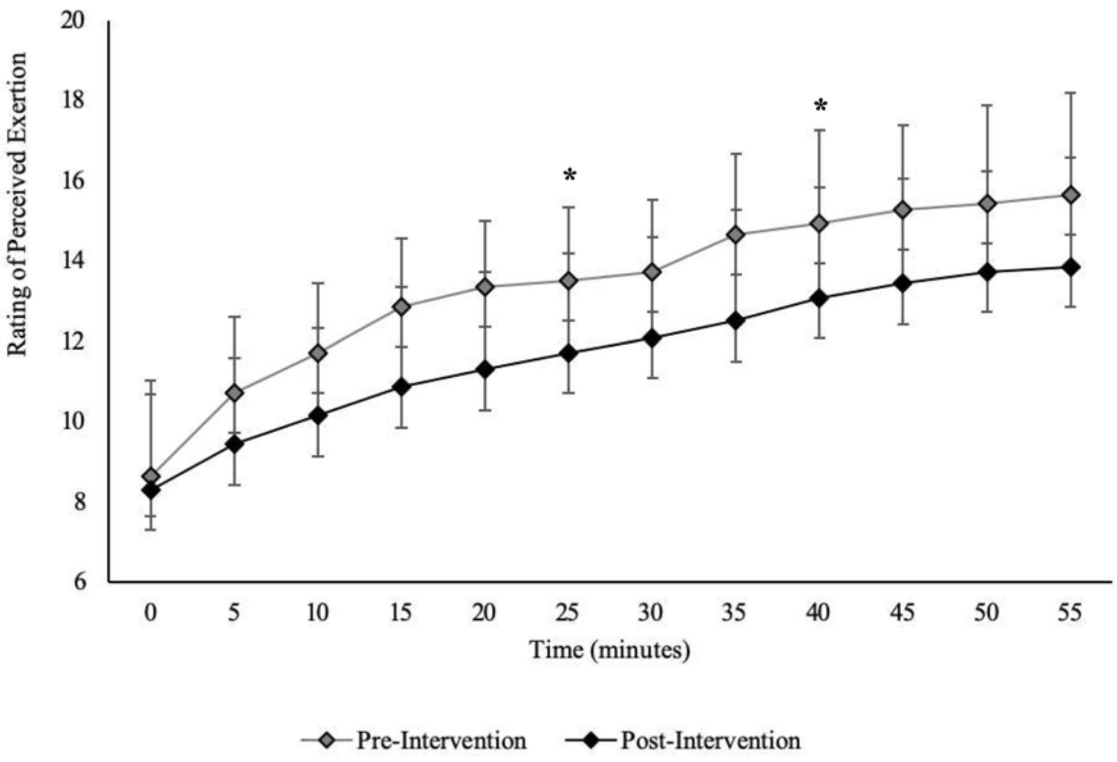

Figure 7. Rating of perceived exertion changes during a load carriage task before and after a 10-week training program. Data are presented as mean±standard deviation. *significant differences ($p < 0.05$).

3.5. Discussion

The purpose of this study was to identify and characterise physical and psychophysical performance responses to an evidence-based 10-week training program that was focused on load carriage. Participant strength, as measured by maximal jump force, improved as did push-up, sit-up, and beep test performance. Notably, participants perceived the demands of the task to decrease after training as measured by a lowered RPE. Results indicate that an evidence-based training program elicits physical and psychophysical adaptations that positively enhance individuals' performance on a specific load carriage task.

The primary goal of the training program in our study was to increase lower limb strength. Improvement in maximal force production during SJ indicates enhanced capacity to generate concentric strength through the lower limbs (McGuigan et al., 2006). The technical demands of the SJ does not rely on the elastic recoil of muscle-tendons at the ankle in the same way that the CMJ does. Thus, a greater contribution from the hip joint has previously been observed during the SJ as an alternative movement strategy (Wade, Lichtwark, & Farris, 2018). As the current training program was focussed on developing the hip musculature, an increased capacity of the hip extensors to produce force during a predominantly concentric only contraction may specifically account for force production improvements in the SJ. CMJ performance is commonly reported within the literature as an outcome measure for lower limb power adaptations in response to resistance-based training (Häkkinen et al., 2003; Kraemer et al., 2004). The lack of CMJ improvements observed in our study demonstrate that neuromuscular adaptations were specific to the training stimulus (Cormie, Mcguigan, & Newton, 2010; Häkkinen et al., 2003), i.e. strength training elicited adaptive responses as evidenced by improvements in SJ maximal force production. Positive adaptations in both the push-up (13 %) and sit-up (7 %) tests were recorded after training, which are in line with previous studies that have reported pre-post increases ranging between 32-43 % in push-up scores, and 28-38 % in sit-up scores (Harman et al., 2008b; Kraemer et al., 1987). Though performance improvements are less in the current study compared to those previously reported, they still indicate muscular endurance of the upper body and trunk was improved. The relevance of these tests in relation to occupational military tasks have previously been questioned as they predominately measure upper body local muscle endurance, rather than muscular strength (Vanderburgh, 2008). However, during load carriage tasks, the upper body bears a substantial portion of the pack load (Lenton et al., 2018). Muscular strength, therefore, may be reflected through improved postural support and torso stabilisation resulting in improved load carriage performance (Kraemer et al., 2001).

Matching the physical and physiological demands during load carriage are critical to ensure successful task performance (Brushøj et al., 2008; Groeller et al., 2015). Although cardiovascular improvements were not specifically targeted, estimated maximal oxygen uptake improved from 42.9 $\text{ml}\cdot\text{kg}_{-1}\cdot\text{min}_{-1}$ to 45.2 $\text{ml}\cdot\text{kg}_{-1}\cdot\text{min}_{-1}$, suggesting cardiovascular adaptations. Increases in maximal strength may result in improved mechanical efficacy (Kraemer et al., 2001), which could translate to enhance load carriage performance as demonstrated by reductions in RPE values. Previous research has demonstrated that resistance training alone does not increase maximal oxygen uptake (Kraemer et al., 1995). However, it has been postulated that improving maximal strength can lessen cardiovascular stress during tasks including load carriage (Deschenes & Kraemer, 2002). Though no specific aerobic training was administered within the current training program, the inclusion of weekly load carriage walking tasks may have played a vital role in the adaptations demonstrated via estimated maximal oxygen uptake. For example, previous studies including progressive load carriage tasks within training programs have observed larger improvement in load carriage performance (Harman et al., 2008b; Kraemer et al., 2001; Kraemer et al., 2004) compared to those studies that did not (Williams et al., 1999). Improvements in performance capacity suggest that repeated task exposure may increase an individual's tolerance towards the increased physical demands experienced during load carriage tasks.

A primary goal of the 10-week training program was to optimise conditioning for load carriage. The RPE values decreased over the duration of the load carriage task after training. This finding is particularly interesting given that the load carriage task itself remined the same (i.e., walking on a treadmill for 5 km at 5.5 $km.h^{-1}$, wearing a 23 kg torso-borne vest). Limited research to date has reported psychophysical measures in response to a load carriage task. One of the few studies to report such measures in response to training observed no changes in pre-post RPE values during a 2-mile loaded running task (Kraemer et al., 2004). Differences in psychophysical responses between the current study and those of Kraemer et al. (2004) may be accounted for by variations in the load carriage task modalities. Kraemer et al. (2004) used a time to completion task compared to the set distance load carriage task used in the current study as a criterion for performance improvement. In contrast with previous literature, our study implemented task-specific conditioning using an evidence-based training program; the improved physical conditioning may have led to decreased perception of task demands. Further, an increased physical capability that matched the task-specific physical demands could have improved movement efficiency during locomotion (Kraemer et al., 2001). This, combined with repeated, progressive load carriage exposure throughout the 10-week training program appears to have improved task performance and enhancements in overall physical capacity (Sauers & Scofield, 2014). Reduced perceived task demands suggest that individuals were successfully conditioned for load carriage using an evidence-based physical conditioning program.

Findings related to strength changes would be enhanced by a dedicated strength measure e.g., isometric mid-thigh pull. This would give a clear indication of the muscular strength adaptation to the program. Additionally, in addition to heart rate response, the inclusion of oxygen consumption measures during the load carriage task would provide additional insights to physiological adaptations to the training. It is acknowledged that these are limitations of the current study.

In conclusion, the current study was the first to investigate physical performance responses to an evidence-based 10-week training program targeted towards load carriage. Results demonstrate that a periodised resistance training program can induce physical performance improvements and neuromuscular adaptations in males. Further investigations of sex-specific responses could provide insight into specific training adaptations of males and females. Understanding such responses could provide direction in the optimisation of military training and the integration of female soldiers into physically demanding combat roles within the Australian Defence Force.

3.6. Conclusion

The current study is the first to the authors' knowledge to link evidence-based physical training responses to task-specific performance. Results demonstrate that a hip-focussed resistance training program induces physical performance improvements and physiological adaptations in males. Additionally, it appears that focussing on load carriage task demands can effectively condition individuals for a specific loaded walking task. Evidence-based designed programs such as the current could be utilised by military organisations to effectively train soldiers for specific tasks to optimise overall load carriage capacity and performance.

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Chapter 4: Sex-Specific Physical Performance Adaptive Responses are Elicited after 10-weeks of Load Carriage Conditioning

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This chapter has been re-formatted for this thesis, however all content (i.e., text, structure, tables, and figures) has remained as submitted for publication as an original article to The Journal of Science and Medicine in Sport.

In Chapter 3 it was identified that a hip-focussed resistance training program elicits physical performance improvements and physiological adaptations in males. Specifically, participants' lower limb strength improved as did push-up, sit-up, and beep test performance. Participants' perception of the 5 km load carriage task decreased after training. These findings demonstrated that the 10-week training program effectively condition key physical characteristics associated with load carriage task performance.

In this Chapter, I comparatively analysed male and female data to identify and characterise potential sex-specific performance differences in response to the same 10-week physical training program as the previous chapter. Limited investigations into sex-specific responses to physical training have been conducted, with most research mainly reporting data in a male-only population. Interestingly, those that have studied differences between males and females have commonly reported that men generally outperform women in all physical performance tasks (Knapik et al., 2005), even after completing the same training. These findings seemingly indicate that the same training may not necessarily equate to the same physical adaptive responses between sexes (Varley-Campbell et al., 2018). Despite these findings, males and females in combat-related roles are required to complete the same physical training, and the same physically demanding tasks since the removal of sex-restrictions in Australia in 2014. As loads carried in the military are standardised (i.e., are absolute loads irrespective of individual mass) it is important to identify and understand potential sex-specific responses, especially as females have different physical capacities compared to males that influence how well they perform load carriage tasks.

The aim of this Chapter was to identify and characterise sex-specific physical and psychophysical adaptations in response to the same 10-week training program for load carriage.

4.1. Abstract

Objectives: To identify and characterise sex-specific physical and psychophysical performance adaptations in response to the same 10-week physical training program.

Design: Within-subjects repeated measures to determine the effects of a 10-week lower body focussed training program for load carriage on sex-specific adaptive responses.

Method: Twenty-eight healthy civilians (males [n=15]: 22.6 ± 1.5 years, 1.82 ± 0.06 m, 84.1 ± 6.9 kg; females [n=13]: 21.3 ± 2 years, 1.7 ± 0.8 m, 64.8 ± 7.5 kg) completed a standardised load carriage task (5 km at 5.5 $km.h^{-1}$, wearing a 23 kg torso-borne vest) before and after 10-weeks of resistance and load carriage training. Physical and psychophysical responses (i.e., heart rate and rating of perceived exertion) were measured throughout the load carriage task. Physical performance (i.e., countermovement and squat jumps, push-ups, sit-ups, and beep test) was measured before, mid-way, and after the training program (weeks 0, 6, and 11, respectively).

Results: Training resulted in significant improvements in squat jump maximal force, push-ups, and beep test performance ($p < 0.05$). Males outperformed females in all performance measures, with interactions (time by sex) for push-ups, sit-ups, and beep test performance. After training, aerobic capacity improved by 5.4 % (42.9 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ to 45.2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) for males but did not improve in females. Rating of perceived exertion and heart rate responses decreased for both sexes ($p < 0.05$) during the load carriage task post-training.

Conclusions: Despite physical performance improvements, sex-specific differences were still evident after completing the same physical training. To lessen this performance gap, females should be trained differently to males to optimise performance on load carriage tasks.

Practical Implications

- The same 10-week training stimulus elicited similar lower body strength improvements for both sexes, but greater upper body improvements for females compared to males.
- Targeted training reduces perceived load carriage task demands in both sexes.
- Physical conditioning should be sex-specific, as the same training elicited different adaptive responses for males and females.

4.2. Introduction

In the military, men and women regularly undertake the same training for the same roles, despite known physiological differences between sexes. In combat-related occupations, external loads are primarily determined by training or operational task demands rather than an individual's physical capacity, fitness, or sex (Nindl, 2015). As military organisations globally open previously closed combat-related roles to women, this seemingly places them at a disadvantage, especially as women display reduced physical capabilities compared to men (Nindl et al., 2016). Therefore, identifying sex-specific responses during a standardised load carriage task will provide essential information of how task demands are met and if different programs are needed for males and females.

In combat-related occupations, soldiers from mixed-sex platoons of are required to complete the same physical training and physical employment standard tasks (Australian Defence Force). However, the inherent differences in physical capacities between men and women (i.e., strength, power, and aerobic fitness) (Nindl et al., 2016) influence performance of crucial combat tasks (e.g., load carriage) (Brushøj et al., 2008; Groeller et al., 2015). Importantly, physical capacities can be improved through physical conditioning targeted to meet the task-specific physical demands (Knapik et al., 2005). Strength is essential to military roles, and resistance training is effective in enhancing load carriage performance (Knapik, Reynolds, Santee, & Friedl, 2011). For example, 8-12 weeks of progressive resistance training prompted neuromuscular adaptations through increases in physical fitness and load carriage performance (Harman et al., 2008a; Kraemer et al., 2001; Kraemer et al., 2004; Santtila et al., 2012; Williams & Rayson, 2006; Williams et al., 1999). Interestingly, the inclusion of progressive load carriage tasks combined with resistance training generally leads to greater load carriage performance (e.g., quicker course completion time after training compared to before training) compared to those programs that do not include such tasks (Williams et al., 1999). These findings suggest that physical training interventions targeting the specific neuromuscular demands of load carriage lead to improvements in fitness and load carriage performance, regardless of the training modality.

Physical and neuromuscular adaptive responses to training have mainly been reported in males, with few studies focused on female-specific responses to physical training. Commonly it is found that men outperform women in all physical performance tasks (Knapik et al., 2005). Despite research reporting sex-specific improvements in various fitness components and performance outcome measures that narrow the gap between male and female performance (Harwood, Rayson, & Nevill, 1999; Patterson et al., 2005; Yanovich et al., 2008), there is still a physical performance gap between sexes. Thus, it seems the same physical training stimulus may not elicit the same adaptive response for both sexes, meaning females may require specific training to optimise their performance improvements. Indeed, the opening of combat roles to females highlights the importance of understanding such training responses, especially given the challenges females face to successfully meet the physical demands of military load carriage tasks.

Therefore, based on these known physical and neuromuscular differences between males and females, we hypothesised that lower limb maximal strength, cardiovascular fitness, and general fitness performance would increase after training. Furthermore, lower body strength would increase similarly for both sexes, but upper body strength would increase for females only given the known deficits in strength capacities (Nindl et al., 2016) Rating of perceived exertion (RPE) and heart rate (HR) responses during the load carriage task were hypothesised to decrease for both sexes after training.

4.3. Methods

Twenty-eight healthy civilians (females [n=13]: 21.3 ± 2 years, 1.7 ± 0.8 m, 64.8 ± 7.5 kg; males [n=15]: 22.6 ± 1.5 years, 1.82 ± 0.06 m, 84.1 ± 6.9 kg) participated, and had no acute or chronic injuries, or previous experience with load carriage at the commencement of testing. Participants were required to meet or exceed pre-determined inclusion criteria based on the Australian Army basic fitness standards (Australian Defence Force; Mullins et al., 2015), relative to sex and age (Table 10). Participants who met inclusion criteria were informed of experimental procedures and risks associated with participation and subsequently their written informed consent. Protocols were approved by Macquarie University Human Research Ethics Committee (protocol numbers: 5201700406, 5201700997).

Table 10. Inclusion criteria for male and female soldiers, adapted from the Australian Army Training Continuum, Australian Defence Force).

Sex	Age Range (years)	Sit-ups (reps)	Push-ups (reps)	Beep Test (level, shuttle)
Female	18-25	70	21	7.5
	26-30	65	18	7.5
Male	18-25	70	40	7.5

Reps, Arbitrary units; **Beep Test**, level and shuttle number.

Participants completed a load carriage treadmill walking task in a laboratory setting (5 km at 5.5 $km \cdot h^{-1}$, wearing a 23 kg torso-borne vest), equivalent to the Australian Army All Corps minimum physical employment standard (Australian Defence Force), before and after a 10-week training program. Physical performance measures were assessed in separate testing sessions before, mid-way, and after training completion (weeks 0, 6, and 11, respectively).

The 10-week training program is the same as that previously conducted by Wills et al. (2019a) consisted of up to three resistance, and two load carriage sessions per week. Supplementary Table 1 details the full 10 weeks of resistance training, highlighting progressive changes in acute variables (i.e., exercises, sets, repetitions, and rest). The initial two weeks of training involved general strength training, familiarizing participants to training procedures and enabling coaches to correct exercise technique. A level 1 accredited Australian Strength and Conditioning Association coach delivered all resistance training sessions, with weekly resistance and progressions tailored to individual performance. Progressions in resistance training were implemented if participants successfully completed the required number of repetitions and sets for individual exercises. If not, the number successfully performed was recorded and informed adjustments to exercise resistance. Load carriage training sessions were self-directed, and conducted on a treadmill, on a separate day to resistance training sessions. Load, distance, and speed incrementally increased over the 10-week program ranging from 0 kg to 25 kg (Supplementary Table 2). Overall training compliance and individual session information was recorded throughout the 10 weeks.

As many physical performance tests were common recreation tasks (i.e., jumping, running, etc.), no familiarization sessions were provided. Tests were conducted according to previously published methodology (Wills et al., 2019a), detailed below.

Jumps. Countermovement jumps (CMJ) were collected using a portable force plate, sampled at 1000 Hz (400-series, Fitness Technology, Adelaide, SA, Australia). A linear position transducer was attached to a lightweight wooden bar held across participants shoulders. Participants were instructed to jump for maximal height in one continuous motion. Three maximum jumps efforts were completed, each separated by a one-minute rest. Squat jumps (SJ) were conducted similarly except participants were instructed to commence the movement from a semi-squat position, which was held for several seconds prior to receiving a cue to 'jump' prompting participants to commence the upward (concentric) phase of the jump. Force-time data for CMJ and SJ were collected using Ballistic Measurement System software (Innervations, Perth, WA, Australia) and were analysed using the Advanced Jump Analysis Package (TLAD Solutions, Sydney, NSW, Australia). Lower limb power was analysed using the maximum absolute peak power output value (Cormack et al., 2008), and the maximal absolute force output was used for as a surrogate measure of lower limb strength.

Push-ups. The greatest number of repetitions each participant successfully completed within two-minutes was used to determine push-up performance. Participants commenced push-ups in the 'start' position: straight back and legs, feet shoulder width apart, and arms extended underneath the shoulders. A successful repetition was achieved when the participant descended from the start position bending the elbows to 90-degrees and returned to a locked-out, extended arm position. Rest was permitted throughout the two-minute test, but participants were required to remain in the start position.

Sit-ups. The greatest number of sit-up repetitions each participant successfully completed within two minutes was used to determine sit-up performance. The 'start' position required participants to lay supine with their feet flat on the floor, and their knees flexed at 90-degrees. Anchored support fixing the feet to the floor was provided throughout the test. A successful repetition required participants to keep their arms extended and raise their body until the wrists reached the top of the knees (contact between the hands and thighs maintained), prior to descending until the shoulder blades reached the floor. Rest was permitted throughout the two-minute test.

Beep Test. Estimated maximal oxygen uptake was determined by a multi-stage fitness test before and after the 10-week physical training program. Participants ran continuously between two parallel lines 20 m apart, reaching the lines prior to the subsequent beep. Prescribed speeds incrementally increased, which participants matched until failure. The last successfully completed 20 m run within each stage was recorded and subsequently used to calculate estimated maximal oxygen uptake (Ramsbottom et al., 1988).

Physiological and Psychophysical Response. RPE and HR responses were collected at 5-minute intervals during the load carriage task using a Borg scale (Borg, 1998) and a HR monitor (Polar, NSW, Australia), respectively.

Statistical analyses were conducted using IBM SPSS Statistics 25.0 software for Windows (IBM Corp, Armonk, NY, USA).

A mixed-design repeated-measures ANOVA with within-subject factor of training and a between-subject factor of sex were conducted for push-ups, sit-ups, CMJ, and SJ performance measures. Post-hoc paired t-tests with a Bonferroni correction comparison were performed when significant interactions or main effects were found for dependent variables between pre, mid, and post measures (week 0, week 6, week 11, respectively). Paired t-tests were conducted to compare pre- and post-training means for estimated maximal oxygen uptake (as determined by beep test scores). Statistical analysis for the IMTP performance measure was conducted for female data only. The value of the Cohen's d statistic (Cohen, 1988), corrected for the biased estimate of the population effect size for small samples ($n < 25$) using Hedges's g (Hedges & Olkin, 1985). Mean differences were computed for each significant main effect and post-hoc test to determine the effect size. Effect sizes for all physical performance variables were calculated using difference in means (d) and were interpreted as trivial (0.0-0.1), small (0.2-0.6), moderate (0.6-1.2), and large effects (≥ 1.2) (Hopkins, 2016).

4.4. Results

Overall, training adherence was 97 % for males (resistance training, 99 %: load carriage, 94 %), and 89 % for females (resistance training, 97 %: load carriage, 87 %).

There were no main or interaction effects for time or sex observed for CMJ variables ($p > 0.05$), with no interactions were found for SJ variables ($p < 0.05$). SJ maximal force demonstrated a main effect of time ($F[1, 26] = 4.962$, $p < 0.01$), with no changes observed for SJ power or velocity measures ($p > 0.05$) (Table 11). Post-hoc pairwise comparisons showed SJ maximal force increased from pre-to-post training only (1660.7 ± 406.7 N *vs* 1757.3 ± 407.6 N, d = -2.5, $p < 0.01$).

There was a significant time by sex interaction effect (d, -0.5 to -1.4) for maximal push-up repetitions where females achieved a larger increase in maximal repetitions at pre- ($p < 0.01$) and mid-testing ($p < 0.05$) compared to males (Table 11). Pre-training measures were significantly different between females and males (35 ± 8 vs. 51 ± 8, $p < 0.01$), but did not differ between sexes after training (48 ± 11 vs. 57 ± 13, $p > 0.05$).

Following training, a significant time by sex interaction ($F[1, 26] = 3.364$, d = -0.4, $p < 0.05$) was shown for sit-ups. Maximal repetitions were maintained from pre-to-post-tests for females (77 ± 6 *vs* 76 ± 8, $p > 0.05$), but increased for males between pre-to-mid (76 ± 4 *vs* 78 ± 7, $p > 0.05$), mid-to-post (78 ± 7 *vs* 81 ± 9, $p > 0.05$), and pre-to-post (76 ± 4 *vs* 81 ± 9, $p > 0.05$) measures.

Estimated $\dot{V}O_{2max}$ increased after training (41.5 ± 4.0 *vs* 42.7 ± 5.4 $mL \cdot kg^{-1} \cdot min^{-1}$, $p < 0.05$) and significantly differed between sexes ($F[1, 26] = 7.527$ $p < 0.01$). A significant time by sex interaction (d=-1.1, $p = 0.001$) was shown as estimated $\dot{V}O_{2max}$ increased pre-to-post-training for males (42.9 ± 4.6 *vs* 45.2 ± 5.4 $mL \cdot kg^{-1} \cdot min^{-1}$), but not females (39.9 ± 2.4 *vs* 39.7 ± 3.8 $mL \cdot kg^{-1} \cdot min^{-1}$).

RPE from one male participant was excluded from analysis as they reported they were not genuinely indicating their RPE during testing. RPE and HR data from one female was excluded from analysis as she did not complete the pre-training load carriage task. Therefore, RPE results are based on n=26 and HR results are based on n=27.

RPE responses demonstrated a main effect of time decreased through decreased values during the load carriage task after training across all measures (Figure 8A) ($p < 0.05$) except the '0' minute measure, which was not significantly different compared to before training. No statistically significant main effects of sex or interactions (time by sex) were found.

There was a main effect of time at several time points, but no interaction effect based on sex. After training, HR significantly decreased at numerous time points during the load carriage task; 5 ($F[1, 25] = 7.796$, $p < 0.01$), 10 ($F[1, 25] = 4.927$, $p < 0.05$), 15 ($F[1, 25] = 5.456$, $p < 0.05$), 20 ($F[1, 25] = 6.063$, $p < 0.05$), 30 ($F[1, 25] = 5.130$, $p < 0.05$), 35 ($F[1, 25] = 4.456$, $p < 0.05$), 40 (F[1, 25] =

6.035, $p < 0.05$), 55 ($F[1, 25] = 4.493$, $p < 0.05$) minutes. Additionally, there was a main effect of sex ($p < 0.01$). Specifically, male HR was lower pre- and post-training compared to females (Figure 8B).

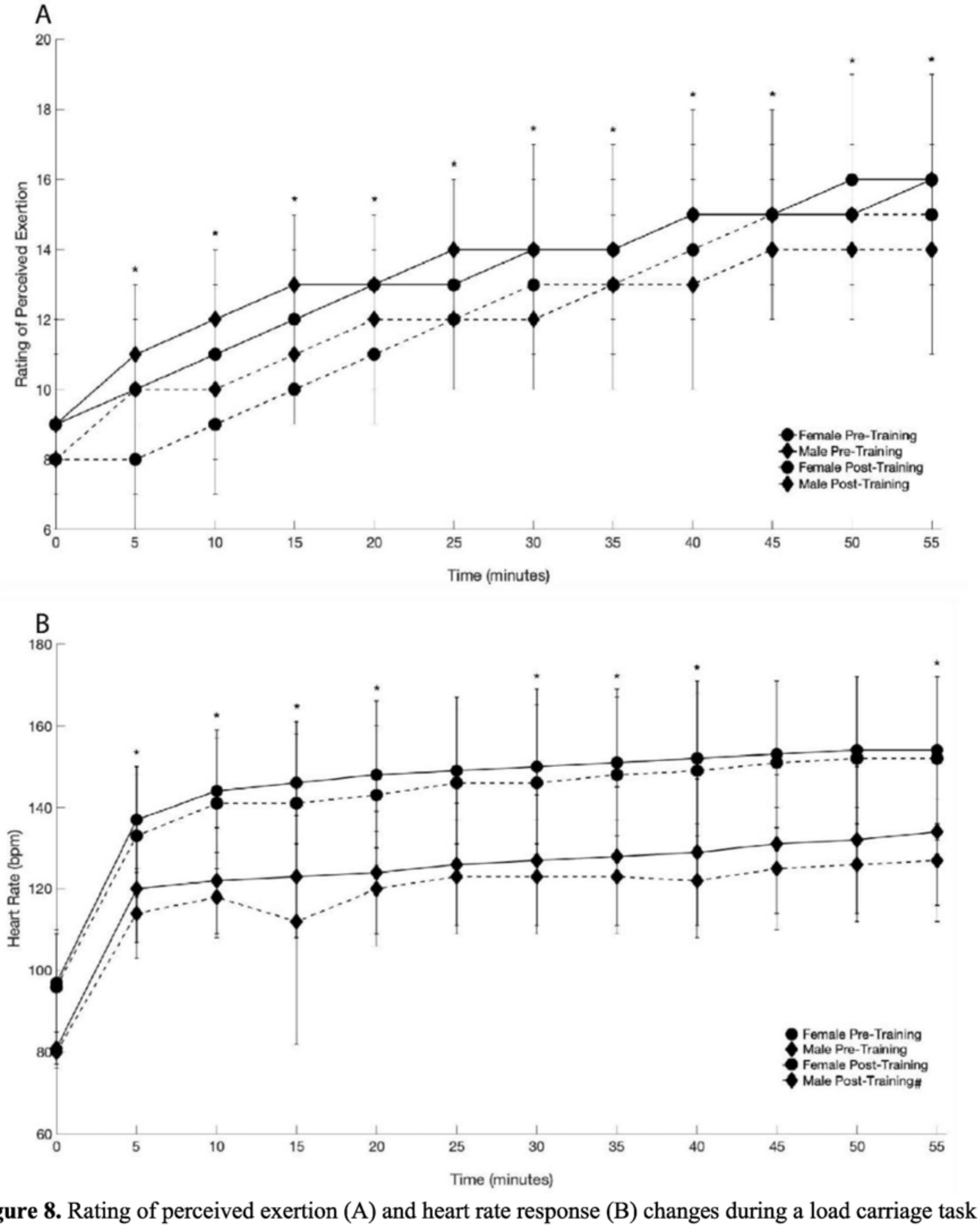

Figure 8. Rating of perceived exertion (A) and heart rate response (B) changes during a load carriage task before and after a 10-week training program. Data are presented as mean±standard deviation. *significant main effect of time, #indicates a significant main

Table 11. Physical performance variable data at pre, mid, and post-training measures. Data are presented as mean±standard deviation, CI (95% confidence interval). *Indicates a significant main effect of time, #indicates a significant main effect of sex, **indicates a significant time by sex interaction effect ($p < 0.05$). ǂindicates a trivial effect size within sex compared to pre-testing, ɣindicates a small effect size within sex compared to pre-testing, ‡indicates a medium effect size within sex compared to pre-testing, †indicates a large effect size within sex compared to pre-testing.

Performance Measure	Variable	Pre			Mid			Post		
		Female	Male	Effect Size	Female	Male	Effect Size	Female	Male	Effect Size
		Mean(±SD)	Mean(±SD)		Mean(±SD)	Mean(±SD)		Mean(±SD)	Mean(±SD)	
SJ	Maximal Force (N)*	1318(137)	1958(315)	-1.9†	1343(115)	2024(302)	-2.1†	1383(143)	2082(245)	-2.5†
	Maximal Power (W)	2509(324)	4172(729)	-2.1†	2499(262)	4271(887)	-1.9†	2545(324)	4270(887)	-1.8†
	Maximal Velocity ($m \cdot s^{-1}$)	2.3(0.2)	2.6(0.2)	-1.1‡	2.2(0.2)	2.6(0.3)	-1.1‡	2.2(0.2)	2.6(0.4)	-0.9‡
CMJ	Maximal Force (N)	1290(115)	1899(182)	-2.8†	1311(115)	1924(179)	-2.9†	1311(100)	1930(214)	-2.6†
	Maximal Power (W)	2539(339)	4291(718)	-2.2†	2603(292)	4454(690)	-2.5†	2629(350)	4363(635)	-2.4†
	Maximal Velocity ($m \cdot s^{-1}$)	2.3(0.2)	2.8(0.2)	-1.8†	2.3(0.2)	2.8(0.2)	-1.8†	2.3(0.2)	2.8(0.2)	-1.8†
General Fitness Tests	Push-Ups(reps)*/#/**	35(8)	51(8)	-1.4†	41(11)	54(12)	-0.8‡	48(11)	57(13)	-0.5ɣ
	Sit-Ups(reps)**	77(6)	76(4)	0.1ǂ	78(7)	78(7)	0.0ǂ	76(8)	81(9)	-0.4ɣ
	Estimated $\dot{V}O_2$#/**	39.9(2.4)	42.9(4.6)	-0.6ɣ	**N/A**	**N/A**	**N/A**	39.7(3.8)	45.2(5.4)	-0.8‡

SJ, squat jump; **CMJ**, countermovement jump; **DJ**, drop jump; **N**, Newtons; **W,** Watts; **cm**, centimetres; **Reps,** Arbitrary units; **Estimated $\dot{V}O_2$**, maximal oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$); **N/A**, no data to present.

4.5. Discussion

The purpose of this study was to identify and characterise sex-specific physical and psychophysical responses to a 10-week training program for load carriage performance. In line with our hypothesis, lower body strength improved for both sexes. Interestingly, females improved their upper body strength whereas males did not. In contrast to our hypothesis, cardiovascular fitness improved in males over the course of training but did not improve in females. However, both males and females reported the load carriage task became easier after training, showing similar positive adaptive responses as indicated by a decreased RPE and HR after training for both sexes. Differences in physical, psychophysical, and cardiovascular responses to the same training indicate sex-specific responses and suggest the need for sex-specific exercise prescription when integrating female soldiers in to training for combat-related roles.

Regardless of sex, psychophysical measures during the load carriage task, improved following 10-weeks of training. Limited research is currently available on psychophysical responses during load carriage tasks in females (Lidstone et al., 2017; Simpson et al., 2011) and in response to training. However, enhanced load carriage tolerance, as demonstrated by reductions in RPE, are thought to result from improvements in task-specific physical capability (Sauers & Scofield, 2014). For example, enhancements in mechanical efficiency have been associated with improvements in overall strength (Kraemer et al., 2001), as well as increased task resilience from repeated load carriage exposures (Harman et al., 2008a; Kraemer et al., 2001; Kraemer et al., 2004). Combined, these factors contribute to increases in individual's physical capabilities to better match task-specific physical requirements. Strength increases, evidenced by improvements in SJ maximal force production, indicate a greater capacity to generate concentric strength through the lower limbs (McGuigan et al., 2006). Consequently, these strength adaptations may have contributed towards an increased capacity for load carriage through increased efficiency, although this was not directly measured. Reductions in RPE following training also suggest individuals were successfully conditioned for load carriage, which was the primary goal of the 10-week training program.

Consistent with previous research, HR increased linearly with walk duration in response to a sustained load carriage task for both sexes (Pihlainen, Santtila, Häkkinen, Lindholm, & Kyröläinen, 2014; Simpson et al., 2010), with females generally demonstrating a higher average heart rate than males during pre-and-post training marches. Overall, reductions in

HR responses were displayed after training for both sexes, potentially indicating that the repeated task exposure of progressive load carriage training throughout the 10-week program lessened the cardiovascular stress experienced over the 5 km march duration (Deschenes & Kraemer, 2002). Given the load carriage task remained the same (i.e., treadmill walking for 5 km at 5.5 km.h^{-1}, wearing a 23 kg torso-borne vest), these findings suggest that both sexes perceived the task to be easier after training and demonstrated favourable physiological adaptations.

Periodised physical training programs, like that used in the current study, consisting of both resistance and aerobic training have been shown to effectively reduce the performance gap between sexes (Harwood et al., 1999; Kraemer et al., 2001). Consistent with Harman et al. (2008a), improvements in general physical fitness tests were observed (i.e., push-ups, sit-ups, and maximal jumps) after training in comparison to before training. Considering the current study's training program was lower body focussed, increases in lower limb strength indicates the training stimulus provided was sufficient. Additionally, results demonstrated upper-body muscular endurance was improved in both sexes, with females achieving the same capacity as males by the end of training in the push-up test. The upper body stimulus of one training session per week over 10 weeks of training appears sufficient to elicit performance improvements in females, but not males. This finding is unsurprising as prior work found improvements in push-ups were greater for females compared to males (Patterson et al., 2005), with more recent research highlighting the need to focus training on improving female upper body to reduce the performance gap between sexes (Nindl et al., 2016). Compared to pre-training, trunk endurance as measured by sit-up performance was maintained in females but improved in males. These results may suggest a more specific training stimulus targeting the trunk area is required in order to elicit positive adaptations in sit-up performance in a female population. Overall, key changes in physical performance demonstrate some sex-specific adaptations to load carriage training, especially since males and females received the same training stimulus throughout the 10-week training program. However, it should be noted that baseline physiological measures which differed between the sexes may have impacted on final results.

Training-induced sex-specific adaptations were also shown for cardiovascular fitness, as measured by estimated maximal oxygen uptake. With the exception of the weekly load carriage walking tasks, aerobic training was not implemented within the current program. However, males still significantly improved their beep test performance by 5.4 %, in comparison to females who demonstrated a 0.05 % decrement in performance after training, which is likely an inconsequential change. Similar improvements in cardiovascular fitness were observed by Harwood et al. (1999), where males outperformed females by achieving a higher shuttle run test score post-training. The mechanisms eluding to these improvements are still unclear as this is the only study to date to compare sex differences for this specific outcome measure. Recent studies have identified that the inclusion of progressive load carriage tasks within training programs elicit larger improvements in load carriage performance (Harman et al., 2008a; Kraemer et al., 2004) compared to interventions that did not (Williams et al., 1999). Potentially males physical capacity for the increased physical demands experienced during the load carriage task (as indicated by decreases in HR) improved in the current study as a result of repeated task exposure via the load carriage training sessions (Sauers & Scofield, 2014). Interestingly, a higher adherence to these sessions was observed in males compared to females (94 % vs 89 %) further supporting this claim. Nonetheless, results suggest females may require specific cardiovascular training to achieve the same aerobic capacity improvements as their male counterparts.

The authors acknowledge that HR was used as a surrogate measure of cardiovascular responses during load carriage, however, HR has been previously used as a valid predictive measure (Pihlainen et al., 2014; Simpson et al., 2010). The authors also acknowledge that the inclusion of civilian participants, representative of a military population may limit the application of findings within the current study to initial recruits compared to a more experienced soldier population. Additionally, standardising for baseline fitness and other physiological qualities may change the overall results and this warrants further investigation.

4.6. Conclusions

The current study was the first, to our knowledge, to demonstrate sex-specific physical performance responses to an evidence-based 10-week training program for military load carriage. For example, males improved cardiovascular fitness whereas females did not, conversely, females improved upper body strength while males maintained upper body strength. Tailoring physical training to the requirements of each sex may contribute towards optimising physical preparedness of males and females undertaking combat operations. Implementing such training could further facilitate the integration of female soldiers into physically demanding combat roles in military organizations globally.

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Chapter 5: Ankle and Knee Moment and Power Adaptations are Elicited through Load Carriage Conditioning in Males

Jodie A. Wills, David J. Saxby, Gavin K. Lenton, Timothy L.A. Doyle

This chapter has been re-formatted for this thesis, however all content (i.e., text, structure, tables, and figures) has remained as accepted for publication in The Journal of Biomechanics as Wills, J. A., Saxby, D. J., Lenton, G. K., & Doyle, T. L. A. (2019). Ankle and knee joint moment and power adaptations are elicited through load carriage conditioning in males. *Journal of Biomechanics, 97*. DOI: https://doi.org/10.1016/j.jbiomech.2019.109341.

In Chapters 3 and 4, I demonstrated training induced adaptations in both males and females. Interestingly, elicited adaptive neuromuscular and physical performance responses between sexes were similar for some outcome measures (i.e., lower limb maximal force output), but different for others (i.e., push-ups and beep test performance). Similar to previous research, males still outperformed females in most performance measures. Such findings strongly indicate that physical training should be tailored to the specific requirements of each sex.

To expand on initial findings presented in Chapter 3, this Chapter focusses on the male population only. Specifically, Chapter 5 investigates lower limb biomechanical changes during a load carriage task, before and after 10 weeks of training. It is important to understand these responses as walking and carrying external load exacerbates the mechanical work required at the lower limbs to meet task demands. Measurements of joint moments, work, and power provide key information relevant to identifying potential injury mechanisms during load carriage. For example, Seay et al. (2014) reported increases in knee joint moments and powers, suggesting the knee joint primarily contributes to loaded walking. Conversely, Lenton et al. (2019) recently identified that task demands shift from distal to proximal joints, highlighting that the hip joint primarily contributes towards forward progression when carrying external load. Targeting these specific neuromuscular demands through training may enhance load carriage performance and reduce injury risks in military personnel through targeting potential injury mechanisms (Coppack et al., 2011; Friedl et al., 2015; Sharma et al., 2014).

The aim of this chapter was to investigate lower limb biomechanical changes in males during a load carriage task, in response to 10 weeks of physical training targeting specific neuromuscular task demands.

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Ankle and knee moment and power adaptations are elicited through load carriage conditioning in males

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ABSTRACT

Soldiers routinely conduct load carriage and physical training to meet occupational requirements. These tasks are physically arduous and are believed to be the primary cause of musculoskeletal injury. Physical training can help mitigate injury risk when specifically designed to address injury mechanisms and meet task demands. This study aimed to assess lower-limb biomechanics and neuromuscular adaptations during load carriage walking in response to a 10-week evidence-based physical training program. Thirteen male civilian participants donned 23 kg and completed 5 km of load carriage treadmill walking, at 5.5 km h^{-1} before and after a 10-week physical training program. Three-dimensional motion capture and force plate data were acquired in over-ground walking trials before and after treadmill walking. These data were inputs to a musculoskeletal model which estimated lower-limb joint kinematics and kinetics (i.e., moments and powers) using inverse kinematics and dynamics, respectively. A two-way analysis of variance revealed significant main effect of training for kinematic and kinetics parameters at the knee and ankle joints ($p < 0.05$). Post-Hoc comparisons demonstrated a significant decrease (4.2%) in total negative knee power between pre- and post-March 5 km measures after training ($p < 0.05$). Positive power contribution shifted distally after training, increasing at the post-march measure from 39.9% to 43.6% at the ankle joint ($p < 0.05$). These findings demonstrate that a periodised training program may reduce injury risk through favourable ankle and knee joint adaptations.

1. Introduction

Military personnel routinely conduct occupational load carriage tasks and associated physical training. Exposure to load carriage is known to increase physical demands and is believed to increase injury risk of musculoskeletal injury (Brushøj et al., 2008). Despite this, exposure to load carriage cannot be reduced as it remains essential to supporting and sustaining military operations. As an alternative, physical training can help mitigate musculoskeletal injury risk if designed and implemented to target specific injury mechanisms using an evidence-based approach (Finch et al., 2016). Therefore, developing and implementing a physical training program that decreases the gap between specific task demands and soldier's physical capacity may be a simple and effective method to optimise load carriage performance and minimise injury risk.

Emerging evidence suggests that interventions focussing on specific injuries and associated mechanisms using an evidence-based approach are effective in reducing injury incidence during initial physical training in the military (Coppack et al., 2011; Friedl et al., 2015; Sharma et al., 2014). Many studies have examined the effects of physical training on load carriage performance, and generally it has been established that occupational load carriage demands high muscular strength and aerobic capacity (Friedl et al., 2015). Progressive resistance training and repeated task exposure (e.g., simulated loaded walking tasks) are known to result in improved occupational task performance (Kraemer et al., 2001; Szivak and Kraemer, 2015). Combining these modalities into a periodised training program could assist in the reduction of cumulative demands and detrimental effects that are often experienced by soldiers during physical training and load carriage tasks (Kraemer et al., 2001; Szivak and Kraemer, 2015; Williams et al., 2002).

To successfully develop a physical training program for load carriage, the primary joints and muscle groups responsible for movement during task specific load carriage need to be identified. Mechanical work describes the amount of, or change in energy

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5.1. Abstract

Soldiers routinely conduct load carriage and physical training to meet occupational requirements. These tasks are physically arduous and are believed to be the primary cause of musculoskeletal injury. Physical training can help mitigate injury risk when specifically designed to address injury mechanisms and meet task demands. This study aimed to assess lower limb biomechanics and neuromuscular adaptations during load carriage walking in response to a 10-week evidence-based physical training program. Thirteen male civilian participants donned 23 kg and completed 5 km of load carriage treadmill walking, at 5.5 $km \cdot h^{-1}$ before and after a 10-week physical training program. Three-dimensional motion capture and force plate data were acquired in over-ground walking trials before and after treadmill walking. These data were inputs to a musculoskeletal model which estimated lower limb joint kinematics and kinetics (i.e., moments and powers) using inverse kinematics and dynamics, respectively. A two-way analysis of variance revealed significant main effect of training for kinematic and kinetics parameters at the knee and ankle joints ($p < 0.05$). Post-Hoc comparisons demonstrated a significant decrease (4.2 %) in total negative knee power between pre- and post-March 5 km measures after training ($p < 0.05$). Positive power contribution shifted distally after training, increasing at the post-march measure from 39.9 % to 43.6 % at the ankle joint ($p < 0.05$). These findings demonstrate that a periodised training program may reduce injury risk through favourable ankle and knee joint adaptations.

5.2. Introduction

Military personnel routinely conduct occupational load carriage tasks and associated physical training. Exposure to load carriage is known to increase physical demands and is believed to increase injury risk of musculoskeletal injury (Brushøj et al., 2008). Despite this, exposure to load carriage cannot be reduced as it remains essential to supporting and sustaining military operations. As an alternative, physical training can help mitigate musculoskeletal injury risk if designed and implemented to target specific injury mechanisms using an evidence-based approach (Finch et al., 2016). Therefore, developing and implementing a physical training program that decreases the gap between specific task demands and soldier's physical capacity may be a simple and effective method to optimise load carriage performance and minimise injury risk.

Emerging evidence suggests that interventions focussing on specific injuries and associated mechanisms using an evidence-based approach are effective in reducing injury incidence during initial physical training in the military (Coppack et al., 2011; Friedl et al., 2015; Sharma et al., 2014). Many studies have examined the effects of physical training on load carriage performance, and generally it has been established that occupational load carriage demands high muscular strength and aerobic capacity (Friedl et al., 2015). Progressive resistance training and repeated task exposure (e.g., simulated loaded walking tasks) are known to result in improved occupational task performance (Kraemer et al., 2001; Szivak & Kraemer, 2015). Combining these modalities into a periodised training program could assist in the reduction of cumulative demands and detrimental effects that are often experienced by soldiers during physical training and load carriage tasks (Kraemer et al., 2001; Szivak & Kraemer, 2015; Williams et al., 2002).

To successfully develop a physical training program for load carriage, the primary joints and muscle groups responsible for movement during task-specific load carriage need to be identified. Mechanical work describes the amount, or change in energy transferred by force, internal (i.e., muscle) or external (i.e., gravity) over time (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2013). Joint moments and powers are representative of net muscular contributions effectively controlling and counteracting external loads being carried , and reportedly increase in response to increased loads carried during walking (Huang & Kuo, 2014; Seay et al., 2014; Wang et al., 2013). Seay et al. (2014) concluded that carrying 15 kg of external load substantially increased knee joint moments during walking, suggesting the knee is the primary joint contributing towards adaptive responses. Similarly, Wang et al. (2013) reported increases in knee joint moments and an increase in hip joint moments, suggesting an increased demand on joints up the kinetic chain during such tasks. These findings are further supported through observations by Lenton et al. (2019) who identified approximately 65 % of positive power is generated by the hip during load carriage walking, followed by the ankle (25 %), and knee (10 %). Shifting power production to proximal joints would increase the work performed by the hip musculature and increase active work by hip-spanning muscles due to the muscle-tendon architecture (Neptune et al., 2009).The shift towards a hip-dominated strategy during load carriage reduces reliance on knee musculature to produce positive work/power during physically demanding load carriage tasks (Blacker et al., 2013; Teng & Powers, 2014, 2016). Furthermore, this facilitates reductions in stress and loading at the knee, which is the most commonly injured site for army personnel (Department of Defence, 2000). As a result, a training program targeting the hip musculature has the potential to enhance load carriage performance whilst mitigating injury risks in military personnel.

The purpose of this study was to investigate lower limb biomechanical changes during a load carriage task, in response to a 10-week evidence-based physical training program. We hypothesised that before training, knee joint moments will increase more pre-march to post-march the load carriage task than after training. Additionally, we hypothesised that after training, lower limb net joint powers will be maintained from pre-march to post-march compared to before training.

5.3. Methods

5.3.1. Participants

Thirteen male civilians (age: 22.4 ± 1.7 years, height: 1.82 ± 0.06 m, mass 83.91 ± 6.5 kg) participated in this study. Participants had no recent (< 6 months) acute or chronic injuries at the time of testing. Previous experience with load carriage was not required. Participants provided their written informed consent to the protocol, which was approved by Macquarie University Human Research Ethics Committee (Protocol 5201700406).

5.3.2. Inclusion criteria

Study eligibility required participants to meet or exceed the Australian Army Basic Fitness Assessment (BFA) standards for male soldiers ≤ 25 years including: (i) achieve a minimum of 40 push-ups and 70 sit-ups in 2 minutes each, and (ii) achieve a minimum of level 7.5 on the beep test (to calculate estimated maximal aerobic power ($\dot{V}O_{2max}$, $ml \cdot kg^{-1} \cdot min^{-1}$) (Australian Defence Force). Participants were also required to have a body mass ≥ 73 kg, to ensure the 23 kg load carried was < 30% body mass, (Mullins et al., 2015).

5.3.3. Physical Training Intervention

A 10-week physical training program was completed by all participants and consisted of up to three resistance training sessions and two weighted walking sessions per week (Supplementary Table 1 outlines resistance training and Supplementary Table 2 outlines weighted walking training included in the 10-week training program). An accredited strength and conditioning coach delivered all resistance training sessions, with resistance and weekly progressions tailored to individual abilities. Exercise resistance incrementally increased weekly if participants successfully completed the required number of repetitions and sets for individual exercises. If participants were unable to perform the required repetitions, the number of repetitions performed was recorded and the resistance was adjusted accordingly. Weighted walking sessions were self-directed on a separate day to the resistance training sessions, with load incrementally increasing over the 10-week training program from 0 kg to 25 kg.

5.3.4. Procedures

Participants completed a standardised treadmill walking task of 5 km at 5.5 $km \cdot h^{-1}$, wearing a 23 kg torso-borne vest before and after the 10-week training program, which is the equivalent of the Australian Army All Corps minimum employment standard (Australian Defence Force). For testing, participants wore their own footwear, which were standard athletics trainers. Ten successful over-ground walking trials were completed immediately before and immediately after the 5 km walk (< 3 minutes lapse between treadmill to over-ground transition). Prior to walking trials, participants were randomly assigned either their left or right limb to strike the in-ground force plate. To ensure this did not influence foot strike mechanics (e.g., targeting), participants were informed to take their initial step with the randomly allocated limb. During the trials, ground reaction forces (GRF) were collected using an in-ground force plate (Type 9281E, Kistler, Germany), sampling at 1000 Hz, synchronously with three-dimensional (3D) motion data using an eight-camera motion capture system (T40, Vicon, Oxford, UK), sampling at 100 Hz. Trials were successful if the participant: (i) struck the force plate cleanly, (ii) struck the force plate with the randomly allocated left or right limb, and (iii) walked at a speed of 5.5 km·h-1 ± 0.1%. Walking speed was monitored using a portable timing gate system (OptoSmart Sensor Porta Kit, Fitness Technology, Adelaide, SA, Australia). Spherical, retro-reflective 14 mm diameter markers, and marker clusters were placed on the participant's torso and bilaterally on landmarks including the head, arms, and legs consistent with a previously validated marker set (Lenton et al., 2017). 3D positions of 12 markers were acquired via static standing calibration and pointer trials (Cappozzo, Catani, Della Croce, & Leardini, 1995) which were used to define joint centres and track body segments during over-ground walking trials.

5.3.5. Data Processing

Static and dynamic trial raw marker trajectories data were reconstructed and marker gaps (< 10 frames) were interpolated using cubic splines in Vicon Nexus (version 2.7.0). Cleaned experimental data were then exported into Matlab (R2017b, The Mathworks) and processed using a modified version of MOtoNMS (Mantoan et al., 2015). Lower limb joint centers were defined from static calibration trials using Harrington regression equations (Harrington et al., 2007) at the hip, and the midpoint of the medial and lateral femoral condyles and malleoli at the knee and ankle, respectively. A single gait cycle per successful over-ground trial was determined using the vertical ground reaction force data of the foot in contact with the plate, with the detection threshold set to 20 N for both heel-strike and toe-off. Spatio-temporal and angular variables were determined using a velocity-based algorithm (Zeni et al., 2008). Gait events of heel strike and toe off were automatically detected using changes in the direction of velocity of heel and toe markers. Marker trajectories and GRFs were filtered using a 4th order zero-lag (Robertson & Dowling, 2003) Butterworth low-pass filter, with a 10 Hz cutoff. Subsequently, marker position data were transformed from the laboratory coordinate system to the global coordinate system used within OpenSim (Delp et al., 2007).

5.3.6. Biomechanical Modelling

A generic, full-body OpenSim musculoskeletal model was created for each participant (Rajagopal et al., 2016), comprising of three rotational degrees of freedom (DOF) for the hip, one DOF for the knee, and one DOF for the ankle. At the knee joint, abduction/adduction and internal/external rotations were prescribed as a function of knee flexion angle. Generic models were scaled using marker pairs on each body within the model to match the gross anatomy, mass, and inertia of each participant. Scaled models were then used to determine model kinematics and kinetics using inverse kinematics (IK) (Reinbolt et al., 2005) and inverse dynamics (ID). From the IK and ID analyses, joint angular velocities and moments were used to determine sagittal plane hip, knee, and ankle joint powers, which were normalized to each participant's body mass (W.kg-1). Hip, knee, and ankle powers were calculated and represented by instantaneous joint power curves which were split into positive (energy generation) and negative (energy absorption) phases throughout the gait cycle (Winter, 1983). From these defined phases, positive and negative joint work (J.kg-1) were calculated through numerical integration of the instantaneous joint power curves. The sum of positive and negative hip, knee, and ankle joint work determined total positive (W_j^+) and negative (W_j^-) limb work. Individual joint contributions towards total positive work (W_{tot}^+) and total negative work (W_{tot}^-), throughout the gait cycle were identified through expressing W_j^+ and W_j^- as a percentage of W_{tot}^+ and W_{tot}^-, respectively.

5.3.7. Statistical Analysis

Statistical analysis was performed using IBM SPSS statistics version 25 software for Windows (IBM Corp Armonk, NY, USA). A two-way analysis of variance tested for significant interactions between, and main effects of training and march distance. Normal distribution of data was confirmed using the Shapiro-Wilk test. Post-hoc Tukey tests with Bonferroni corrections were performed on significant main and interaction effects to identify specific differences between training and march distance measures. Significance was set at $p < 0.05$. Effect sizes were calculated using the partial Eta squared (η_p^2), with small, medium, and large effects defined as η_p^2 between 0.01 and 0.06, 0.06 and 0.14, and greater than 0.14, respectively (Richardson, 2011).

5.4. Results

Data are presented as mean±standard deviation for n=13. Overall, participant adherence to the 10-week training program was 97 %, with participants completing 99 % of total resistance training sessions and 94 % of loaded walking sessions.

5.4.1. Kinematics

Significant main effects due to the march were observed in sagittal plane kinematics (Figure 9) for peak hip extension ($p < 0.05$, η_p^2 =0.73), hip flexion angle ($p < 0.05$, $\eta_p^2 = 0.41$), knee flexion ($p < 0.05$, $\eta_p^2 = 0.31$), and mean trunk flexion ($p < 0.05$, $\eta_p^2 = 0.85$) angles, in addition to knee pose ($p < 0.05$, $\eta_p^2 = 0.29$) and hip pose ($p < 0.05$, $\eta_p^2 = 0.35$) at heel strike. Specifically, peak hip flexion angle and hip pose at heel strike values decreased from pre-to-post march measures, before and after training, whereas all other variable values increased. A significant main effect of training was observed at the ankle ($p < 0.05$, $\eta_p^2 = 0.52$), with no significant differences found at the hip or knee joint (Table 12). Additionally, a significant interaction effect was found for step width ($p < 0.05$, $\eta_p^2 = 0.40$); compared to before training, values decreased from the pre-to post-march measure, whereas values increased march after training pre-to post. Non-sagittal plane joint angle variables demonstrated no main effects or interactions of distance or training (Supplementary Table 3).

5.4.2. Joint Moments, Powers, and Work

A significant main effect of distance was observed for peak hip extension ($p < 0.05$, $\eta_p^2 = 0.75$) and second peak moment knee extension ($p < 0.05$, $\eta_p^2 = 0.48$), with both values significantly increasing from pre-march to post-march measures. Percentage contribution of the hip to total positive power increased from pre-march to post-march, while ankle joint contribution towards total positive power decreased ($p < 0.05$, $\eta_p^2 = 0.35$) from pre-march to post-march (Table 13).

Knee extension moment peak values at initial contact of the stance phase (0-40 %) significantly increased ($p < 0.05$, $\eta_p^2 = 0.28$) from pre-march to post-march after training. Negative ankle power significantly increased from pre-march and post-march and this effect was consistent before ($p < 0.05$, $\eta_p^2 = 0.03$) and after training ($p < 0.05$, $\eta_p^2 = 0.55$). Percentage contribution of the knee towards total negative power decreased post-march compared to pre-march after training (Figure 10). Ankle joint contribution towards total positive power significantly increased at the post-march measurement of the loaded walk after training, increasing from 39.9 % (pre-training post-march) to 43.6 % (post-training post-march) (Figure 11). Joint work variables demonstrated no significant interactions or main effects of distance or training.

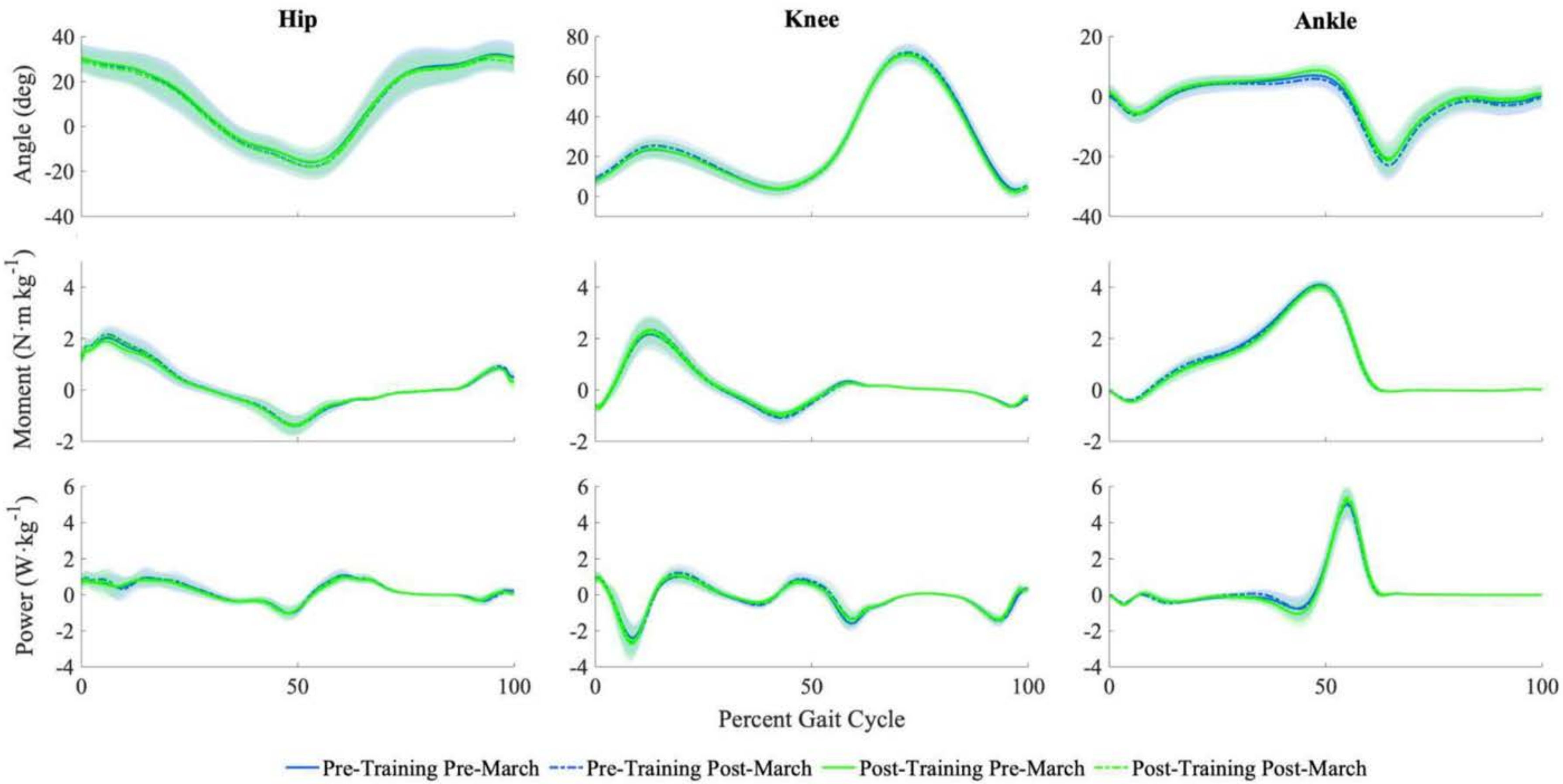

Figure 9. Mean (lines) and standard deviation (shaded regions) for joint angles, moments, and powers for the hip, knee, and ankle during the 5 km load carriage walking task before and after the 10-week physical training intervention. Asterisks (*) indicate significant differences in variable values.

Table 12. Mean ± standard deviation magnitudes for spatial-temporal and kinematic variables. *Indicates a significant main effect of distance, #indicates a significant main effect of training, ‡indicates a significant interaction effect ($p < 0.05$).

Variable	Pre-Training				Post-Training				Effect Size (η_p^2)	
	Pre-March		Post-March		Pre-March		Post-March			
	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Training	Distance
Spatial temporal										
Stride Length (m)	1.61 ± 0.05	1.58, 1.64	1.61 ± 0.06	1.58, 1.64	1.59 ±0.06	1.55,1.62	1.61 ± 0.07	1.57, 1.65	0.10	0.15
Stride Time (s)	1.06 ± 0.05	1.03, 1.09	1.07 ± 0.06	1.03, 1.11	1.07 ± 0.05	1.04, 1.10	1.07 ± 0.06	1.04, 1.10	0.06	0.09
Step Width (m)	0.06 ± 0.03	0.05, 0.08	0.05 ± 0.03	0.04, 0.07	0.07 ± 0.04	0.04, 0.09	0.07 ± 0.04‡	0.04, 0.09	0.19	0.19
Walk Speed (Km/h)	5.45 ± 0.17	5.35, 5.55	5.42 ± 0.21	5.29, 5.55	5.35 ± 0.16	5.25, 5.44	5.39 ± 0.13	5.33, 5.47	0.18	0.01
Hip										
Extension Peak Angle (°)	-15.59 ± 6.89	-19.76, -11.43	-17.71 ± 6.25*	-21.50, -13.94	-16.32 ± 6.04	-20.03, -12.62	-18.63 ± 6.04	-22.29, -14.98	0.03	0.73
Flexion Peak Angle (°)	34.00 ± 6.69	29.96, 38.05	33.00 ± 6.57	29.04, 36.98	31.86 ± 5.92	28.28, 35.43	30.90 ± 5.86	27.59, 34.22	0.16	0.41
Pose at Heel Strike (°)	31.80 ± 6.00	28.18, 35.42	30.98 ± 6.01	27.35, 34.61	29.84 ± 5.63	26.44, 33.24	29.08 ± 5.89	25.52, 32.64	0.014	0.35
Knee										
Extension Peak Angle (°)	1.96 ± 2.94	-0.18, 3.74	1.55 ± 3.24	-0.41, 3.50	0.90 ± 2.82	-0.81, 2.60	0.53 ± 2.7	-1.13, 2.18	0.20	0.07
Flexion Peak Angle (°)	71.66 ± 5.50	68.34, 74.98	72.65 ± 4.70*	69.80, 75.50	71.08 ± 3.68	68.86, 73.30	71.67 ± 3.73	69.41, 73.92	0.07	0.04
Pose at Heel Strike (°)	7.82 ± 3.41	5.77, 9.88	9.05 ± 4.35*	6.42, 11.67	7.06 ± 2.64	5.47, 8.66	7.40 ± 2.90	5.65, 9.16	0.16	0.05
Ankle										
Dorsiflexion Peak Angle (°)	8.34 ± 2.93	6.56, 10.11	7.19 ± 2.45	5.71, 8.67	9.15 ± 2.23	7.81, 10.50	9.13 ± 1.98#	7.94, 10.33	0.52	0.36
Plantarflexion Peak Angle	-21.74 ± -7.41	-26.22, -17.26	-23.38 ± 5.42	-26.65, -20.10	-21.65 ± 5.87	-25.19, -18.10	-22.21 ± 5.88	-25.77, -18.61	0.10	0.13
Pose at Heel Strike (°)	1.17 ± 3.68	-1.06, 3.40	0.07 ± 3.45	-2.01, 2.16	1.42 ± 3.02	-0.40, 3.24	1.46 ± 3.00	-0.36, 3.27	0.18	0.34
Torso										
Extension Peak Angle (°)	3.66 ± 8.89	9.04, 1.70	6.29 ± 8.50	11.42, -1.16	5.26 ± 8.03	10.11, -4.02	7.87 ± 8.03	12.72, -3.02	0.12	0.19
Flexion Peak Angle (°)	-11.28 ± 8.47	-16.40, -6.16	-14.13 ± 7.87	-18.89, -9.38	-11.84 ± 7.15	-16.16, -7.52	-14.75 ± 6.61	-18.78, -10.72	0.02	0.83
Pose at Heel Strike (°)	-8.52 ± 8.20	-13.47, -3.57	-11.55 ± 7.40	-16.01, -7.07	-9.24 ± 7.34	-13.47, -3.57	-12.19 ± 7.27	-16.58, -7.8	0.03	0.81
Extension / Flexion Mean Angle (°)	-7.93 ± 8.40	-13.00, -2.86	-10.84 ± 7.70*	-15.49, -6.18	-8.74 ± 7.44	-13.23, -4.24	-11.60 ± 7.10	-15.89, -7.31	0.03	0.85

Table 13. Mean ± standard deviation magnitudes for external joint moment and power variables. Joint moment values are reported as $N \cdot m/kg^{-1}$ and power values are reported as $W \cdot kg^{-1}$. *Indicates a significant main effect of distance, #indicates a significant main effect of training, ‡indicates a significant interaction effect ($p < 0.05$).

Variable	Pre-Training				Post-Training				Effect Size (η_p^2)	
	Pre-March		Post-March		Pre-March		Post-March			
	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Mean ± SD	95% CI (lower, upper)	Training	Distance
Hip										
Hip Extension Moment	-2.12 ± 0.34	-2.33, -1.92	-2.30 ± 0.33*	-2.50, -2.01	-2.00 ± 0.32	-2.19, -1.81	-2.18 ± 0.31	-2.36, -1.99	0.17	0.75
Hip Flexion Moment	1.37 ± 0.39	1.13, 1.60	1.33 ± 0.35	1.12, 1.55	1.43 ± 0.39	1.19, 1.67	1.47 ± 0.46	1.19, 1.75	0.07	0.00
Positive Hip Power	0.67 ± 0.14	0.59, 0.75	0.60 ± 0.12*	0.64, 0.76	0.63 ± 0.12	0.53, 0.68	0.63 ± 0.11	0.56, 0.69	0.20	0.21
Negative Hip Power	-0.82 ± 0.15	-0.91, -0.73	-0.83 ± 0.20	-0.95, -0.71	-0.81 ± 0.18	-0.92, -0.71	-0.79 ± 0.16	-0.89, -0.69	0.08	0.01
Knee										
Knee Extension Moment	-1.04 ± 0.26	-0.88, -1.19	-1.10 ± 0.26*	-0.95, -1.26	-0.97 ± 0.17	-0.86, -1.07	-1.05 ± 0.21#	-0.93, -1.18	0.11	0.48
Knee Flexion Moment	2.30 ± 0.61	2.70, 1.94	2.36 ± 0.64	2.75, 1.98	2.31 ± 0.58	2.66, 1.96	2.33 ± 0.56	2.66, 1.99	0.00	0.03
Positive Knee Power	0.39 ± 0.09	0.33, 0.44	0.44 ± 0.16	0.34, 0.54	0.37 ± 0.08	0.32, 0.41	0.40 ± 0.11	0.33, 0.46	0.25	0.21
Negative Knee Power	-0.82 ± 0.15	-0.91, -0.73	-0.83 ± 0.20	-0.95, -0.71	-0.81 ± 0.18	-0.92, -0.71	-0.79 ± 0.16#	-0.89, -0.69	0.08	0.01
Ankle										
Ankle Dorsiflexion Moment	0.50 ± 0.06	0.46, 0.54	0.45 ± 0.12	0.38, 0.53	0.48 ± 0.10	0.42, 0.54	0.47 ± 0.10	0.41, 0.53	0.00	0.09
Ankle Plantarflexion Moment	-4.1 ± 0.19	-4.21, -3.98	-4.03 ± 0.22	-4.16, -3.89	-4.08 ± 0.21	-4.20, -3.95	-4.10 ± 0.23	-4.23, -3.96	0.03	0.05
Positive Ankle Power	0.79 ± 0.09	0.73, 0.84	0.75 ± 0.11*	0.69, 0.82	0.78 ± 0.09	0.73, 0.84	0.79 ± 0.13*	0.71, 0.87	0.06	0.02
Negative Ankle Power	-0.30 ± 0.13	-0.38, -0.22	-0.28 ± 0.87	-0.33, -0.28	-0.33 ± 0.13	-0.41, -0.26	-0.33 ± 0.08	-0.38, -0.29	0.55	0.03
Net										
Positive Power Total	1.84 ± 0.15	1.75, 1.93	1.90 ± 0.25	1.75, 2.05	1.75 ± 0.18	1.64, 1.86	1.81 ± 0.23	1.68, 1.95	0.26	0.15
Negative Power Total	-1.38 ± 0.17	-1.48, -1.27	-1.36 ± 0.21	-1.49, -1.23	-1.41 ± 1.78	-1.52, -1.30	-1.40 ± 0.18	-1.51, -1.29	0.10	0.03

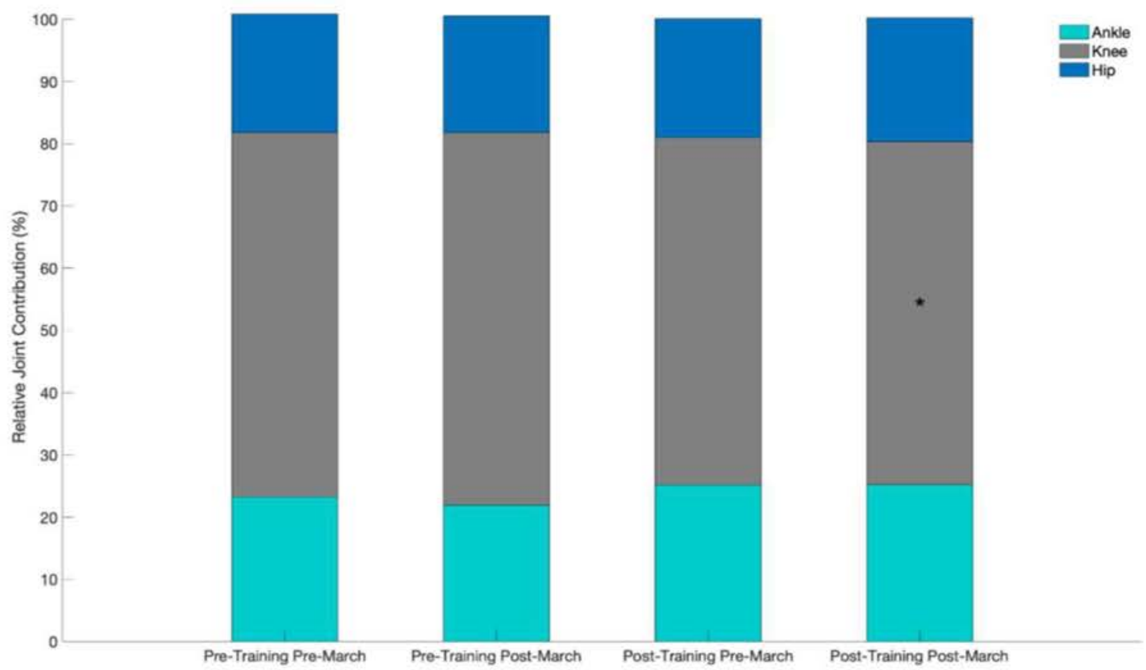

Figure 10. Relative contributions of hip, knee, and ankle joints to stance phase total mechanical negative power over the 5 km load carriage walking task, before and after the 10-week physical training intervention. Asterisks (*) indicate a significant difference in knee joint contribution to total negative power after training.

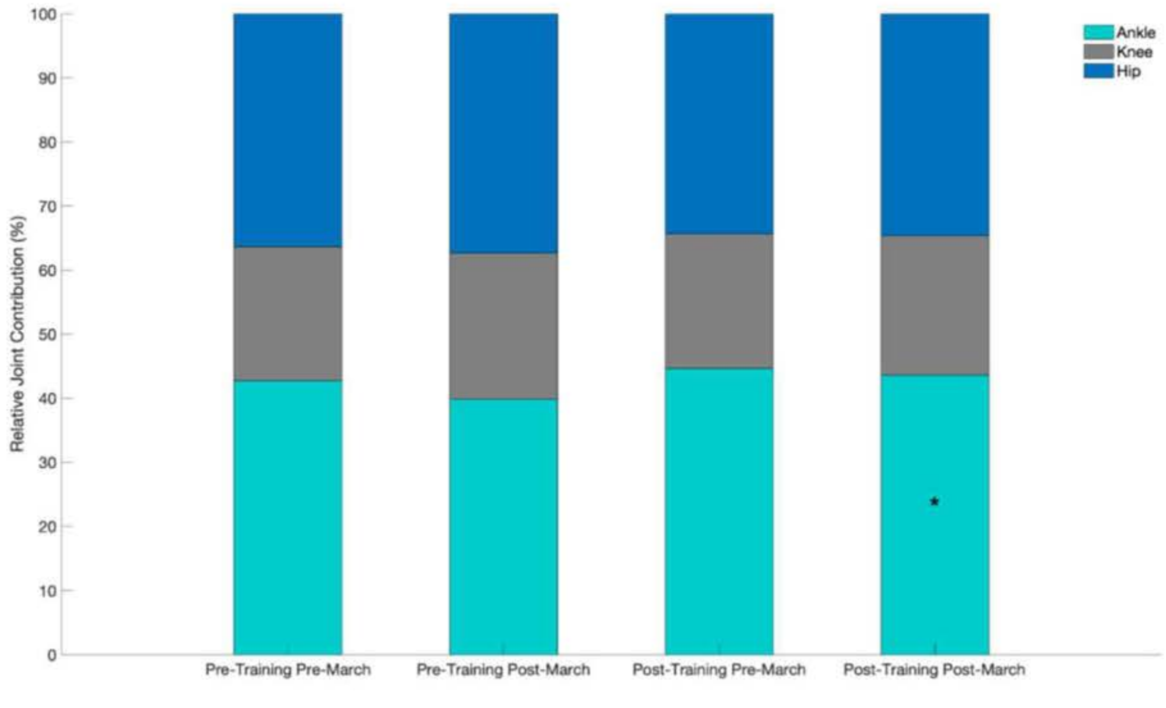

Figure 11. Relative contributions of hip, knee, and ankle joints to stance phase total mechanical positive power over the 5 km load carriage walking task, before and after the 10-week physical training intervention. Asterisks (*) indicate a significant difference in ankle joint contribution to total positive power after training.

5.5. Discussion

The purpose of this study was to determine lower limb biomechanical changes during a load carriage task and in response to a 10-week evidence-based physical training program. We found that the main effects of training elicited responses in kinematic and kinetic variables primarily at the knee and ankle joints, with limited changes observed at the hip joint. Joint power contribution shifted distally after training, whereby negative knee power contribution decreased, and positive ankle power increased. To our knowledge, this study is the first to identify and quantify neuromuscular adaptations of the lower limbs in response to a load carriage physical training program.

Consistent with prior research, hip and knee joint extensor moments increased over the 5 km load carriage task (Haff et al., 2005; Harman et al., 2000; Wang et al., 2013). Changes in extensor moments appear to correspond with observed changes in estimated hip and knee joint level kinematics. Knee flexion increases at heel strike, likely pre-stretching the knee extensors and increasing the quadriceps extension moment arm, resulting in an increased knee extensor moment for a given muscle activation (Seay et al., 2014; Wang et al., 2013). After training, hip moments remained stable suggesting training did not impair normal hip biomechanics and may have helped to sustain normal hip motion. In agreement with our first hypothesis, knee joint moments were larger before training compared to after training. Despite larger relative increases in knee moments from pre-march to post-march post-training compared with pre-training, these findings potentially indicate a reduced risk of injury as joint moments were lower over the duration of the load carriage task after training. No other study has compared joint-level changes during a standardised load carriage task in response to a physical training program, meaning further research is required to independently corroborate our findings.

Consistent with our second hypothesis, lower limb net joint negative powers were unchanged from pre-march to post-march across the load carriage task after training compared to before training. Increases in total positive ankle joint power from 39.9 % to 43.6 % were observed after the 5 km march after training. The distal shift in power production accompanied by an increase in peak ankle dorsiflexion angle indicates an ankle driven strategy was adopted (Attwells et al., 2006; Majumdar et al., 2010; Silder et al., 2013a) after the 10-week training in order to effectively meet the demands of loaded walking (Huang & Kuo, 2014). These findings contrast those reported by Lenton et al. (2019), and are interpreted as a means to accelerate soldier's centre of mass (COM) when performing loaded walking. However, making direct comparisons with previous research is difficult as these studies compare changes in joint power when walking with load vs. without load (Huang & Kuo, 2014), or different load configurations (Lenton et al., 2019), and were not measured over an extended time period. Despite the primary focus of the 10-week training intervention being focused on training the lower limb musculature, with a specific focus on the hip extensor and flexor muscles, the main effects of training were realised at the ankle. Indeed, shifting relative joint power contributions distally is an efficient strategy to assist with forward progression when carrying evenly distributed load configurations, as increased ankle push-off propels the COM forward and upward (Lewis & Ferris, 2008). This may explain the decreased hip extension moments as the COM is adequately accelerated via an ankle driven mechanism. These findings combined with the maintenance of hip and knee joint powers over the 5 km load carriage task after training may indicate an increased capacity of sustained performance.

Step width decreased from pre-march to post-march during the load carriage task before training and increased over the walk duration after training. This interaction effect suggests after training, participants increased the base of support to actively increase stability and decreased lower limb internal loading during load carriage (Birrell & Haslam, 2009; Kinoshita, 1985). Hip and knee kinematics demonstrated the most changes over the duration of the 5 km load carriage walking task. A decrease in peak hip flexion combined with increases in peak knee flexion and mean trunk flexion angles suggests a more upright posture at the hip is adopted over the 5 km walk duration before and after training. These findings contrast previous studies where increases in peak hip flexion were observed, which suggests a lower COM is facilitated to increase stability when carrying external loads (Birrell & Haslam, 2009; Harman et al., 2000). Differences may be accounted for by variations in experimental load configurations as increased peak hip flexion often occurs with greater trunk lean when loads are posteriorly donned compared to the current study where load was evenly donned (Harman et al., 2000; Majumdar et al., 2010). In response to the 10-week training program, changes in lower limb kinematics were only found at the ankle joint. Ankle dorsiflexion angle increased at pre- and post-march measurements after training, though no significant changes in ankle excursion were observed. Combined, these findings suggest that the 10-week training program elicited no effects on ankle control during the load carriage walking task.

The current study has some limitations that should be acknowledged. Knee flexion and extension degrees of freedom (DOF) were used to determine non-sagittal knee joint motions (abduction/adduction, internal/external rotations, as well as tibial translations) using the same base functions which were then scaled for each subject. This method was chosen as secondary knee motion measures taken from skin-surface marker data is error prone (Benoit et al., 2006). Although the current study recruited civilian participants who were representative of male Australian Army recruits, participants had no prior load carriage experience. We acknowledge that as a result of this, some differences in responses may be apparent between a civilian and an experienced military population. The application of findings may therefore be limited to initial recruits compared to a more experienced soldier population.

5.6. Conclusion

In conclusion, this study was the first to investigate and quantify the biomechanical changes in response to a physical training program for a military specific load carriage task. Results demonstrate an evidence-based training program may facilitate injury risk reduction through favourable changes in knee and ankle joint moments and powers, enabling an individual to sustain performance during a load carriage task. As combat-centric roles are now open to female soldiers, the current findings could help direct future research in investigating sex-specific responses to load carriage tasks. Further investigations could provide insight into lower limb biomechanical changes specific to males and females in response to evidence-based training for load carriage. Understanding these responses could provide direction in the improvement of Military training and the integration of female soldiers into physically demanding combat roles within the Australian Defence Force.

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Chapter 6: Lower Limb Biomechanical Responses during a Standardised Load Carriage Task are Sex-Specific

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This chapter has been re-formatted for this thesis, however all content (i.e., text, structure, tables, and figures) has remained as submitted for publication in The Journal of Biomechanics.

In Chapter 5, males presented adaptive responses in gait mechanics during the load carriage task after training compared to before. Specifically, favourable changes in knee and ankle joint moments and powers were observed, indicating increased capacity to sustain performance during the load carriage task.

Around sixty-six countries to date globally have removed sex-restrictions that were previously placed on military combat-related roles. Despite the continuous growth in this ban being lifted, the majority of research to date has conducted investigations into the effects of load carriage on gait mechanics in a male population (Attwells et al., 2006; Birrell & Haslam, 2009; Seay et al., 2014). Interestingly, of the available research comparing male and female lower limb biomechanics during load carriage, none have reported sex-specific differences (Simpson et al., 2012a; Simpson et al., 2012b). This is particularly interesting, especially as military loads are allocated regardless of sex, and it is well known that females have a reduced ability to tolerate heavy external loads. However, prescribed loads have predominately been relative (normalised to % body mass), which is not reflective of standardised tasks usually performed, or have been performed with standardised loads for short periods of time. In order to successfully integrate female soldiers into combat-related roles, it is important to understand potential differences in lower limb mechanical responses between sexes during standardised load carriage tasks.

The purpose of this Chapter was to investigate sex-specific adaptations in lower limb biomechanics during a standardised load carriage task, in response to a 10-week evidence-based physical training program.

6.1. Abstract

Differences in physical capabilities between men and women (i.e., strength) influence how well they perform crucial combat tasks (e.g., load carriage). Importantly, this performance discrepancy, as well as injury risk, may be reduced through physical conditioning specific to task demands. The purpose of this study was to investigate sex-specific changes in lower limb biomechanics during a standardised load carriage task in response to a 10-week evidence-based physical training program. Twenty-five healthy civilians (males (n=13); females (n=12)) completed a load carriage task (5 km at 5.5 km·h-1, wearing a 23 kg vest) before and after a 10-week lower body focussed training intervention. Three-dimensional lower limb kinematics and ground reaction force data were collected during the load carriage task and were used to estimate lower limb joint kinematics and kinetics (i.e., moments and powers) from inverse kinematics and dynamics, respectively. A significant distance by sex interaction ($p < 0.001$, $\eta_p^2 = 0.29$) revealed hip joint percentage contribution towards total positive power increased more so for females compared to males by the end of the march. Training elicited increases in hip flexion joint moments and the amount of positive mechanical power generated at the hip joint for females only. Overall reductions in knee joint moments were observed over the distance marched after training, compared to before training for both sexes. Sex-specific differences were primarily realised at the hip joint, with most biomechanical adaptations observed in females compare to males. Such findings strongly indicate that sex-specific physical training should be considered to optimally train soldiers based on individual requirements.

6.2. Introduction

Walking while carrying external loads, comprises essential equipment for operational success, is a vital part of military training and operations. Unfortunately heavy load carriage is associated with increased lower limb injury risk and performance detriments (Brushøj et al., 2008; Groeller et al., 2015). The characteristics of loads carried are often determined by occupational requirements regardless of individuals' sex, stature, or physical capabilities (Knapik et al., 1997; Nindl, 2015). Consequently, men and women undertake the same physical tasks while carrying the same standardised loads despite known differences in physical capability (Nindl et al., 2016). Prior military load carriage research has reported limited sex-differences, with investigations generally limited to shorter duration tasks. As prolonged load carriage tasks evoke larger gait alterations in comparison, further assessments into potential sex-specific biomechanical responses in lower limb mechanics are required (Simpson et al., 2012a).

Moderate to heavy load carriage alters lower limb gait patterns and joint loading in both males (Attwells et al., 2006; Birrell & Haslam, 2009; Seay et al., 2014), and females (Simpson et al., 2012a; Simpson et al., 2012b). Yet, when comparatively analysed during the same load carriage tasks, limited sex-differences have been observed to date. Silder et al. (2013a) reported no sex-specific differences in spatial-temporal measures or peak joint angles, moments, and ground reaction forces when carrying 10 %, 20 % or 30 % of body mass. The lack of observed gait adaptations may be due to the normalisation of the loads carried, especially as absolute strength and load carriage ability is correlated with body mass (Pandorf et al., 2003; Patterson et al., 2005; Zatsiorsky & Kraemer, 2006). However, carrying absolute loads reportedly result in similar gait mechanics between sexes; suggesting that adaptive gait mechanics are not adopted by females to compensate for their smaller statures and absolute strength compared to males. Conversely, Loverro et al. (2019) recently identified that females alter their hip and knee mechanics when carrying medium (15 kg) and heavy (26 kg) loads. As available findings remain equivocal, further investigations are required to clarify if time-course sex-specific differences exist between males and females during standardised load carriage tasks.

In modern military organisations, soldiers are integrated into platoons consisting of males and females where they are required to complete the same physical training and physical employment standard (PES) tasks (Australian Defence Force). Known differences in key physical characteristics between sexes (i.e., strength, power, and aerobic fitness) (Nindl et al., 2016) generally place women at a disadvantage for physically demanding military roles. Importantly, these sex-related differences in performance can potentially be minimised through tailored physical conditioning (e.g., progressive strength training) targeting task-specific physical demands (Knapik et al., 2005; Nindl et al., 2017). For example, the hip joint has been identified to contribute ~60 % of total joint power towards forward progression during load carriage (Lenton et al., 2019). Therefore, a training program focussed towards the hip musculature has the potential to enhance load carriage performance and attenuate the detrimental effects experienced when carrying external load.

The purpose of this study was to investigate sex-specific changes in lower limb biomechanics during a standardised load carriage task, and in response to a 10-week evidence-based physical training program. It was hypothesised that: (i) lower limb kinematic and kinetic responses will differ between males and females over the march duration and after training, (ii) knee joint moments will be maintained or reduce over the distance marched after training compared to before training, (iii) lower limb net joint powers will be maintained over the march duration after training compared to before training.

6.3. Methods

6.3.1. Participants

Twenty-five healthy civilians (males (n=13): 22.4 ± 1.7 years, 1.82 ± 0.06 m, 83.91 ± 6.5 kg; females (n=12): 21.3 ± 2 years, 1.7 ± 0.8 m, 64.8 ± 7.5 kg) participated and had no recent (< 6 months) acute or chronic injuries at the time of testing. No previous experience of load carriage was required. Participants who met inclusion criteria provided their written informed consent to the study which was approved by Macquarie University Human Research Ethics Committee (Protocol 5201700406, 5201700997).

6.3.2. Inclusion criteria

Participants met or exceeded the Australian Army Basic Fitness Assessment (BFA) standards based on sex and age (Table 14). Additional inclusion criteria required a body mass of ≥ 73 kg for males (Mullins et al., 2015) and ≥ 55 kg for females (Lidstone et al., 2017).

Table 14. Inclusion criteria for male and female soldiers, adapted from the Australian Army Training Continuum, Australian Defence Force).

	Male	**Female**	
Age Range (years)	18-25	18-25	26-30
Sit-ups (reps)	70	70	65
Push-ups (reps)	40	21	18
Beep Test (Shuttle, level)	7.5	7.5	7.5

Reps, Arbitrary units; **Beep Test**, level and shuttle number.

6.3.3. Physical Training Intervention

Aligned with previously conducted research (Wills et al., 2019a), participants completed a 10-week lower body focussed physical training program including up to three resistance training sessions and two weighted walking training sessions per week (Supplementary Table 1 details all resistance training and Supplementary Table 2 weighted walking training sessions). All resistance training sessions were supervised and delivered by an accredited strength and conditioning coach (level 1 minimum accredited Australian Strength and Conditioning Association coach). Weighted walking sessions were conducted on a treadmill and were self-directed on a separate day to resistance training sessions throughout the 10-week program. Exercise resistance and weekly progressions were tailored to individual abilities and increased incrementally each week when individuals achieved the required sets and repetitions for individual exercises. If this was not possible, the number of repetitions and sets completed were recorded, and the resistance was adjusted accordingly. Weighted walking session variables (distance, speed, and load) incrementally increased over the 10-week training program.

6.3.4. Procedures

A load carriage task, equal to the Australian Army All Corps physical employment standard (5 km at 5.5 km·h^{-1}, wearing a 23 kg vest), was completed before and after the 10-week lower body focussed training program. Participants wore their own athletic trainers and clothing during all testing sessions. Male participants completed ten successful over-ground walking trials immediately before and after the load carriage task (< 3 minutes lapse between treadmill to over-ground transition) to collect GRF data using an in-ground force plate (Type 9281E, Kistler, Germany), sampled at 1000 Hz. Participants were randomly assigned to strike the in-ground force plate with either their left or right limb. Prior to trial commencement, participants were informed to take their initial step with their allocated limb to avoid influencing foot strike mechanics (e.g., targeting). Successful trials were counted when the participant: (i) cleanly struck the force plate with their allocated limb, and (ii) walked at a speed equivalent to 5.5km·h-1 ± 0.1%, assessed using a portable timing gate system (OptoSmart Sensor Porta Kit, Fitness Technology, Adelaide, SA, Australia) during over-ground trials. Female participants completed the load carriage task on a force-instrumented treadmill (AMTI force-sensing tandem treadmill, MA, USA). GRF data were acquired for 30 seconds (sampled at 1000 Hz) at the beginning (0 km) and end (5 km) of the load carriage task. For both sexes, three-dimensional (3D) motion capture data were acquired synchronously with GRF data during over-ground and treadmill walking trials using an eight-camera system (T40, Vicon, Oxford, UK), sampling at 100 Hz.

Prior to the load carriage task, retro-reflective markers, and marker clusters were placed on each participant's torso and bilaterally on the head, arms, and legs according to methodology previously published (Lenton et al., 2017; Wills et al., 2019a). Static standing calibration and wand pointer trials determined the 3D positions of 12 marker locations (Cappozzo et al., 1995), which were later used to define ankle, knee, and hip joint centres for musculoskeletal model scaling.

6.3.5. Data Processing

Raw marker trajectories were reconstructed and gaps (≤ 10 frames) were filled within Vicon Nexus (Version 2.7.0). Data were then processed using a modified version of MOtoNMS (Mantoan et al., 2015), followed by custom Matlab scripts to define lower limb joint centers within static calibration trials using Harrington regression equations (Harrington et al., 2007) at the hip, and the midpoint of the medial and lateral femoral condyles and malleoli at the knee and ankle, respectively. For males, a single gait cycle per successful trial was determined during over-ground walking trials (average of 10 gait cycles) using the vertical ground reaction force data of the foot in contact with the plate (detection threshold ≥ 20 N for heel-strike and toe-off events). Spatial-temporal and angular variables for the hip, knee, and ankle were determined using a velocity-based algorithm (Zeni et al., 2008). For females, gait cycles used for analysis (average of 10-30 gait cycles) were obtained from each 30 second collection at the beginning (0 km) and end (5 km) of the load carriage task. Marker trajectories and GRF's were filtered using a 4th order zero-lag (Robertson & Dowling, 2003) Butterworth low-pass filter (10 Hz cut off). Marker position data for over-ground and treadmill walking trials were subsequently transformed from the laboratory coordinate system to the global coordinate system used within OpenSim (Delp et al., 2007).

6.3.6. Biomechanical Modelling

OpenSim version 3.3 was used to scale a generic musculoskeletal model (Rajagopal et al., 2016) to match the gross anatomy of each participant through defined distances between marker pairs and corresponding virtual marker pairs acquired during the static standing calibration trial. The model comprises of three rotational degrees of freedom (DOF) for the hip, one DOF for the knee, and one DOF for the ankle. Using the scaled model, inverse kinematics (IK) (Reinbolt et al., 2005) and inverse dynamics (ID) tools estimated joint angles, joint angular velocities, and moments (normalised to each participant's body mass ($W.kg^{-1}$)). From ensemble averages, the 3D peak joint angles (°), joint ranges of motion (ROM) (max–min), and joint angle waveforms across the gait cycle were calculated and used in subsequent statistical analyses. Instantaneous joint power curves ($W \cdot kg^{-1}$) were split into positive (energy generation) and negative (energy absorption) phases throughout the gait cycle (Winter, 1983), and represented hip, knee, and ankle powers. Positive and negative joint work ($J.kg^{-1}$) were calculated through defined phases using numerical integration of the instantaneous joint power curves. The sum of positive and negative hip, knee, and ankle joint work determined total positive (W_j^+) and negative (W_j^-) limb work. Individual joint contributions towards total positive work (W_{tot}^+) and total negative work (W_{tot}^-), throughout the gait cycle were identified through expressing W_j^+ and W_j^- as a percentage of W_{tot}^+ and W_{tot}^-, respectively.

6.3.7. Statistical Analysis

Statistical analysis was performed using IBM SPSS statistics version 25 software for Windows (IBM Corp Armonk, NY, USA). The normality of data was confirmed using the Shapiro-Wilk test ($p > 0.05$). A two-way ANOVA repeated measures with sex as a between-subject factor and load as a within-subject factor was used to identify significant interactions between, and main effects training and distance marched. Non-normalized (spatial-temporal and three-dimensional joint kinematics) and normalized (joint moments, power, and work) variables were analysed across the gait cycle. Normal distribution of data was confirmed using the Shapiro-Wilk test. Bonferroni pairwise comparisons were used to detect differences between sexes when significant main and/or interaction effects of distance marched and training were found. Partial eta squared (η_p^2) effects sizes are reported for significant interaction and main effects. Small, medium and large effects were defined as 0.01, 0.06, and greater than 0.14 (Richardson, 2011). Statistical significance was set at $p < 0.05$.

6.4. Results

6.4.1. Main Effects of Distance Marched

Main effects of the distance marched ($p < 0.001$, $\eta_p^2 = 0.98$) were detected for spatial-temporal and lower limb kinematic variables for both males and females (Table 15). There was an increase in stride length ($p < 0.01$, $\eta_p^2 = 0.30$) and stride time ($p < 0.01$, $\eta_p^2 = 0.28$) from pre- to post-march measurements. At the end of the march, trunk flexion was significantly greater at heel strike ($p < 0.01$, $\eta_p^2 = 0.83$) and when averaged across stance ($p < 0.01$, $\eta_p^2 = 0.81$) compared to the beginning of the march.

Changes in sagittal plane kinematics were observed at the hip, knee, and ankle joints. At the hip joint, there was an increase in peak hip extension angle, ($p < 0.01$, $\eta_p^2 = 0.65$), but a decrease in hip flexion peak angle ($p < 0.05$, $\eta_p^2 = 0.22$) over the distance marched with load. At the knee joint, there was an increase in knee pose angle at heel strike ($p < 0.01$, $\eta_p^2 = 0.25$), the first flexion peak angle at initial contact of the stance phase (0-40 %) ($p < 0.01$, $\eta_p^2 = 0.27$), and the second flexion peak angle during swing ($p < 0.01$, $\eta_p^2 = 0.40$). The addition of load also resulted in a reduced peak knee extension angle ($p < 0.05$, $\eta_p^2 = 0.23$) by the end of the march. At the ankle joint, the magnitude of peak plantarflexion angle ($p < 0.05$, $\eta_p^2 = 0.22$) and ankle excursion ($p < 0.05$, $\eta_p^2 = 0.19$) increased over the 5 km march duration.

Load affected the magnitude of positive hip mechanical power ($p < 0.01$, $\eta_p^2 = 0.28$) and total positive joint power ($p < 0.05$, $\eta_p^2 = 0.25$) as values were larger at the end of the march compared to the beginning. Reductions were shown for the percentage contribution of the ankle towards total positive power generation ($p < 0.01$, $\eta_p^2 = 0.48$) over the march duration.

Table 15. Mean ± standard deviation magnitudes for spatial-temporal and sagittal plane kinematic variables. *Indicates a significant main effect of distance marched, #indicates a significant main effect of training, ‡indicates a significant sex by distance marched interaction effect, ^indicates a significant sex by training interaction effect ($p < 0.05$).

Variable	Pre-Training				Post-Training				Effect Size (η_p^2)	
	Female		Male		Female		Male			
	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March		
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Training	Distance
Spatial temporal										
Stride Length (m)*	1.47 ± 0.75	1.50 ± 0.90	1.61 ± 0.05	1.61 ± 0.06	1.47 ± 0.71	1.50 ±0.82	1.59 ±0.06	1.61 ± 0.07	.04	.30
Stride Time (s)*	0.96 ± 0.05	0.98 ± 0.06	1.06 ± 0.05	1.07 ± 0.06	0.96 ± 0.05	0.98 ± 0.05	1.07 ± 0.05	1.07 ± 0.06	.01	.28
Step Width (m)#, ‡	0.05 ± 0.19	0.05 ±0.02	0.06 ± 0.03	0.05 ± 0.03	0.06 ± 0.02	0.07 ± 0.03	0.07 ± 0.04	0.07 ± 0.04	.29	.00
Walk Speed (km/h)	1.53 ± 0.00	1.53 ± 0.00	5.45 ± 0.17	5.42 ± 0.21	1.53 ± 0.00	1.53 ± 0.00	5.35 ± 0.16	5.39 ± 0.13	.10	.00
Trunk										
Extension Peak Angle (°)*	8.55 ± 4.50	12.19 ± 6.33	3.66 ± 8.89	6.29 ± 8.50	7.90 ± 5.21	11.81 ± 5.56	5.26 ± 8.03	7.87 ± 8.03	.01	.75
Flexion Peak Angle (°)*, ‡	-14.54 ± .79	-19.44 ± 6.10	-11.28 ± 8.47	-14.13 ± 7.87	-13.69 ± 5.62	-18.41 ± 5.87	-11.84 ± 7.15	-14.75 ± 6.61	.00	.84
Pose at Heel Strike (°)*, ‡	-11.83 ± 5.03	-16.77 ± 6.47	-8.52 ± 8.20	-11.55 ± 7.40	-10.65 ± 4.80	-15.60 ± 5.35	-9.24 ± 7.34	-12.19 ± 7.27	.00	.83
Extension / Flexion Mean Angle (°)*, ‡	-11.84 ± 4.65	-16.35 ± 6.34	-7.93 ± 8.40	-10.84 ± 7.70	-10.97 ± 5.34	-15.45 ± 5.51	-8.74 ± 7.44	-11.60 ± 7.10	.00	.81
Hip										
Extension Peak Angle (°)*	-13.12 ± 4.85	-15.37 ± 6.86	-15.59 ± 6.89	-17.71 ± 6.25	-12.04 ± 5.15	-15.04 ± 4.89	-16.32 ± 6.04	-18.63 ± 6.04	.00	.65
Flexion Peak Angle (°)*	33.85 ± 6.69	33.33 ± 5.04	34.00 ± 6.69	33.00 ± 6.57	34.53 ± 5.66	34.0 ± 6.02	31.86 ± 5.92	30.90 ± 5.86	.02	.22
Pose at Heel Strike (°)	31.02 ± 5.72	30.54 ± 5.63	31.80 ± 6.00	30.98 ± 6.01	31.77 ± 5.79	31.61 ± 7.40	29.84 ± 5.63	29.08 ± 5.89	.01	.13
Knee										
Extension Peak Angle (°)*	-7.53 ± 2.89	-6.87 ± 3.74	-1.96 ± 2.94	-1.55 ± 3.24	-6.75 ± 4.71	-5.80 ± 4.87	-0.90 ± 2.82	-0.53 ± 2.7	.10	.23
First Flexion Peak Angle (°)*	23.15 ± 4.22	23.86 ± 4.41	24.51 ± 5.12	25.66 ± 5.62	21.93 ± 5.08	23.16 ± 6.34	27.06 ± 13.99	28.59 ± 14.40	.01	.27
Second Flexion Peak Angle (°)*	68.20 ± 3.19	69.99 ± 2.83	71.53 ± 5.50	72.59 ± 4.75	67.96 ± 6.34	68.20 ± 3.36	71.21 ± 3.68	72.40 ± 4.11	.02	.40
Pose at Heel Strike (°)*	16.20 ± 3.51	17.08 ± 4.01	7.82 ± 3.41	9.05 ± 4.35	15.72 ± 4.42	16.60 ± 5.17	7.06 ± 2.64	7.40 ± 2.90	.08	.25
Ankle										
Dorsiflexion Peak Angle (°)#	7.26 ± 2.46	7.22 ± 2.70	8.34 ± 2.93	7.19 ± 2.45	8.44 ± 2.07	8.66 ± 2.47	9.15 ± 2.23	9.13 ± 1.98	.35	.02
Plantarflexion Peak Angle (°)*	-12.05 ± 3.44	-13.68 ± 4.55	-21.74 ± -7.41	-23.38 ± 5.42	-12.05 ± 2.70	-12.89 ± 3.35	-21.65 ± 5.87	-22.21 ± 5.88	.08	.22
Pose at Heel Strike (°)#	-3.57 ± 3.16	-4.31 ± 3.10	1.17 ± 3.68	0.07 ± 3.45	-2.33 ± 2.60	-2.67 ± 2.26	1.42 ± 3.02	1.46 ± 3.00	.24	.11

6.4.2. Main Effects of Training

Significant main effects of training were detected for both kinematic and kinetic variables (Figure 12). Peak extension moments at the hip ($p < 0.05$, $\eta_p^2 = 0.16$) and knee ($p < 0.05$, $\eta_p^2 = 0.23$) joints significantly increased over the distance marched after training compared to before training.

At the ankle joint the peak dorsiflexion angle ($p < 0.05$, $\eta_p^2 = 0.24$) and peak pose at heel strike were greater by the end of the load carriage task after training compared to before ($p < 0.01$, $\eta_p^2 = 0.35$). The magnitude of negative ankle joint power generated significantly increased after training ($p < 0.001$, $\eta_p^2 = 0.42$), whereas the magnitude of positive ankle power did not ($p > 0.05$). Training further elicited increases at the ankle joint for the percentage contribution towards total negative power when carrying additional load ($p < 0.05$, $\eta_p^2 = 0.23$) (Figure 13).

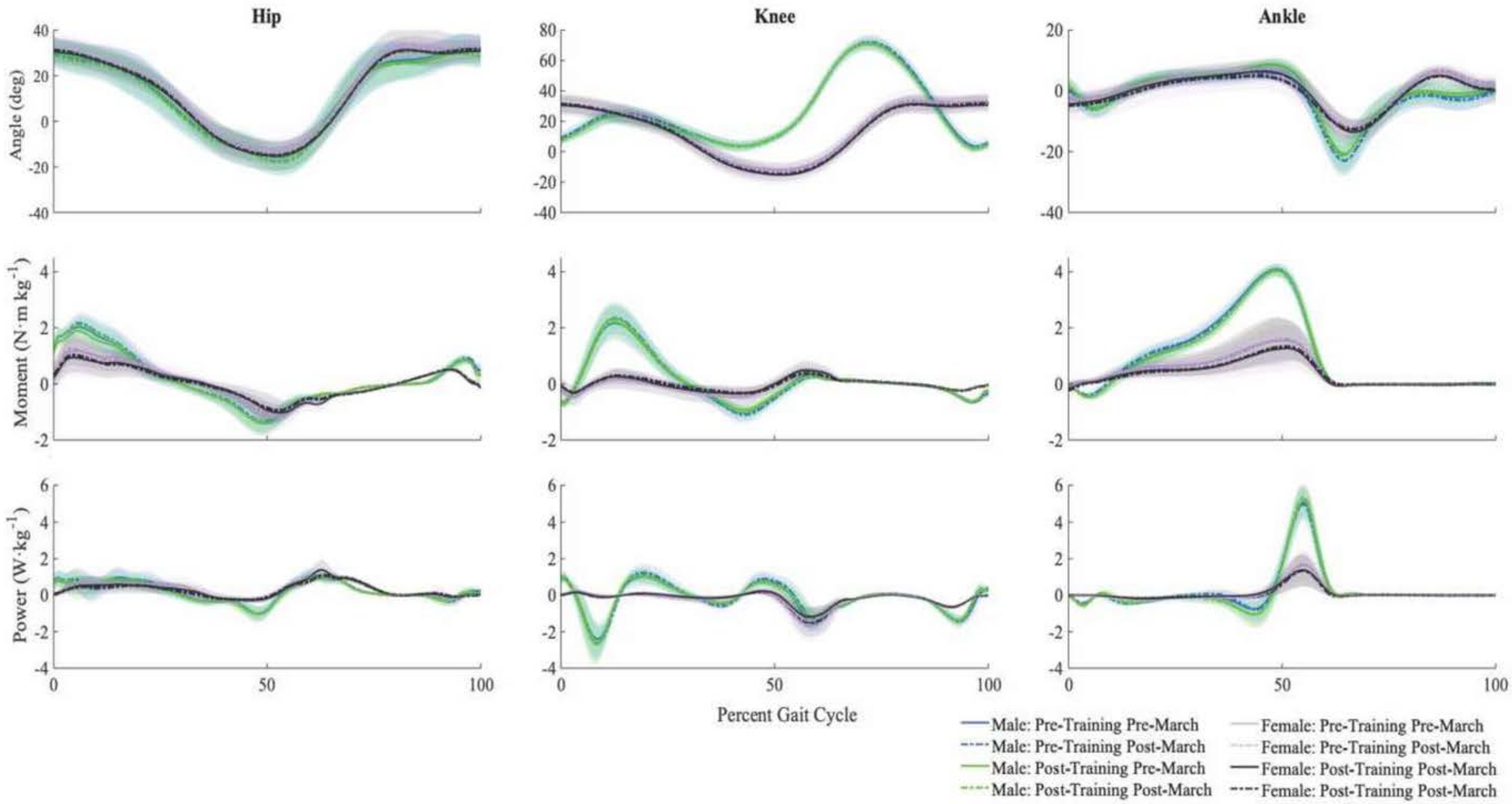

Figure 12. Mean (lines) and standard deviation (shaded regions) for joint angles, moments, and powers for the hip, knee, and ankle joints over the 5 km distance marched. Male and female data is presented during the load carriage task before and after the 10-week physical training intervention.

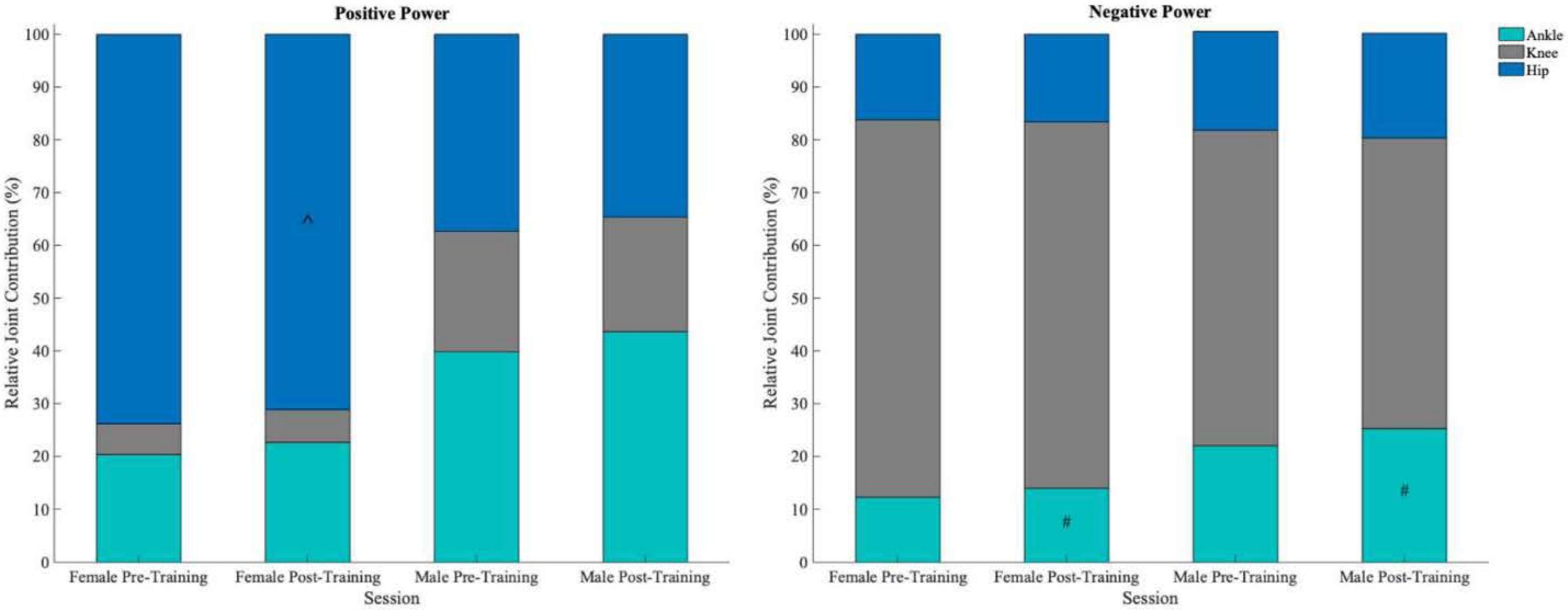

Figure 13. Relative contributions of hip, knee, and ankle joints to total mechanical positive and negative power during stance over the 5 km distance marched. Male and female data is presented during the load carriage task before and after the 10-week physical training intervention. # Indicates a significant main effect of training at the ankle joint, ^indicates a significant training by sex interaction effect at the hip joint ($p < 0.05$).

6.4.3. Interaction Effects: Sex by Distance

A significant interaction effect of sex by distance was found for step width in males only ($p < 0.01$, $\eta_p^2 = 0.18$); step-width increased between pre-post march measures before training and decreased between pre-post march measures after training. Trunk pose at heel strike ($p < 0.05$, $\eta_p^2 = 0.22$) and mean trunk extension-flexion angle ($p < 0.05$, $\eta_p^2 = 0.17$) was greater at the end of the loaded march compared to the beginning for both sexes ($p < 0.01$). Specifically, over the distance females exhibited a greater increase in trunk flexion (~9.2 %) compared to males ($p < 0.05$) (Table 15).

Changes in frontal and transverse plane kinematics ($p < 0.001$, $\eta_p^2 = 0.88$) were detected for females at the hip and knee joints (Table 16). Specifically, females peak variable values increased from pre- to post-march measures, while peak values for males decreased over the 5 km march duration. Hip adduction ($p < 0.001$, $\eta_p^2 = 0.45$), hip internal rotation ($p < 0.05$, $\eta_p^2 = 0.35$), and knee internal rotation ($p < 0.05$, $\eta_p^2 = 0.31$) peak angles, were significantly larger at the end of the end of the loaded march compared to the beginning. Similar increases were observed at the hip for the peak extension moment ($p < 0.001$, $\eta_p^2 = 0.48$). Results further revealed relative contribution of hip power to total positive joint power increased at the end of the march compared to the start of the march (~19 %) to a greater extent for females compared to males (~5 %) ($p < 0.001$, $\eta_p^2 = 0.29$) (Figure 14). Relative negative knee power contributions towards total negative joint power increased significantly from pre-to-post march for females ($p < 0.05$, $\eta_p^2 = 0.18$) but remained consistent for males. Knee flexion moment peak values during the swing phase ($p < 0.05$, $\eta_p^2 = 0.24$) were also greater for females compared to males over the total distance marched.

6.4.4. Interaction Effects: Sex by Training

There was no sex by training interactions were observed for spatial-temporal or lower limb kinematic variables, but there were changes detected in lower limb kinetics. At the hip joint, the magnitude of peak hip flexion moment ($p < 0.05$, $\eta_p^2 = 0.17$), positive joint power ($p < 0.05$, $\eta_p^2 = 0.24$), net joint work ($p < 0.05$, $\eta_p^2 = 0.16$), and positive work ($p < 0.05$, $\eta_p^2 = 0.22$) was significantly larger after training compared to before training (Table 17 and Table 18, respectively).

Table 16. Mean ± standard deviation magnitudes for frontal and transverse kinematic variables. *Indicates a significant main effect of distance marched, #indicates a significant main effect of training, ‡indicates a significant distance marched by sex interaction effect, ^indicates a significant training by sex interaction effect ($p < 0.05$).

	Pre-Training				**Post-Training**				**Effect Size (η_p^2)**	
	Female		**Male**		**Female**		**Male**			
	Pre-March	**Post-March**	**Pre-March**	**Post-March**	**Pre-March**	**Post-March**	**Pre-March**	**Post-March**		
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Training	Distance
Hip										
Adduction Peak Angle (°)*	-15.31 ± 2.43	-17.65 ± 3.12‡	-17.26 ± 4.41	-16.94 ± 4.15	-16.37 ± 2.83	-19.01 ± 2.58	-17.33 ± 4.41	-18.33 ± 4.83	.10	.58
Abduction Peak Angle (°)*	12.51 ± 1.74	13.65 ± 2.16	11.85 ± 2.80	12.87 ± 2.18	12.53 ± 2.86	13.40 ± 3.36	11.01 ± 2.03	11.15 ± 2.36	.08	.36
Internal Rotation Peak Angle (°)	-15.68 ± 6.23	-17.31 ± 6.60‡	-18.00 ± 5.73	-17.41 ± 6.23	-15.04 ± 5.26	-16.72 ± 6.52	-18.14 ± 6.46	-17.65 ± 8.05	.00	.12
External Rotation Peak Angle (°)*	9.04 ± 5.66	9.89 ± 4.94	7.99 ± 5.84	9.72 ± 7.75	8.68 ± 5.00	9.63 ± 5.27	7.00 ± 6.55	7.51 ± 6.95	.03	.23
Excursion (°)*	46.97 ± 4.10	48.70 ± 6.12	49.94 ± 4.13	51.03 ± 3.49	46.57 ± 5.26	49.03 ± 4.71	47.84 ± 4.21	49.22 ± 4.00	.10	.42
Knee										
Internal Rotation Peak Angle (°)	0.09 ± 0.09	0.13 ± 0.09‡	0.16 ± 0.08	0.14 ± 0.06	0.09 ± 0.07	0.14 ± 0.07	0.14 ± 0.08	0.12 ± 0.06	.02	.11
External Rotation Peak Angle (°)	0.11 ± 0.08	0.13 ± 0.10	0.12 ± 0.08	0.12 ± 0.10	0.11 ± 0.06	0.12 ± 0.09	0.12 ± 0.09	0.13 ± 0.09	.00	.08
Excursion (°)	75.73 ± 4.30	76.86 ± 4.93	74.68 ± 6.37	75.92 ± 5.89	74.75 ± 5.62	74.43 ± 5.06	73.70 ± 5.15	73.99 ± 4.83	.09	.10
Ankle										
Excursion (°)*	19.76 ± 2.29	20.89 ± 3.50	30.18 ± 6.08	32.19 ± 6.33	20.49 ± 2.33	21.55 ± 3.10	30.70 ± 4.83	31.38 ± 4.76	.01	.19

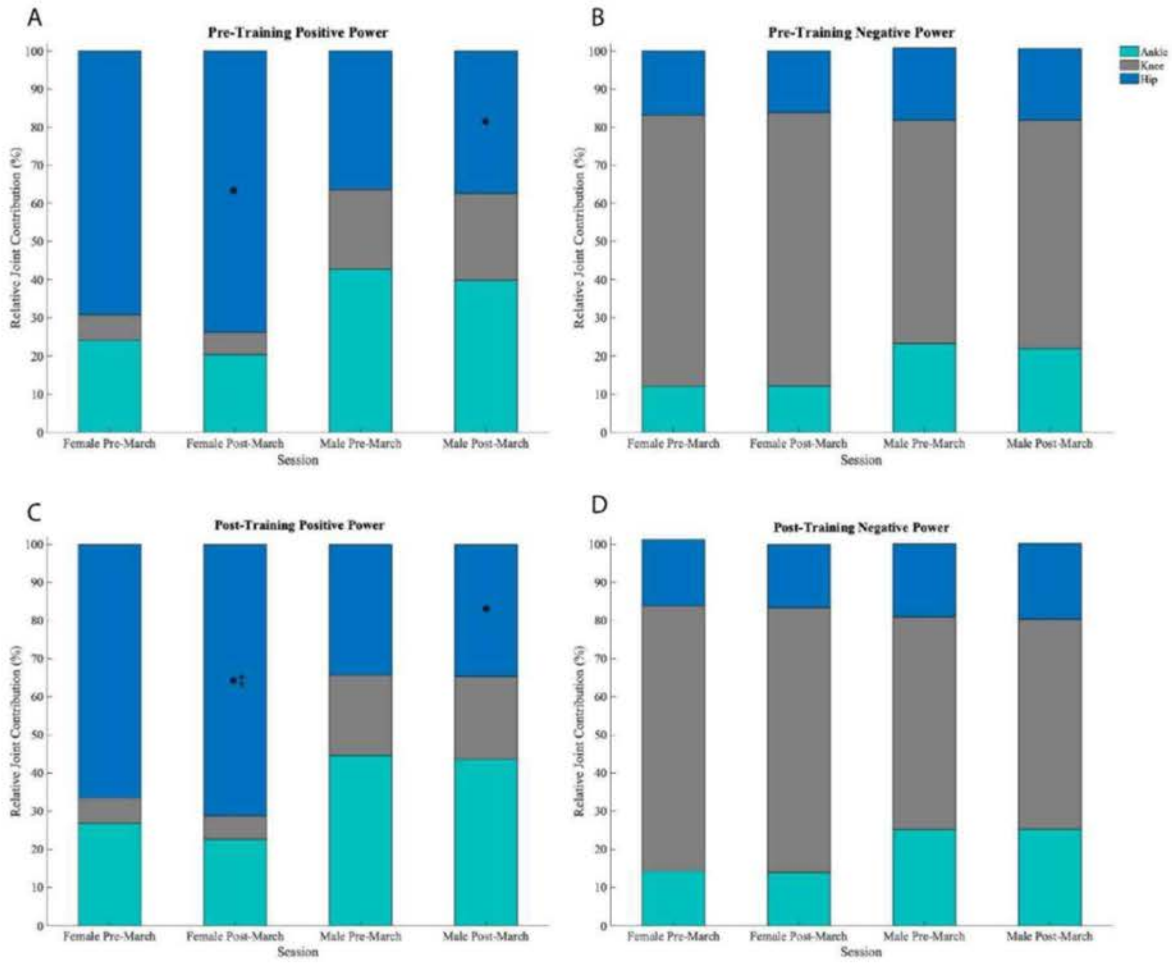

Figure 14. Relative contributions of hip, knee, and ankle joints to stance phase total mechanical negative (Figure 14B and Figure 14D) and positive (Figure 14A and Figure 14C) power over the duration of the 5 km load carriage task, before and after the 10-week physical training intervention. •Indicates a significant main effect of distance marched and ‡indicates a significant distance marched by sex interaction effect, both at the hip joint ($p < 0.05$).

Table 17. Mean ± standard deviation magnitudes for positive, negative, and net external joint work ($J \cdot kg^{-1}$). *Indicates a significant main effect of distance marched, #indicates a significant main effect of training, ‡indicates a significant distance marched by sex interaction effect, ^ indicates a significant training by sex interaction effect ($p < 0.05$).

Variable	Pre-Training				Pre-Training				Pre-Post Training	
	Female		Male		Female		Male		Effect Size (η_p^2)	
	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March		
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Training	Distance
Hip										
Joint Work Positive ($J \cdot kg^{-1}$)*	0.31 ± 0.10	0.37 ± 0.18	0.36 ± 0.07	0.37 ± 0.05	0.35 ± 0.11	0.42 ± 0.16^	0.32 ± 0.06	0.33 ± 0.05	.00	.31
Joint Work Negative ($J \cdot kg^{-1}$)	-0.05 ± 0.32	-0.05 ± 0.03	-0.14 ± 0.06	-0.13 ± 0.04	-0.05 ± 0.02	-0.06 ± 0.03	-0.14 ± 0.05	-0.15 ± 0.06	.03	.02
Joint Work Net ($J \cdot kg^{-1}$)*	0.26 ± 0.10	0.32 ± 0.16	0.22 ± 0.11	0.24 ± 0.08	0.30 ± 0.10	0.36 ± 0.16^	0.18 ± 0.07	0.19 ± 0.07	.00	.28
Knee										
Joint Work Positive ($J \cdot kg^{-1}$)	0.04 ± 0.03	0.03 ± 0.02	0.21 ± 0.05	0.23 ± 0.08	0.04 ± 0.02	0.04 ± 0.02	0.20 ± 0.04	0.21 ± 0.05	.06	.09
Joint Work Negative ($J \cdot kg^{-1}$)*, ‡	-0.22 ± 0.08	-0.26 ± 0.11	-0.43 ± 0.07	-0.44 ± 0.09	-0.24 ± 0.07	-0.28 ± 0.11	-0.43 ± 0.08	-0.42 ± 0.08	.01	.19
Joint Work Net ($J \cdot kg^{-1}$)‡	-0.18 ± 0.07	-0.23 ± 0.01	-0.22 ± 0.11	0.24 ± 0.08	-0.20 ± 0.07	-0.24 ± 0.10	0.18 ± 0.07	0.19 ± 0.07	.09	.14
Ankle										
Joint Work Positive ($J \cdot kg^{-1}$)#	0.15 ± 0.09	0.12 ± 0.08	0.42 ± 0.05	0.40 ± 0.05	0.16 ± 0.08	0.15 ± 0.08	0.42 ± 0.04	0.42 ± 0.06	.16	.08
Joint Work Negative ($J \cdot kg^{-1}$)	-0.04 ± 0.03	-0.05 ± 0.04	-0.43 ± 0.07	-0.44 ± 0.09	-0.05 ± 0.03	-0.06 ± 0.04	-0.43 ± 0.08	-0.42 ± 0.08	.00	.01
Joint Work Net ($J \cdot kg^{-1}$)	0.10 ± 0.07	0.07 ± 0.06	0.26 ± 0.10	0.25 ± 0.09	0.11 ± 0.06	0.09 ± 0.06	0.24 ± 0.09	0.24 ± 0.07	.00	.09
Net										
Positive Work Total ($J \cdot kg^{-1}$)*	0.49 ± 0.21	0.53 ± 0.25	0.98 ± 0.07	1.01 ± 0.09	0.55 ± 0.19	0.61 ± 0.23^	0.93 ± 0.07	0.97 ± 0.1	.03	.20
Negative Work Total ($J \cdot kg^{-1}$)*, ‡	-0.31 ± 0.12	-0.36 ± 0.16	-0.73 ± 0.08	-0.72 ± 0.08	-0.34 ± 0.01	-0.40 ± 0.14	-0.75 ± 0.09	-0.75 ± 0.09	.12	.18

Table 18. Mean ± standard deviation magnitudes for external joint moment and power variables. *Indicates a significant main effect of distance marched, #indicates a significant main effect of training, ‡indicates a significant distance marched by sex interaction effect, ^indicates a significant training by sex interaction effect ($p < 0.05$).

Variable	Pre-Training				Pre-Training				Pre-Post Training	
	Female		Male		Female		Male		Effect Size (η_p^2)	
	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March	Pre-March	Post-March		
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Training	Distance
Hip										
Hip Extension Moment (N·m/kg^{-1})#, ‡	-1.05 ± 0.41	-1.22 ± 0.59	-2.12 ± 0.34	-2.30 ± 0.33	-1.17 ± 0.40	-1.36 ± 0.49	-2.00 ± 0.32	-2.18 ± 0.31	.16	.00
Hip Flexion Moment (N·m/kg^{-1})	1.18 ± 0.48	1.28 ± 0.64	1.37 ± 0.39	1.33 ± 0.35	1.39 ± 0.49	1.47 ± 0.60^	1.43 ± 0.39	1.47 ± 0.46	.02	.04
Positive Hip Power (W·kg^{-1})*	0.64 ± 0.23	0.76 ± 0.36	0.67 ± 0.14	0.70 ± 0.10	0.73 ± 0.24	0.86 ± .34^	0.60 ± 0.12	0.63 ± 0.11	.01	.25
Negative Hip Power (W·kg^{-1})	-0.11 ± 0.05	-0.11 ± 0.06	-0.82 ± 0.15	-0.83 ± 0.20	-0.11 ± 0.36	-0.12 ± 0.07	-0.81 ± 0.18	-0.79 ± 0.16	.09	.00
Knee										
Knee Extension Moment (First Peak) (N·m/kg^{-1})#, ‡	-0.33 ± 0.39	-0.25 ± 0.31	-0.83 ± 0.18	-0.84 ± 0.24	-0.21 ± 0.29	-0.20 ± 0.29	-0.74 ± 0.14	-0.80 ± 0.14	.23	.02
Knee Extension Moment (Second Peak) (N·m/kg^{-1})	-0.29 ± 0.31	-0.35 ± 0.38	-1.03 ±0.26	-1.10 ± 0.26	-0.28 ± 0.29	-0.33 ± 0.35	-0.97 ± 0.17	-1.05 ±0.21	.08	.34
Knee Flexion Moment (First Peak) (N·m/kg^{-1})	0.26 ± 0.28	0.34 ± .39	2.30 ± 0.60	2.35 ± 0.64	0.32 ± 0.34	0.40 ± 0.43	2.31 ± 0.58	2.33 ± 0.56	.08	.10
Knee Flexion Moment (Second Peak) (N·m/kg^{-1})*, ‡	0.25 ± .27	0.35 ± 0.41	0.34 ± 0.11	0.35 ± 0.12	0.26 ± 0.30	0.35 ±0.40	0.34 ± 0.12	0.32 ± 0.12	.00	.10
Positive Knee Power (W·kg^{-1})	0.08 ± 0.06	0.07 ± 0.04	0.39 ± 0.09	0.44 ± 0.16	0.08 ± 0.04	0.08 ± 0.05	0.37 ± 0.08	0.40 ± 0.11	.07	.08
Negative Knee Power (W·kg^{-1})‡	-0.45 ± 0.17	-0.53 ± 0.23	-0.82 ± 0.15	-0.83 ± 0.20	-0.50 ± 0.16	-0.58 ± 0.24	-0.81 ± 0.18	-0.79 ± 0.16	.01	.14
Ankle										
Ankle Dorsiflexion Moment (N·m/kg^{-1})	0.42 ± 0.58	0.35 ± 0.45	0.50 ± 0.60	0.45 ± 0.12	0.13 ± 0.08	0.14 ± 0.07	0.48 ± 0.10	0.47 ± 0.10	.14	.00
Ankle Plantarflexion Moment (N·m/kg^{-1})	-1.40 ± 0.88	-1.43 ± 0.90	-4.09 ± 0.19	-4.03 ± 0.22	-1.64 ± 0.78	-1.67 ± 0.81	-4.08 ± 0.21	-4.09 ± 0.23	.14	.04
Positive Ankle Power (W·kg^{-1})	0.30 ± 0.20	0.25 ± 0.17	0.79 ± 0.09	0.75 ± 0.11	0.34 ± 0.17	0.32 ± 0.17	0.78 ± 0.09	0.79 ± 0.13	.15	.15
Negative Ankle Power (W·kg^{-1})#	-0.90 ± 0.05	-0.11 ± 0.08	-0.30 ± 0.13	-0.28 ± 0.08	-0.11 ± 0.07	0.13 ± 0.08	-0.33 ± 0.13	-0.33 ± 0.08	.42	.00
Net										
Positive Power Total (W·kg^{-1})	1.03 ± 0.45	1.08 ± 0.51	1.84 ± 0.15	1.90 ± 0.25	1.15 ± 0.41	1.26 ± 0.50^	1.75 ± 0.18	1.81 ± 0.23	.035	.202
Negative Power Total (W·kg^{-1})‡	-0.65 ± 0.26	-0.71 ± 0.23	-1.38 ± 0.17	-1.36 ± 0.21	-0.71 ± 0.23	-0.83 ± 0.30	-1.41 ± 1.78	-1.40 ± 0.18	.118	.184

6.5. Discussion

The purpose of this study was to determine sex-specific responses in lower limb biomechanical changes during a load carriage task, and in response to a 10-week evidence-based physical training program. We detected sex-specific differences in response to the load carriage task and training. Specifically, adaptive responses were observed at the hip and knee joints during the 5 km loaded march, and at the hip joint only as a result of training. Interestingly, training elicited increases in hip joint power contributions for females only, whereas ankle joint power contributions increased for both sexes as a result of training. To our knowledge, this study is the first to identify and quantify sex-specific lower limb adaptations in response to a prolonged load carriage task and a specific physical training program.

Sex-specific differences in spatial-temporal variables when walking with a 23 kg load were not detected in the current study, with the exception of a significant interaction effect found for step width in males. Increased step width values after training suggests that males adapted their gait to facilitate a wider base of support which in turn would increase stability when under heavy load (Birrell & Haslam, 2009; Kinoshita, 1985). It may be that the larger hip adduction values found in females may account for the lack of changes observed in step width whilst carrying additional load (Birrell & Haslam, 2009). In contrast to previous studies (Krupenevich et al., 2015; Silder et al., 2013a), stride length increases were observed. Typically, decreases in stride length are observed to attenuate effects of additional load and as a mechanism to restore stability (Kinoshita, 1985). However, this may have been achieved via adaptive responses observed at the torso. An interaction effect demonstrated that females exhibited greater trunk flexion in response to the 23 kg torso-borne load compared to the males over the 5 km loaded march. Walking with additional external load requires greater torque at the pelvis, hips, and lower back (Polcyn et al., 2002; Ren et al., 2005; Silder et al., 2013a), which is actively counteracted by an increase in forward trunk lean. (Krupenevich et al., 2015) identified that the greater trunk lean exhibited by females could be as a result of a smaller mass compared to their male counterparts as a compensatory strategy to reduce hip flexion and knee extension moments during the load carriage task (Teng & Powers, 2014, 2016). Consequently, as loads are standardised within combat-related roles, task tolerance or the capability of female soldiers to complete heavy load carriage tasks over a prolonged time period may be negatively affected through accentuated effects of additional external load (Simpson et al., 2012a; Simpson et al., 2011b).

In line with our first hypothesis, sex-specific differences in adaptive gait responses during the load carriage task and in response to training were primarily realised at the hip joint. Females demonstrated greater changes in hip adduction and hip internal rotation, whereas males did not. Interesting, Loverro et al. (2019) identified changes in hip mechanics that oppose these findings, as hip adduction angles increased for males only. However, the moderate and heavy load carriage tasks were only conducted over a short duration in comparison to the current study (2 minutes vs. 55 minutes). Movement pattern variations between sexes may be accounted for by known structural differences, particularly at the hip and knee joints. For example, Horton and Hall (1989) highlighted that females exhibit a greater Q angle (i.e., hip width to femoral length ratio) and natural internal hip rotation angle compared to males (Lewis, Laudicina, Khuu, & Loverro, 2017), which potentially pre-disposes them to lower limb injuries (Simoneau, Hoenig, Lepley, & Papanek, 1998). After training, peak hip flexion moments increased in females, which is in contrast to findings from Krupenevich et al. (2015) where a similar load amount (22 kg) was donned. It could be postulated that in the current study participants were more sensitive to peak moment adaptations over the march duration as conditions were examined during more prolonged load carriage tasks in comparison to previous studies (Harman et al., 2000; Krupenevich et al., 2015; Seay et al., 2014; Silder et al., 2013a).

After training, increases in hip generation was elicited in females only, which contributed more towards overall mechanical power. Increased positive power production after training indicates a shift towards a more hip-dominated strategy during the load carriage task. As the focus of the 10-week training program was to improve strength of hip-spanning muscles, this finding suggests that the stimulus provided was sufficient enough to elicit positive neuromuscular adaptations (Lenton et al., 2019; Wills et al., 2019a) to meet the demands of the task (Huang & Kuo, 2014). Furthermore, shifting task requirements more proximally would actively decreased reliance on the knee musculature to produce positive work/power (Blacker et al., 2013; Teng & Powers, 2014, 2016), potentially decreasing injury risks at one of the most commonly injured sites in military personnel (Department of Defence, 2000).

In agreement with our hypothesis, peak knee joint extension moment at initial contact gait (0-40 % stance) significantly decreased from pre-post march measures after training. During early stance, knee extensor moments increase to effectively counteract centre of mass excursions in response to additional external loads (Holt et al., 2003; Seay et al., 2014; Wang et al., 2013). However, relying on eccentric knee muscle contractions to control body posture may precipitate muscular fatigue in loaded soldiers and increase injury risk (Quesada et al., 2000). Therefore, the reductions in peak knee extensor moments observed as a direct result of the 10-weeks of lower limb focussed physical training may have minimised injury risks associated with load carriage tasks. Over the 5 km march, females also demonstrated increases in peak knee flexion moment values during the swing phase. Such increases in flexion moments per step contribute towards increases in the cumulative loading experienced at the knee joint (Teng & Powers, 2014) which may substantially contribute towards lower limb injury, especially due to the repetitive nature of walking.

The current study has some limitations that should be acknowledged. While it is important to acknowledge that kinetic data for males and females were acquired using over-ground and treadmill-based protocols, previous studies have found similarities between acquisition methods (Lee et al., 2017; Riley et al., 2007). We also acknowledge that participants were recreationally active civilians, representative of a military population. Therefore, the applicable of current findings may be limited to initial recruits compared to experienced soldiers.

6.6. Conclusion

In conclusion, this study was the first to demonstrate that males and females adapt differently over a 5 km walk and in response to load carriage specific training. Sex-specific differences were primarily realised at the hip joint, with most mechanical gait changes observed in females. Such responses strongly indicate that physical training needs to be tailored to each sex to maximise benefits of training based on individual requirements. To corroborate and extend our findings, future studies could compare joint-level changes between males and females during a standardised load carriage task in response to differently targeted physical training programs. Additionally, understanding these responses will provide an evidence-base to inform Military training within the Australian Defence Force which could facilitate the successful integration of female soldiers into physically demanding combat roles.

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Conflict of Interest Statement and Funding Source

The authors declare no conflicts of interest that could bias this research, including financial and/or personal relationships with other people or organisations.

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Chapter 7: Physiological Responses of Female Load Carriage Improves after 10 weeks of Training

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In Chapter 6, I found that sex-specific differences were primarily realised at the hip joint, with most mechanical gait changes being observed in females over the 5 km march distance and after training. Combined with findings detailed in Chapter 4, it appears that there are differences in responses elicited by the 10 weeks of load carriage training between males and females for neuromuscular, physical, and psychophysical responses.

Based on these findings, this Chapter explores female-specific physiological and psychophysical responses during the standardised load carriage task. To successfully complete the same load carriage task as males, females are typically required to work at a higher relative intensity (Blacker et al., 2009b; O'Leary et al., 2018; Patterson et al., 2005). This excessive physiological stress placed on the body can have negative connotations towards task performance and/or sustainment (Drain, Billing, Neesham-Smith, & Aisbett, 2016; Pollock et al., 1998). Similar to previous chapters, investigations into the physiological demands of load carriage tasks have been predominately focussed on male-only populations, with few studies detailing female-specific responses (Nindl et al., 2017). Characterising physiological demands of females during load carriage will enable a broad understanding of how females adapt to adequately meet task demands, providing further information which will facilitate and inform the best way to integrate females into the physically demanding combat occupations in military organisations.

The purpose of this Chapter was to investigate physiological and psychophysical responses in a female cohort during a load carriage walking task before and after a 10-week physical training program.

7.1. Abstract

Purpose: To characterize and evaluate female-specific physiological and perceptual responses during a load carriage walking task before and after a 10-week physical training program.

Methods: Eleven recreationally active females (age; 21.5 ± 2.2 years, stature; 1.66 ± 0.8 m, body mass; 64.4 ± 6.8 kg) completed a load carriage task (5 km at 5.5 $km.h^{-1}$, wearing a 23 kg torso-borne vest) before and after a 10-week physical training program. Physiological (i.e., maximal oxygen uptake ($\dot{V}O_{2max}$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER), breathing frequency (Rf), and pulmonary ventilation ($\dot{V}_E$)) and perceptual (i.e., rating of perceived exertion) responses were collected during the load carriage task. Additional physical performance measures (i.e., push-ups, sit-ups, beep test, and isometric mid-thigh pull) were collected in a separate session before and after the 10-weeks of training.

Results: Compared to before training, maximal oxygen uptake ($\dot{V}O_2$) requirements reduced during the load carriage task ($p < 0.05$), while heart rate and ratings of perceived exertion remained similar. RER reductions over the 5 km march indicated a shift towards fat utilisation, with other physiological responses demonstrating an increased ability to sustain the metabolic demands of the load carriage task. Increases in push-up and isometric mid-thigh pull performance demonstrated improvements in upper body muscular endurance and lower body strength after the 10-week training program ($p < 0.05$).

Conclusion: During a standardised load carriage task, physiological and perceptual responses indicated physical adaptations to specific training in females. Although positive physiological responses were elicited, additional strategies (i.e. cognitive resilience training, female-specific vest design to reduce pain burden) to build load carriage task-specific resilience (perceptual responses) may be required.

7.2. Introduction

Carrying external load is a critical requirement in many military roles. Regardless of training and operational requirements, load carriage tasks can impose substantial physical and physiological stress that may induce premature fatigue and/or impair job performance. For example, it is well established that the energy cost of load carriage increases with the load carried, and this relationship appears to be linear within a range of 0 to ~60 kg (Epstein et al., 2013; Li et al., 2018; Quesada et al., 2000; Ricciardi et al., 2008). The physical and physiological burden experienced during load carriage tasks can impact both physiological and perceptual responses, potentially resulting in degraded soldier performance (e.g., vigilance, decision making, physical performance) (Giles, Hasselquist, Caruso, & Eddy, 2019; Nindl et al., 2018) and/or task sustainment (Drain et al., 2016; Pollock et al., 1998).

During prolonged load carriage $\dot{V}O_2$ and heart rate (HR) drift, and increased ratings of perceived exertion (RPE) have commonly been observed (Mullins et al., 2015; Pandolf, 1978; Patton et al., 1990). The majority of these studies however, have involved male participants, with limited research investigating physiological responses in females (Phillips et al., 2016). One of the few studies examining females found that $\dot{V}O_2$, heart rate, $\%\dot{V}O_{2\,max}$, and RPE all significantly increased over a 5.4 km load carriage walk while carrying operational loads of 55 % body mass (Lidstone et al., 2017). Despite findings in females generally aligning with those found in males, a major limitation is that loads carried were relative to body mass (Li et al., 2018) rather than absolute loads. Military loads are primarily determined by occupation or task requirements rather than an individual's physical characteristics (Nindl, 2015), therefore making it difficult to translate these findings to the military setting (Drain et al., 2012). As females are now eligible for combat-related roles in many military organisations, it is important to understand physical and physiological responses during ecologically valid military tasks.

Research indicates that when undertaking marching tasks or activities, females are typically required to work at a higher relative intensity than their male counterparts (Blacker et al., 2009b; O'Leary et al., 2018; Patterson et al., 2005). Although appropriately designed physical training programs can effectively increase soldiers' physical capacity and physical preparedness, sex-based differences in physical capacity and performance tend to persist (Harwood et al., 1999; Knapik et al., 2005; Kraemer et al., 2001; Patterson et al., 2005). In order to adequately prepare females to operate successfully in physically arduous combat-related roles, the physiological demands of essential occupational tasks such as load carriage tasks need to be determined and understood. Characterising female-specific capacities and responses can help to inform training strategies and thereby reduce the relative strain during load carriage tasks.

The effects of load carriage have been extensively investigated in male populations, however, there is considerably less research in females. As military organizations globally are opening previously closed combat roles to females, there is a need to characterise and understand the physiological demands during load carriage tasks in females Therefore, the primary aim of the current study was to investigate physiological and perceptual responses in a female cohort during a load carriage walking task before and after a 10-week physical training program.

7.3. Methods

7.3.1. Study Design

Participants representative of a military recruit population (Australian Defence Force) completed a 10-week load carriage specific physical training program. Lower-body strength, local muscular endurance and cardiorespiratory endurance were measured before and after a 10-week training intervention, with perceptual and heart rate responses assessed during loaded marching task. The load carriage marching task was equivalent to the Australian Army minimum physical employment standards (PES) for incumbents (Australian Defence Force), and was conducted on a force-instrumented treadmill (AMTI force-sensing tandem treadmill, MA, USA). A short familiarisation session was conducted within the week prior to the load carriage task which required participants to walk for 5 minutes on a treadmill at 5.5 $km.h^{-1}$ wearing a 23 kg weighted vest. Weight was distributed evenly between the front and back of the torso-borne vest (IronEdge, Power Vest).

7.3.2. Participants

Eleven recreationally active female participants were recruited from a student population (age; 21.5 ± 2.2 years, stature; 1.66 ± 0.8 m, body mass; 64.4 ± 6.8 kg). At the time of recruitment, to be considered recreationally active, participants were undertaking some form of social sport. Participants self-reported no acute or chronic musculoskeletal injuries and had no previous load carriage experience. Participants provided written informed consent to the protocol, which was approved by the Macquarie University Human Research Ethics Committee (protocol number: 5201700997).

7.3.3. Inclusion Criteria

Participants were required to meet the Australian Army recruit graduation physical fitness standards for females: (i) minimum of 21 push-ups and 70 sit-ups in 2 minutes each, and (ii) a minimum of level 7.5 on the multi-stage shuttle run test (Australian Defence Force). Maximum oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$) was predicted from the multi-stage shuttle run test score (Ramsbottom et al., 1988).

7.3.4. Physical Training Intervention

A 10-week physical training program was undertaken by all participants which required up to three resistance training sessions and two weighted walking sessions per week (Wills et al., 2019a). All resistance training sessions were delivered by an accredited Australian Strength and Conditioning Association (ASCA) coach (minimum level 1 accreditation), who tailored weekly progressions to individual abilities. Resistance was progressively increased when participants successfully completed the required number of repetitions and sets for a given exercise (Supplementary Table 1). All weighted walking sessions were self-directed on a separate day to the resistance training sessions, with load, distance, and speed incrementally increasing over the 10-week training program (Figure 15).

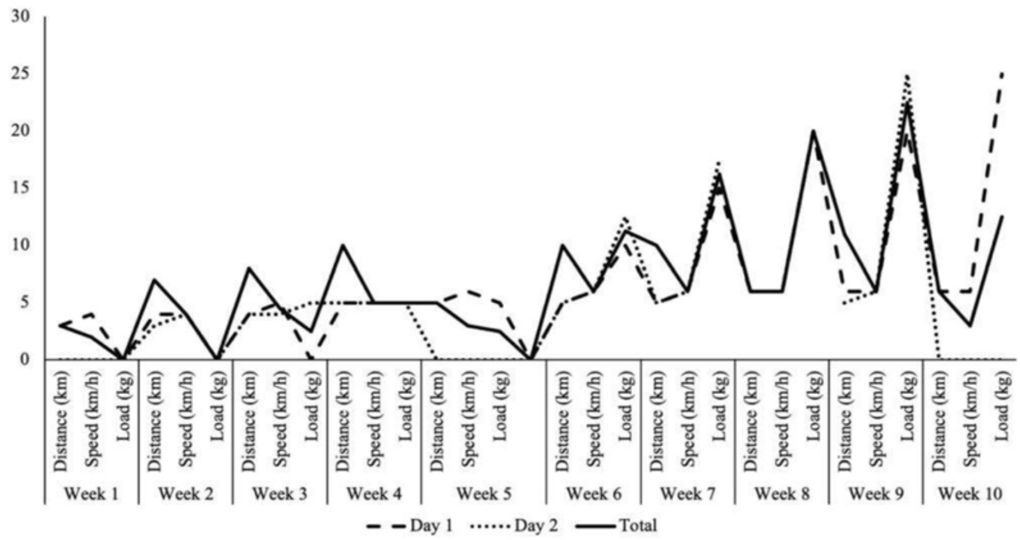

Figure 15. Load carriage training sessions included in the 10-week program.

7.3.5. Physical Performance

Maximal push-ups, maximal sit-ups, isometric mid-thigh pull (IMTP), and the multi-stage shuttle run test were assessed before and after the 10-week training program. All tests conducted are described below and were carried out using methodology as previously described (Wills et al., 2019a).

7.3.5.1. Push-ups

Participants completed the maximal number of push-ups within two-minutes. The start position required feet shoulder-width apart, back straight and arms in a locked-out position. A repetition was counted when the participant descended towards the ground until the elbows reached a 90° angle, and the upper arm was parallel with the ground, prior to returning to a locked-out arm position. Participants were able to take a rest throughout the test but were required to remain in the start position.

7.3.5.2. Isometric Mid-thigh Pull

IMTP measures were conducted using a portable force plate (400-series, Fitness Technology, Adelaide, SA, Australia) and a Fitness Technology IMTP rack (Innervations, Perth, WA, Australia) that allows the fixation of the bar at a specified height. The pulling position of participants required the knee angle to be between 130-150° (measured using a goniometer), replicating a commonly used position to measure maximal lower limb strength (Beckham et al., 2017; Haff et al., 2005). Participants were instructed to stand on the force plate and grip the bar as they would to perform a deadlift with the knees and hips flexed, back straight, chest up, and head looking forward. Once in position, participants received a countdown to begin the pull, and were instructed to “pull as hard and fast as possible” whilst being provided verbal encouragement throughout the effort, which was maintained until the force output began to decline. Participants were further instructed to use minimal pre-tension to ensure there was limited amounts of slack in the participants body prior to pull initiation (Beckham et al., 2017). Three successful maximal efforts were collected, and the maximal absolute force output value was extracted and used for statistical analysis as a surrogate measure of lower limb strength (Cormack et al., 2008).

7.3.5.3. Multi-stage shuttle run

Predicted $\dot{V}O_{2max}$ was estimated from the maximal score achieved during the multi-stage shuttle run test. Participants ran between two parallel lines set 20 m apart and were required to reach the lines prior to the beep. Participants were required to maintain speed as prescribed by the beeps until failure (participants do not successfully reach the line twice throughout the duration of the test). The last successful completed shuttle within each stage was recorded and was used to calculate predicted $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) (Ramsbottom et al., 1988).

7.3.6. Physiological Measures

Expired air samples were collected continuously during the load carriage task ('All Corps Standard'; 5 km at 5.5 $km.h^{-1}$ with a 23 kg external load) before and after training via a portable metabolic system (COSMED K5, COSMED, Italy) for the measurement of oxygen uptake ($\dot{V}O_2$), oxygen uptake reserve ($\dot{V}O_2R\%$, calculated using $\dot{V}O_{2max}$) carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER), breathing frequency (Rf), and pulmonary ventilation ($\dot{V}_E$). The COSMED K5 device was calibrated in accordance with manufacturer guidelines prior to each trial (flowmeter, scrubber, reference gas calibration, and delay time). Data were collected via the breath-by-breath mode (BxB) as this has previously been shown to accurately measure metabolic data under walking speeds similar to the current study (< 6 $km \cdot h^{-1}$) (Perez-Suarez et al., 2018). The body-mounted elements of the system were included in the total external load carried and consisted of the COSMED K5 portable unit, a face mask (covering the mouth and nose), and a connecting sample and flow line. Heart rate was measured continuously via telemetry (Polar-Electro, Finland) and logged by the COSMED K5. Respiratory and heart rate data were reported in 5 min epochs every 10 min, starting at 10 minutes (i.e. 10-15, 20-25, 30-35, 40-45 and 50-55 min). %HRMax was calculated from age predicted maximal HR (220-age). Rating of perceived exertion was collected every 5 minutes over the trial, starting at 5 minutes, using the 15-point scale ranging between 6-20 (Borg, 1998). Laboratory conditions were maintained at 25.0 ± 0.7°C and 68 ± 12% relative humidity.

7.3.7. Statistical Analysis

Data are summarized as mean ± 95 % confidence intervals (95 %CI) unless otherwise stated. The work intensity of measured variables (defined as the classification of the activity intensity) during the load carriage marching task were determined using classification thresholds from previously published work (Pollock et al., 1998). 'Light, 'moderate', 'hard', and 'very hard' intensities were defined for RPE (10-11, 12-13, 14-16, 17-19, respectively), maximal HR% (35-54 %, 55-69 %, 70-89 %, ≥ 85 %, respectively), and %$\dot{V}O_{2max}$ (20-39 %, 40-59 %, 60-84 %, ≥84 %, respectively). The normality of data was confirmed using the Shapiro-Wilk test. A two-way analysis of variance (ANOVA) was used to assess time (5-levels: 10-15, 20-25, 30-35, 40-45, 50-55 min) × training (2 levels: pre, post) interactions. Tukey's multiple comparisons post-hoc test was used to detect specific differences. Cohen's d was used to calculate effect sizes for differences in perceptual and heart rate responses during the load carriage task (10-15, 20-25, 30-35, 40-45 and 50-55 min) pre *vs* post training (Cohen, 1988). Small, moderate and large effect sizes were considered d statistic values of 0.2, 0.5 and 0.8 respectively (Cohen, 1988). Associations between IMTP maximal force output and %$\dot{V}O_{2max}$ were investigated via bivariate correlations (r). Small, moderate, and large correlations were defined as r values between 0.1-0.3 , 0.3-0.5, and 0.5-0.7 (Cohen, 1988). Paired samples t-tests were conducted on maximal push-ups, IMTP, and multi-stage shuttle run test performance (predicted $\dot{V}O_{2max}$) variables to assess differences in pre-post physical performance. Statistical significance was set at the $p < 0.05$ level. All data were analysed using Microsoft Excel 2010 (Microsoft Corporation, WA, USA) and Graphpad Prism V7.0 (Graphpad Software Inc., CA, USA).

7.4. Results

Training adherence to the 10-week program was 89 % for participants (resistance training sessions, 97 %: load carriage training sessions, 87 %).

7.4.1. Physical Performance

There was no change in predicted $\dot{V}O_{2max}$ following the 10-week physical training program (40.1 ± 2.6 *vs* 39.6 ± 2.6 $mL \cdot kg^{-1} \cdot min^{-1}$, p= 0.54). Both push-ups (36 ± 8 *vs* 48 ± 11, $p < 0.01$) and IMTP maximal force output (1719.5 ± 219.6 *vs* 1839.3 ± 261.5 N, $p < 0.05$) increased significantly after training compared to before training.

7.4.2. Load Carriage Task

There were no significant ($p > 0.05$) time x training interactions for perceptual variables (Table 19). There were main effects ($p < 0.05$) for training in $\dot{V}O_2$, $\%\dot{V}O_{2max}$ and RER. $\dot{V}O_2$ (mean difference; 0.125± 0.03 $L \cdot min^{-1}$, $d = 1.13$, $p < 0.01$) and $\%\dot{V}O_{2max}$ (mean difference; 5.81 ± 1.72, $d = 0.911$, $p < 0.01$) were lower post- compared to pre-training, whereas RER was higher throughout the 5 km march after the 10-week training program (mean difference; 0.04 ± 0.016, $d = 0.679$, $p < 0.01$). Load carriage task intensity was similar during the pre- and post-training marches for HR and RPE, with work intensity being classified as 'hard' for both variables.

Main effects ($p < 0.05$) for march distance were found for Rf, $\dot{V}e$, $\dot{V}O_2$, $\%\dot{V}O_{2max}$, RER, HR and RPE. Increases in Rf, $\dot{V}e$, $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$ and $L \cdot min^{-1}$) and $\%\dot{V}O_{2max}$ were demonstrated over the 5 km march before and after training (Table 19). Work intensity decreased from 'hard' to 'moderate' for $\%\dot{V}O_{2max}$ from the beginning to the end of the load carriage march. RER values decreased over the 5 km march indicating a shift towards fat utilisation.

Small to moderate negative associations between IMTP performance and $\%\dot{V}O_{2max}$ at pre- ($r = 0.25$, $p > 0.05$) and post-training ($r = 0.43$, $p > 0.05$), respectively. A small negative correlation was found between the changes in pre-post-training IMTP performance and $\%\dot{V}O_{2max}$ ($r = 0.1$, $p > 0.05$).

Table 19. Physiological and psychophysical responses to prolonged load carriage pre- and post-physical training intervention.

		15 min	25 min	35 min	45 min	55 min
Rf, breaths·min^{-1} #	Pre	39.0 ± 6.3	41.5 ± 6.8	42.8 ± 6.7^	44.0 ± 6.3^	45.1 ± 7.1^$
	Post	40.1 ± 6.4	42.2 ± 6.4	43.1 ± 6.3	44.8 ± 6.9^	45.9 ± 7.6^$
$\dot{V}e$, L·min^{-1} #	Pre	44.9 ± 5.7	46.6 ± 6.2	46.2 ± 6.0	47.1 ± 6.3^	47.5 ± 5.9^
	Post	42.8 ± 5.0	43.9 ± 4.8	44.7 ± 4.8	45.8 ± 4.9^	46.6 ± 4.3^$
$\dot{V}O_2$, L·min^{-1} # *	Pre	1.61 ± 0.1	1.64 ± 0.1	1.63 ± 0.1	1.65 ± 0.1	1.64 ± 0.1
	Post	1.46 ± 0.1	1.50 ± 0.1	1.52 ± 0.1^	1.54 ± 0.1^	1.53 ± 0.1^
$\dot{V}O_2$, #,* mL·kg^{-1}·min^{-1}	Pre	25.2 ± 2.4	25.7 ± 2.2	25.5 ± 1.8	25.7 ± 1.8	25.7 ± 1.7
	Post	22.6 ± 1.3	23.2 ± 1.1	23.6 ± 1.1^	23.8 ± 1.1^	23.7 ± 1.1^
%$\dot{V}O_{2max}$ # *	Pre	64.1 ± 6.9	65.6 ± 7.2	65.1 ± 5.9	65.5 ± 5.6	65.4 ± 5.5
	Post	57.5 ± 4.0	58.9 ± 3.2	59.9 ± 3.3^	60.3 ± 3.2^	60.0 ± 2.6^
RER # *	Pre	0.84 ± 0.03	0.82 ± 0.03^	0.80 ± 0.04^$	0.79 ± 0.04^$	0.79 ± 0.04^$
	Post	0.88 ± 0.02	0.85 ± 0.02^	0.84 ± 0.02^$	0.83 ± 0.02^$	0.83 ± 0.02^$
HR, bpm #	Pre	144 ± 10	146 ± 12	148 ± 12^	150 ± 11^$	151 ± 11^$+
	Post	141 ± 12	144 ± 12^	146 ± 13^	149 ± 13^$+	150 ± 13^$+
%HR_{max}	Pre	72	74	74	75	76
	Post	71	72	73	75	76
RPE #	Pre	12 ± 2	13 ± 2	14 ± 2^	15 ± 2^$	16 ± 2^$+
	Post	11 ± 1	12 ± 1^	13 ± 1^$	15 ± 1^$+	16 ± 1^$+

Rf, breathing frequency; **Ve**, pulmonary ventilation; **$\dot{V}O_2$**, oxygen uptake; **RER**, respiratory exchange ratio; **HR**, heart rate; **RPE**, rating of perceived exertion.

Data are mean ± 95% CI, * denotes main effect for training, # denotes main effect for march distance, ^ denotes difference to 15 minutes, $ denotes difference to 25 minutes, + denotes difference to 35 minutes.

7.5. Discussion

The purpose of the present study was to investigate physiological and perceptual demands of a female cohort during a military-relevant load carriage task before and after a 10-week physical training program. RPE, HR, and $\dot{V}O_2$ responses indicated that the demands of the load carriage task ranged from 'moderate' to 'hard'. Following training, the oxygen cost of the load carriage task reduced, however, RPE and HR were not different. Decreased oxygen cost was accompanied by increases in upper body muscular endurance and lower body strength, while no changes were demonstrated in aerobic capacity (estimated $\dot{V}O_{2max}$).

Load carriage is a common military task and is often critical to operational capability and mission success. External loads increase the physiological burden placed upon a soldier and can reduce an individual's capacity to maintain a given work intensity (Pollock et al., 1998) and overall task sustainment (Drain et al., 2016). Previous studies (Harman. et al., 1997; Kraemer et al., 2001) have investigated the effect of physical training interventions on best-pace (3.2 km) load carriage performance in females, with limited studies examining physiological responses during load carriage in females following a physical training intervention. Furthermore, several studies have demonstrated that females are often working at a higher relative intensity when undertaking equivalent military tasks or training when compared to their male counterparts. Therefore, it is important to undertake female specific research to better understand physiological adaptations to physical training that support improved load carriage performance and inform physical training strategies.

The 10-week training program implemented in the current study successfully reduced the oxygen cost of a 5 km load carriage task. This improvement likely resulted from a combination of increased lower and upper body strength as well as increased task resilience from repeated load carriage exposures (Harman et al., 2008b; Kraemer et al., 2001; Kraemer et al., 2004). For example, over the 10 weeks of training, participants completed progressive load carriage marches that increased in load, distance, and speed to simulate the 5 km criterion task. Additionally, one upper and two lower body focussed strength sessions per week elicited improvements in both push-ups and IMTP maximal force output performance after 10-weeks of training. Strength changes are known to be associated with improved mechanical efficiency during running in both trained (Balsalobre-Fernández, Santos-Concejero, & Grivas, 2016; Støren, Helgerud, Støa, & Hoff, 2008) and untrained individuals (Meszler et al., 2019), with results in the current study suggesting there is a similar pattern between improved strength and walking economy during load carriage tasks. For instance, enhanced limb coordination improves the efficiency of movement patterns (Kraemer et al., 2001). Neural and muscular responses to the strength training combined with enhanced movement patterns via repeated task exposure (i.e., load carriage specific training) in the current study may have contributed towards participants becoming more familiar with the load carriage task itself. These improvements in mechanical efficiency are further supported by the associations demonstrated between IMTP strength improvements and $\%\dot{V}O_{2max}$, as results indicate that as lower limb strength increases, the oxygen cost of the load carriage task reduces. Additionally, improvements in type I and type II fibre strength require less motor unit activation per given movement, which may have additionally contributed to overall improved movement efficiency. The decreased oxygen cost of transport and improved mechanical efficiency (Kraemer et al., 2001) was also associated with a reduction in work intensity classification from ‘hard’ to ‘moderate’ (Pollock et al., 1998). These favourable findings demonstrate that progressive strength training combined with task-specific training (i.e. load carriage marches) is effective in decreasing cardiorespiratory demands of a load carriage task in a female cohort, even in the absence of improved cardiorespiratory capacity.

In contrast to the improved walking economy, there were no changes in HR or RPE during load carriage following training. It is possible that HR and RPE did not change following training due to components of the load carriage march that are not related to walking efficiency. For example, studies have identified that energy expenditure is not the sole determinant of load carriage task demands and that both metabolic and musculoskeletal factors are important (Pandolf, 1978). External load has been shown to influence factors such as discomfort or pain (Park et al., 2013), and respiratory mechanics (Phillips et al., 2016) in female-specific cohorts completing physically demanding load carriage tasks, which may impact RPE and HR responses. Simpson et al. (2011b) reported that overall discomfort ratings linearly increased over time when carrying 30% BW (wearing 18 kg and walking ~5 $km.h^{-1}$) for 8 km, whilst RPE values remained relatively consistent at a “moderate” intensity. Although RPE responses are similar to the current study, the heightened levels of discomfort observed may explain why the reduced oxygen cost was not reflected in reduced perceived effort (Simpson et al., 2011b). The lack of changes in HR and RPE responses following training suggests that together loaded marching and strength training may not be a sufficient training stimulus to mitigate the discomfort and subjective perceptual/cardiovascular strain experienced during the load carriage task (Kraemer et al., 2004). Additional load carriage exposure and/or greater physical capacity improvements may be required, perhaps combined with additional strategies such as female-specific load carriage equipment to reduce discomfort and improve physical performance.

Irrespective of training adaptations, the physiological and perceptual variables demonstrated different responses to the load carriage march. Over the 5 km march duration HR, $\dot{V}O_2$, and RPE values increased, with RPE demonstrating the largest increase (average increase of 4-

5 points). Conversely, RER decreased significantly over the duration of the 5 km load carriage task. The larger relative increase in RPE compared to HR is consistent with findings from Harper et al. (1997) who investigated relative load carrying capabilities during a self-paced maximal effort 10 km march. Comparatively, task difficulty was greater in women compared to men, reflected by the increased RPE values observed between the 2.5 km and 5 km segments of the march (Harper et al., 1997). In the present study, the reduced oxygen uptake and HR combined with the shift towards greater fat utilisation over the load carriage task suggests that the metabolic demands of the tasks were sustainable. In fact, the observed decrease in energy cost of ~ 0.12 L·min^{-1} following the training intervention translates into a predicted increase in task sustainment time from 1.4 h to 1.9 h, based on a maximum acceptable work duration model (Drain et al., 2016). However, in contrast RPE consistently increased over the load carriage task at both time points. These results suggest that discomfort associated with torso-borne load carriage and perceived effort are more likely to limit task sustainment when compared to metabolic or cardiorespiratory mechanisms of fatigue under conditions similar to the current investigation. This observation supports the consideration of additional strategies (i.e. cognitive resilience training, female-specific vest design to reduce pain and discomfort) to build load carriage task-specific resilience and sustainment capacity in a female cohort (Nindl et al., 2018).

7.5.1. Limitations

There were limitations within the current study that should be considered. Although recruited civilian participants were representative of female Australian Army recruits, participants had no prior load carriage experience. The authors acknowledge that as a result, differences in physical and physiological responses may be apparent between a civilian and an experienced military population. The application of findings may therefore be limited to initial recruits as opposed to an experienced soldier population. Research was conducted in a controlled laboratory environment, meaning that findings may not be immediately generalised to tasks that are typically completed on varying overground terrains. Future research should aim to investigate measures without such external constraints to enhance the transferability of results to 'real-world' settings. Although a familiarisation session was included prior to the load carriage task, the duration discrepancy (5-minutes vs 55-minutes) may have contributed towards potential learning effects in this study. However, based on previous research, a short-duration familiarisation was sufficient enough to familiarise participants to consistent gait when walking on a treadmill (Matsas, Taylor, & McBurney, 2000).

7.6. Conclusions

To the authors knowledge the current study is the first to characterise physiological and psychophysical responses in females during a load carriage task, following a specific training intervention targeting the task demands of load carriage. Reductions in oxygen costs and improvements in strength are associated with improved task economy. As combat-related roles are being opened to females in military organisations across the world, the current findings can help inform sex-specific physical training to reduce physiological demands of load carriage tasks and improve task tolerance. In turn, this could further facilitate the integration of females into combat occupational roles.

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Chapter 8: Discussion

The first purpose of this thesis was to design and implement an evidence-based physical training program to target the specific neuromuscular demands of load carriage tasks. Developing this physical training program was vital to this thesis as the evaluation of male and female responses to the training was fundamental to all thesis chapters. To ensure the quality of the developed intervention, an evidence-based approach was used to design the program over a 10-week period. The second purpose was to examine the neuromuscular and physical performance adaptations in a male-only population in response to the physical training program. In addition to being world-first, findings were highly informative for the development of future physical training programs that could elicit physical performance adaptions translating into improved load carriage performance. Following on from this study, the third purpose of this thesis was addressed through evaluating the same responses in a female population and were compared to male responses. The third purpose was to identify and quantify sex-specific neuromuscular and physical performance adaptations through comparatively analysing male and female data collected before, during, and after the same 10-week physical training program for load carriage. The fourth and fifth purposes were to investigate lower limb biomechanical changes in both males and females during a load carriage task and in response to a 10-week physical training program. Comparative analyses were conducted to examine if sex-specific lower limb biomechanical changes were observed in response to the same 10-week physical training program, and during a standardised load carriage task. This information is particularly important for organisations like the Australian Defence Force as it can inform physical training for one of the Australian Army physical employment standard tasks that are undertaken as a job assessment at the end of All Corps basic training. The sixth, and final purpose of this thesis was to investigate and characterise physiological and psychophysical responses during a standardised load carriage task in females, before and after 10-weeks of physical training.

The first purpose was addressed in Chapter 3 and resulted in the publication of world-first physical and psychophysical responses in a male-only population. This is the first to our knowledge to investigate the effects of a periodised, evidence-based program specifically for load carriage (Wills et al., 2019a). Improvements in lower body strength as indicated by increases in squat jump maximal force output were observed suggesting neuromuscular adaptations were specific to the training stimulus (Cormie et al., 2010; Häkkinen et al., 2003). Further positive adaptations in both the push-up and sit-up tests were recorded after training, which are in line with previous studies that have reported increases ranging between 32-43 % in push-up scores, and 28-38 % in sit-up scores (Harman et al., 2008a; Kraemer et al., 1987). Although performance improvements were less in the current study (13 % and 7 %, respectively) compared to those previously reported, they still indicate muscular endurance of the upper body and trunk was improved. These observed differences in physical performance improvements may be accounted for by contrasting study designs. For example, Kraemer et al. (1987) conducted a 12-week training intervention that included a high volume of training in comparison to the current study. Combined with a soldier-specific population, this may have facilitated a greater window of opportunity to elicit adaptive responses. A surprising key finding after training was that cardiovascular performance improvements were elicited, potentially through maximal lower limb strength enhancing mechanical efficiency (Kraemer et al., 2001), and in turn lessening the cardiovascular stress experienced during the load carriage task (Deschenes & Kraemer, 2002). Combined with evident reductions in RPE values, findings suggest that repeated task exposure included throughout training (i.e., load carriage training sessions) may have increased an individual's tolerance for the physical demands of load carriage. Future research could develop and implement a load carriage-only targeted training intervention to identify if this training alone could enhance load carriage capacity, in comparison to training similar to that conducted in this thesis. Results from this current work corroborates previous findings that demonstrate periodised resistance training program combined with repeated, progressive load carriage exposure induces physical performance improvements and neuromuscular adaptations in males (Sauers & Scofield, 2014).

Chapter 4 was a continuation of the previous study, in which I compared the physical performance data of males and females before, during, and after the same 10-week physical training program. In line with previous findings (Wills et al., 2019a), similar significant improvements in lower limb and upper body muscular endurance (i.e., squat jump maximal force and push-ups, respectively) were demonstrated for both sexes. Furthermore, and regardless of sex, psychophysical measures improved during the load carriage task indicated by reduced RPE values following the 10-week training program. Despite these similar adaptations in response to training, sex-specific responses were observed in response to the same 10-weeks of training. Results demonstrate HR significantly decreased in males but remained stable in females. Given the load carriage task remained the same (i.e., treadmill walking at 5.5 km·h^{-1}, wearing a 23 kg torso-borne vest for 5 km), these findings suggest that despite both sexes perceiving the task to be easier after training; males realised a benefit more so from the training stimulus that females did not and potentially experienced lower cardiovascular stress in comparison to females during the load carriage task (Deschenes & Kraemer, 2002). Conversely, the stimulus provided by the training elicited greater improvements in push-ups for females compared to males. These results are similar to those of previous work and are unsurprising given that the main deficit in physical capacities of females is upper body strength and muscular endurance (Nindl et al., 2016). Interestingly, despite positive adaptive responses in performance after training, males still outperformed females in all performance measures similarly to previous reports (Knapik et al., 2005; Yanovich et al., 2008). Overall, these findings indicate that to lessen the evident performance gap between sexes, females should be trained differently to males to optimise performance for load carriage tasks. Achieving this reduced performance gap may involve strategies such as targeting training towards specific neuromuscular demands and/or areas of weakness (e.g., upper body) identified specifically in a female population. Although, it appears that the integration of females into combat-related roles is still a key challenge in military organisations, suggesting that physical training should be focussed on female soldiers building the physical capacity to successfully execute critical combat-tasks without injury.

In Chapters 5 and Chapter 6, I identified and quantified time-course changes in lower limb biomechanics during a standardised load carriage task, before and after the 10 weeks of training. Specifically, Chapter 5 demonstrated favourable changes in knee and ankle joint moments and powers that are indicative of an increased ability of individuals to sustain performance during a load carriage task (Wills et al., 2019b). Consistent with prior research, hip and knee joint extensor moments increased over the 5 km load carriage task (Seay et al., 2014; Wang et al., 2013). However, upon completion of the training program, hip moments remained stable suggesting training did not impair normal hip biomechanics and may have helped to sustain normal hip motion. After training, males demonstrated reduced knee joint moments over the duration of the load carriage march. Despite larger relative increases in knee moments from pre-march to post-march post-training compared with pre-training, these findings potentially indicate a reduced risk of injury through lower net joint moments as an adaptive response to training.

Sex-specific adaptive gait responses over the load carriage march duration, and in response to training, were reported in Chapter 6. Specifically, adaptive responses were observed at the hip and knee joints during the 5 km loaded march, and at the hip joint only, as a result of training. Training elicited increases in relative contributions of the hip joint to total lower limb power generation for females only, whereas ankle joint positive power contributions increased for both sexes as a result of training. Indeed, movement pattern variations between sexes may be accounted for by known structural differences, particularly at the hip and knee joints (Lewis et al., 2017). However, I identified changes in hip biomechanics in females that contrasts with findings of previous work (Loverro et al., 2019), as such changes have only previously been reported to increase for males only. Furthermore, peak hip flexion moments increased in females, which further contrast with previous findings that investigated a similar load magnitude (Krupenevich et al., 2015). Potentially, the current study participants were more sensitive to peak moment adaptations over the march duration as conditions were examined during prolonged load carriage tasks (which can exacerbate load effects (Simpson et al., 2012a)) in comparison to previous studies (Harman et al., 2000; Krupenevich et al., 2015; Seay et al., 2014; Silder et al., 2013a).

These results showed for the first time that females adopt a more hip-dominant strategy (i.e., a proximal shift in joint contributions to generate power) after training compared to males, who adopted an ankle-dominant strategy (i.e., a more distal shift in joint contributions to generate power) (Attwells et al., 2006; Majumdar et al., 2010). These contrasting findings are surprising given that the primary focus of the 10 weeks of training was to improve strength of hip-spanning muscles. Regardless of these differences, the training stimulus provided appears to be sufficient to elicit favourable neuromuscular adaptations (Lenton et al., 2019; Wills et al., 2019a) that translate to efficient gait strategies to meet the demands of the task (Huang & Kuo, 2014). Thus, these sex-specific lower limb adaptative responses to a standardised military-relevant load carriage task strongly indicate that physical training needs to be tailored to each sex to maximise benefits of training based on individual requirements. To corroborate and extend our findings, future studies should look to complete similar sex comparisons in a military population (e.g., recruits) to further understand adaptive responses to specific physical training and during a standardised load carriage task. Not only would this inform Military training within the Australian Defence Force for all soldiers, but it could further facilitate the successful integration of female soldiers into physically demanding combat-related roles.

Chapter 7 sought to characterise and evaluate female-specific physiological and psychophysical responses during the 5 km load carriage walking task before and after the 10 weeks of training. As a result of training, females perceived the 5 km load carriage task to be easier, likely as a result of a combination of increased lower and upper body strength as well as increased task resilience from repeated load carriage exposures (Harman et al., 2008a; Kraemer et al., 2001; Kraemer et al., 2004). Previous research has identified that adaptations in strength alters muscle activation patterns (Balsalobre-Fernández et al., 2016) which in turn, can enhance limb coordination and improve the efficiency of a given movement pattern (Kraemer et al., 2001). Such favourable findings could have significant implications in terms of effectively decreasing cardiorespiratory demands of a load carriage task experienced by a female cohort, even in the absence of improved cardiorespiratory capacity. Surprisingly, HR did not change following training, however, studies have identified that other determining factors of load carriage task demands (i.e., discomfort or pain (Park et al., 2013) and respiratory mechanics (Phillips et al., 2016)) can impact RPE and HR responses. Combined, this suggests that the training stimulus alone was not sufficient enough to mitigate additional limiting factors of external load carriage. Additional strategies (i.e., cognitive resilience training, and female-specific vest design to reduce pain and discomfort) should therefore be considered to further build load carriage task-specific resilience and sustainment capacity in a female population (Nindl et al., 2018).

8.1. Thesis Conclusions

While physical training in the military is key in developing physically fit, capable and effective soldiers, previous research has failed to directly evaluate performance outcomes between males and females when undertaking the same training. Findings from chapter 4 revealed that males outperformed females in all physical performance measures when provided with the same training stimulus. However, responses observed indicated that sexes adapted to some components of fitness differently (i.e., upper body strength and aerobic capability), whereas adaptations to other fitness components were similar (i.e., lower body strength, lower body power, HR responses, and perceptual responses). Though this standardised approach to elicited positive performance improvements overall, results indicate this approach may not be optimal to elicit positive training adaptations for sexes independently. Rather than trying to achieve equity between performance, a greater consideration of tailoring training to meet the incapacities of each sex independently may be required.

Our analysis further identified that the demands of load carriage are met differently by males and females; as evidenced by sex-specific adaptations in lower limb observed in chapter 6. Importantly, this comparative analysis is the first within the literature to report specific differences between males and females during a standardised load carriage task. Changes in female hip and knee joint kinematics were found compared to males over a 5 km distance, however, these responses diminished after training. The effects of mechanical joint work were important in determining key differences in performance between males and females load carriage performance. In response to training, both sexes adopted different strategies over the 5 km load carriage task. A distal shift of positive power production towards the ankle suggests males adopted an ankle driven strategy (Attwells et al., 2006; Majumdar et al., 2010; Silder, Delp, & Besier, 2013b), whereas females generated greater hip power after training, suggesting they adopted a more hip-dominant strategy. Indeed, shifting relative joint power contributions distally is an efficient strategy to assist with forward progression when carrying evenly distributed load configurations, as increased ankle push-off propels the COM forward and upward (Lewis & Ferris, 2008). However, shifting task requirements proximally would actively decrease reliance on knee musculature to produce positive work/power (Blacker et al., 2013; Teng & Powers, 2014, 2016), potentially decreasing injury risks at one of the most commonly injured sites in military personnel (Department of Defence, 2000).

To provide neuromuscular benefits specific to military load carriage applications, the training program used in this thesis placed an emphasise on developing hip extensors and flexors muscle strength. Regardless of sex, it appears that implementing task-specific conditioning over a 10-week period improves not only physical performance, but also load carrying capabilities. The primary goal of the training program in our study was to increase lower limb strength, which was achieved through both sexes demonstrating an increase in lower limb maximal force production. Given that absolute strength and load carriage ability are seemingly correlated, improvements in strength may have contributed towards individuals successfully maintaining joint moments and powers over duration of the load carriage task. Although sexes adopted different gait strategies to meet the demands of the load carriage task, the lower psychophysiological responses observed after training suggest that individuals' ability to tolerate the loaded task was improved. Combined, these findings indicate that task-specific conditioning enhanced individuals' capacity for a standardised load carriage task.

This thesis evaluated sex differences in response to a standardised physical training program designed to improve individuals' physical capabilities for load carriage. Key findings highlighted that providing the same training stimulus appears to elicit different physical, neuromuscular, and biomechanical adaptations and responses in both males and females. Although, these results indicate the same periodised training reduces the performance gap between sexes, it does not appear to completely eliminate it. Responses to training are not solely determined by stimulus provided, therefore more specific strategies (i.e., individualised training targeting sex specific incapacities, vest design, resilience training) may be required to improve performance outcomes for males and females. The designed and implemented training program used within this thesis provides an evidence base to inform future programs to enhance soldiers' capabilities for load carriage tasks regardless of sex.

8.2. Limitations

Individual study limitations were detailed within each chapter. General limitations in relation to biomechanical modelling and experimental procedures require further discussion.

8.2.1. Experimental Procedures

It is important to acknowledge that experimental data was limited by equipment constraints. First, kinetic data for males and females were acquired using over-ground and treadmill-based protocols, respectively. The force-instrumented treadmill used for female data collection was not available when experimental data collection commenced for the male cohort. This was due to acquisition of the instrumented treadmill after the male data collection period commenced. Riley et al. (2007) identified only small differences in kinematic and kinetic parameters when overground and treadmill gait protocols were evaluated. However, the magnitude of differences found between protocols fall within variability ranges that are classified as accepted thresholds within normal gait parameters (Lee et al., 2017; Riley et al., 2007). As such, we believe the overground and treadmill-based protocols are adequately similar, demonstrating the equivalence kinematic and kinetic data quality for comparison between male and female populations within the current thesis.

Participants recruited within the current thesis were recreationally active civilians, representative of a military recruit population; since they were required to meet the same entry standards as specified by the Australian Army. Therefore, the applicability of current findings may be limited to initial recruits compared to experienced soldiers. Furthermore, load carriage experience and physical fitness of individuals can affect how an individual adapts to external load during walking tasks. However, it is not anticipated that my results were substantially impacted by these factors as: 1) a familiarisation task was undertaken prior to the load carriage laboratory test (Matsas et al., 2000) and, 2). as evidenced by meeting or exceeding initial inclusion criteria (Australian Defence Force; Lidstone et al., 2017; Mullins et al., 2015), all participants were physically active and representative of a recruit population.

8.2.2. Biomechanical Modelling

Knee flexion and extension degrees of freedom (DOF) were used to determine non-sagittal knee joint motions (abduction/adduction, internal/external rotations, as well as tibial translations) using the same base functions which were then scaled for each subject. This method was chosen as secondary knee motion measures taken from skin-surface marker data is error prone and misleading (Benoit et al., 2006). Although the biomechanical modelling involved using generic anatomical models that were personalised to individual participants via linear scaling (Winby, Lloyd, & Kirk, 2008) they were not subject-specific (i.e., built to match personalised anatomy through using magnetic resonance images (MRI)). However, in the current study, data for both males and females were analysed using the same modelling approach for pre-training and post-training enabled relative within-subject comparisons. Therefore, we believe statistical differences and inferences made from these differences would not have changed based upon the generic model used.

8.3. Delimitations

The scope of this thesis was designed to maintain project feasibility and ensure the generalisability of results. First, participants within included studies were recreationally active civilians, who were representative of a military recruit population (as determined by pre-set inclusion criteria which are the same as those set by the Australian Army). Access to military personnel, especially infantry soldiers was not viable for this project at the time of commencement, meaning that the applicability of current findings may be limited to initial recruits compared to experienced soldiers. Second, experimental testing sessions (load carriage and physical performance) were confined to the laboratory due to equipment limitations, but this enabled controlled experimental trial and reliable data collections between sessions of independent studies. Reducing the external constraints applied (e.g., self-paced march time criterion test) would make the task more representative of field conditions, and potentially make the applications of findings more applicable to 'real-world' settings, but at the cost of experimental control.

8.4. Recommendations for future research

Key findings from this thesis combined with the limitations (and delimitations) have led to the formulation of several recommendations for future research. These sections have been classified under the subheadings of "sex-comparisons" and "female-specific" and will detail recommendations for experimental studies focussed on physical training and biomechanical responses in relation to load carriage tasks.

8.4.1. Sex Comparisons

Results from this thesis have posed conflicting findings to the few previous research studies available that investigated sex-specific differences during load carriage (Krupenevich et al., 2015; Loverro et al., 2019; Silder et al., 2013a). To corroborate, extend, and further understand male and female lower limb gait responses during load carriage, prospective studies should be conducted to comparatively analyse potential sex-specific differences. Establishing a body of work to inform how to best train both males and females by meeting their individual needs will ultimately assist in the optimisation of combat soldiers' occupational performance.

8.4.2. Female-Specific Focus

Future experimental studies of physical training for load carriage should conduct comparisons of targeted physical interventions that employ different primary foci (i.e., upper body, lower body, balanced approach). Investigating different physical training programs in females will help to identify what program specifics are required to elicit positive performance and biomechanical responses for a females-only cohort. For example, Kraemer et al. (2001) reported that upper body targeted resistance training elicited greater responses in loaded running performance compared with full body focussed training. However, such responses have only been investigated in relation to physical performance and have not yet been examined in load carriage. Identifying such responses in females will enable the development of an optimised training program that targets load carriage demands that translates to improved performance and potentially reduces injury risks.

8.5. Conclusions

This thesis contributed towards current load carriage research by being the first to design and implement a physical training program specifically targeted at developing the neuromuscular, physiological and psychophysical capabilities for load carriage. Furthermore, findings from this thesis were the first to quantify the physical and neuromuscular adaptations in males and females in response to load carriage specific training. In conducting these interventions, I have established an evidence-base that can inform future physical training programs to assist the facilitation of the integration of females into physically demanding combat military occupations. My findings demonstrate that males and females elicit some similar, and some different responses to the same physical training which highlights the need to tailor training to meet specific needs of each sex independently. First, in relation to physical performance, the training stimulus provided should be targeted to the peculiarities of males and females (i.e., strength, power, aerobic fitness, upper or lower body focus etc.) to optimise performance improvements. Second, in relation to biomechanical adaptations to training, targeting known injury mechanisms assists in conditioning individuals to sustain and tolerate task demands of loaded walking over a prolonged task whilst carrying a moderate load. Finally, the characterisation of physiological and psychophysical responses in females during a standardised military-relevant load carriage task suggests that additional strategies (i.e., cognitive resilience training, female-specific vest design to reduce pain burden) are required to further build load carriage task-specific resilience. With this information Military organisations may save substantial costs in recruitment training and, by training efficiently, enable soldiers to be ready for deployment faster than current training methods. Implementing this scientific evidence-based approach to target load carriage demands will optimise training and build soldiers physical capacities to ensure personnel are physically prepared for combat.

8.6. References

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Chapter 9: Appendices

Please see following pages for appendices associated with the thesis.

Appendix 1. Study 1 Ethics Approval

Please see the following pages for a copy of study 1 ethics approval letter.

Office of the Deputy Vice-Chancellor
(Research)

Research Office
Research Hub, Building C5C East
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NSW 2109 Australia
T: +61 (2) 9850 4459
http://www.research.mq.edu.au/
ABN 90 952 801 237

MACQUARIE University
SYDNEY·AUSTRALIA

7 June 2017

Dear Dr Doyle

Reference No: 5201700406

Title: *Rapid and targeted training to reduce injury and improve performance in males during load-carriage undertaken during physically demanding occupations*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Medical Sciences)).

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated May 2015) (the *National Statement*).

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the *National Statement,* which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol and associated documents must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Medical Sciences) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Medical Sciences) wishes you every success in your research.

Yours sincerely

Professor Tony Eyers
Chair, Macquarie University Human Research Ethics Committee (Medical Sciences)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice*.

Details of this approval are as follows:

Approval Date: 6 June 2017

The following documentation has been reviewed and approved by the HREC (Medical Sciences):

Documents reviewed	Version no.	Date
Correspondence responding to the issues raised by the HREC (Medical Sciences)	N/A	Received 5/5/2017 6/6/2017
Project Description	2	5/5/2017
Human Research Ethics Application Form	3	2/6/2017
Recruitment Poster	3*	5/5/2017
Invitation Email	3	2/6/2017
Macquarie Participant Information and Consent Form (PICF)	3	2/6/2017
Participant Questionnaire - Adult Pre-Exercise Screening Tool	1*	7/3/2017

Documents Noted
Letter of Support from Macquarie University Sport and Aquatic Centre Gymnasium

***If the document has no version date listed one will be created for you. Please ensure the footer of these documents are updated to include this version date to ensure ongoing version control.**

Appendix 2. Study 1 Advertisement

Please see next page for copy of the advertisement leaflet used for recruitment purposes in study 1.

Research Study

Rapid and targeted training to reduce injury and improve performance in males during load-carriage undertaken during physically demanding occupations

Current requirements of heavy load carriage combined with in field activities leave Army personnel exposed to increased risks of injuries. Physical training is known to help reduce injury risks if designed and specifically targeted toward injury mechanisms. The aim of this research is to identify the physical and neuromuscular adaptations to a load carriage specific task in response to a targeted 10-week physical training intervention.

Who can participate:

- Healthy male civilians ≤25 years of age with a body mass ≥73 kg
- Able to perform 70 sit-ups and 40 push ups in 2 min each
- Have a maximal oxygen uptake of ≥45 $mL.kg^{-1} \cdot min^{-1}$ (level 7.5 bleep test)

What's involved:

- Participating in a 10-week physical training intervention, 3 x 1 hr sessions p/week
- Partake in 2 laboratory data collection sessions whilst walking with load

Benefits to you include:

- Free access to gym facilities throughout the physical training intervention
- Personal training three times per week
- Personalised report detailing strength, power and overall performance improvements

If you are interested or would like some further information, please contact;

Dr Tim Doyle

- T: 02 9850 9841
- E: tim.doyle@mq.edu.au

Miss Jodie Wills

- T: 02 9850 2797
- E: Jodie.wills@hdr.mq.edu.au

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Appendix 3. Study 1 Participant Information and Consent Form

Please see the following pages for a copy of specific versions of the participant information and consent form used by investigators and participants in study 1 of this thesis.

Appendix 3.1. Participant Information and Consent Form: Investigators Version

Department of Health Professions
Faculty of Medicine and Health Sciences
MACQUARIE UNIVERSITY NSW 2109

Phone: ***02 9850 9841***
Email: tim.doyle@ mq.edu.au

Chief Investigator's / Supervisor's Name & Title: Dr. Tim Doyle, Senior Lecturer.

Participant Information and Consent Form

Rapid and targeted training to reduce injury and improve performance in males during load-carriage undertaken during physically demanding occupations

Current requirements of heavy load carriage combined with in field activities leave Army personnel exposed to increased risks of injuries. Physical training is known to reduce injury risks if designed and specifically targeted toward injury mechanisms. The purpose of the current study is to identify the physical and neuromuscular adaptations to a load carriage specific task in response to a targeted 10-week physical training intervention.

The study is being conducted by Miss Jodie Wills to meet the requirements of Doctor of Philosophy in Health Professions under the supervision of Dr Tim Doyle (T: 02 9850 9841, E: tim.doyle@mq.edu.au) of the Department of Health Professions.

Study Details

Your participation in this study will help identify physical and neuromuscular adaptations to a load carriage task in response to specific physical training. If you decide to participate, you will be required to attend 3 separate laboratory sessions in addition to participating in a 10-week physical training intervention (specific strength and conditioning for loaded walking ability). A brief description of each visit is detail below;

Laboratory visit 1 will involve:

- Measurement of inclusion criteria variables, performance tests (strength, power and aerobic capacity) and a short duration loaded walking task

Laboratory visit 2 and 3 will involve:

- Completing a 5km treadmill walking task in 55 minutes whilst wearing a weighted vest (22kg)
- Several measures will be recorded during the walking task. Measures will include; movement analysis, surface electromyography (muscle activity), foot pressures, force production, and perceived exertion scale rating (subjective rating)

The periodised 10-week physical training intervention will consist of three main components: resistance (weight) training, cardiovascular exercises, and walking with a weighted vest to simulate load carriage specific tasks undertaken in the army. The following is a brief description of the training structure:

- Supervised training session three times per week at the Macquarie University Sport and Aquatic Centre gymnasium
- Un-supervised general conditioning exercises up to twice per week

Through participating within the current study, you will receive free gym access for the duration of the training intervention (supervised sessions only), individualised personal training and a detailed report of fitness performance improvements.

As this study involves load carriage, to volunteer you must be able to meet the following inclusion criteria: ≤25 years of age, have a body mass ≤73 kg, be able to perform 70 sit-ups and 40 push ups in 2 min each, and have a maximal aerobic capacity ≥45 $mL.kg^{-1}.min^{-1}$.

<u>*Risks*</u>

It is important to remind you that there will be several risks associated with participation in this study. However, a range of safeguards have been put in place to ensure these risks are minimised.

1. You feel that you are being coerced or forced to participate in this study. To minimise the potential for coercion, you are being recruited by a person who is not your superior or employer. You are also free to withdraw at any time should you change your mind about participating in this study, this will not be reported to anyone and will not in any way affect your status as student.
2. The research activities require that you walk on a treadmill for 55 minutes. As such, you will be asked to familiarise yourself with walking on the treadmill until you feel comfortable. In the unlikely case that you do lose your balance, there are rails on either side of the treadmill that you can use to support yourself. There is also an emergency stop button that you will be familiarised with prior to any testing. In addition, cushioning mats will be placed around the treadmill in the highly unlikely case that you were to fall off the back.
3. Surface EMG and 3D motion analysis data collection will all require the use of low-allergenic adhesive tape (for small equipment to be affix to your body). Although rare, some people do have allergies to this tape. If you have any allergies to adhesive tape that may pre-dispose you to skin irritation, please inform the research staff as you may need to be excluded from testing. The information you report will be kept in confidence.
4. There is a small risk of blisters developing through walking on the treadmill with external load. As the walking duration is 55 minutes, you will be asked to wear your own athletic shoes that have been worn in, ensuring this risk is minimal.
5. The research activities require that you carry load in the form of a weighted vest for the duration of testing. While there is a risk of pain arising in your shoulder and torso from this load carriage, it is only typically observed with heavier weight and prolonged duration activities. There is specific inclusion criteria to ensure this load is not too heavy relative to body mass, therefore the likelihood of any pain greater than discomfort is low.

Various safeguards have been enforced to minimise the risk of injury.

1. You will not be able to participate if you are carrying an injury or have an illness that may be made worse due to your involvement in the study. You will be asked to disclose your injury and/or illness status to a researcher and the information that you report will be kept confidential.
2. You have met or exceeded the inclusion criteria set out. You will not be asked to undertake any activities that are more physically demanding than those that you perform in your normal active lifestyle.
3. The environment in which physical activities will be undertaken will be checked to ensure there are no unacceptable physical hazards present.
4. If you do experience an injury, you will be given first aid or medical treatment as necessary by qualified personnel.
5. You may experience some discomfort throughout the physical training intervention however, it is anticipated that the physical demands associated with participating would not exceed that encountered in your normal active lifestyle.

Any information or personal details gathered during the study are confidential, except as required by law. No individual will be identified in any publication of the results. Only members detailed as part of the research team will be able to access collected study data. A summary of the results of your data can be made available to you upon completion of the study if you wish, which can be requested through a member of the research team. There is no anticipated secondary use of the data collected, however, results will be used to inform future research Human Research Ethics Committee-approved projects within this area of interest.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to provide reason and without further consequence.

Should you have any complaints or concerns about the way this project is conducted, please do not hesitate to contact the researchers in person, by email, or phone.

I,.. have read *(or, where appropriate, have had read to me)* and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Participant's Name:____
(Block letters)

Participant's Signature: _______________________ Date:__________________

Investigator's Name:____
(Block letters)

Investigator's Signature:_____________________ __ Date:__________________

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

(INVESTIGATOR'S COPY)

Name of Investigators:

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Appendix 3.2. Participant Information and Consent Form: Participants Version

Department of Health Professions
Faculty of Medicine and Health Sciences
MACQUARIE UNIVERSITY NSW 2109

Phone: *02 9850 9841*
Email: tim.doyle@ mq.edu.au

Chief Investigator's / Supervisor's Name & Title: Dr. Tim Doyle, Senior Lecturer.

Participant Information and Consent Form

<u>Rapid and targeted training to reduce injury and improve performance in males during load-carriage undertaken during physically demanding occupations</u>

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The study is being conducted by Miss Jodie Wills to meet the requirements of Doctor of Philosophy in Health Professions under the supervision of Dr Tim Doyle (T: 02 9850 9841, E: tim.doyle@mq.edu.au) of the Department of Health Professions.

<u>Study Details</u>

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- Several measures will be recorded during the walking task. Measures will include; movement analysis, surface electromyography (muscle activity), foot pressures, force production, and perceived exertion scale rating (subjective rating)

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- Supervised training session three times per week at the Macquarie University Sport and Aquatic Centre gymnasium
- Un-supervised general conditioning exercises up to twice per week

Through participating within the current study, you will receive free gym access for the duration of the training intervention (supervised sessions only), individualised personal training and a detailed report of fitness performance improvements.

As this study involves load carriage, to volunteer you must be able to meet the following inclusion criteria: ≤25 years of age, have a body mass ≥73 kg, be able to perform 70 sit-ups and 40 push ups in 2 min each, and have a maximal aerobic capacity ≥45 $mL.kg^{-1}.min^{-1}$.

Risks

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1. You feel that you are being coerced or forced to participate in this study. To minimise the potential for coercion, you are being recruited by a person who is not your superior or employer. You are also free to withdraw at any time should you change your mind about participating in this study, this will not be reported to anyone and will not in any way affect your status as student.
2. The research activities require that you walk on a treadmill for 55 minutes. As such, you will be asked to familiarise yourself with walking on the treadmill until you feel comfortable. In the unlikely case that you do lose your balance, there are rails on either side of the treadmill that you can use to support yourself. There is also an emergency stop button that you will be familiarised with prior to any testing. In addition, cushioning mats will be placed around the treadmill in the highly unlikely case that you were to fall off the back.
3. Surface EMG and 3D motion analysis data collection will all require the use of low-allergenic adhesive tape (for small equipment to be affix to your body). Although rare, some people do have allergies to this tape. If you have any allergies to adhesive tape that may pre-dispose you to skin irritation, please inform the research staff as you may need to be excluded from testing. The information you report will be kept in confidence.
4. There is a small risk of blisters developing through walking on the treadmill with external load. As the walking duration is 55 minutes, you will be asked to wear your own athletic shoes that have been worn in, ensuring this risk is minimal.
5. The research activities require that you carry load in the form of a weighted vest for the duration of testing. While there is a risk of pain arising in your shoulder and torso from this load carriage, it is only typically observed with heavier weight and prolonged duration activities. There is specific inclusion criteria to ensure this load is not too heavy relative to body mass, therefore the likelihood of any pain greater than discomfort is low.

Various safeguards have been enforced to minimise the risk of injury.

1. You will not be able to participate if you are carrying an injury or have an illness that may be made worse due to your involvement in the study. You will be asked to disclose your injury and/or illness status to a researcher and the information that you report will be kept confidential.
2. You have met or exceeded the inclusion criteria set out. You will not be asked to undertake any activities that are more physically demanding than those that you perform in your normal active lifestyle.
3. The environment in which physical activities will be undertaken will be checked to ensure there are no unacceptable physical hazards present.
4. If you do experience an injury, you will be given first aid or medical treatment as necessary by qualified personnel.
5. You may experience some discomfort throughout the physical training intervention however, it is anticipated that the physical demands associated with participating would not exceed that encountered in your normal active lifestyle.

Any information or personal details gathered during the study are confidential, except as required by law. No individual will be identified in any publication of the results. Only members detailed as part of the research team will be able to access collected study data. A summary of the results of your data can be made available to you upon completion of the study if you wish, which can be requested through a member of the research team. There is no anticipated secondary use of the data collected, however, results will be used to inform future research Human Research Ethics Committee-approved projects within this area of interest.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to provide reason and without further consequence.

Should you have any complaints or concerns about the way this project is conducted, please do not hesitate to contact the researchers in person, by email, or phone.

I,.. have read *(or, where appropriate, have had read to me)* and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Participant's Name:____
(Block letters)

Participant's Signature: _________________________ Date:____________________

Investigator's Name:____
(Block letters)

Investigator's Signature:______________________ __ Date:____________________

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

(PARTICIPANT'S COPY)

Name of Investigators:

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Appendix 4. Study 2 Ethics Approval

Please see the following pages for a copy of the ethics approval letter for study 1.

Office of the Deputy Vice(Research) -Chancellor

Research Services

Research Hub, Building C5C East

Macquarie University

NSW 2109 Australia T: +61 (2) 9850 4459

http://www.researcABN 90 952 801 237h.m q.edu.au/

CRICOS Provider No 00002J

MACQUARIE University SYDNEY·AUSTRALIA

30 November 2017

Dear Dr Doyle

Reference No: 5201700997

Title: *Sex-specific adaptive responses to a load-carriage specific training program*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Medical Sciences)).

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated May 2015) (the *National Statement*).

Standard Conditions of Approval:

1. Approval is contingent on continuing compliance with the requirements of the *National Statement,* which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. Proposed changes to the protocol and associated documents must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Medical Sciences) Terms of Reference and Standard Operating Procedures are available from the Research Office website at: http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Medical Sciences) wishes you every success in your research.

Yours sincerely

Professor Tony Eyers

Chair, Macquarie University Human Research Ethics Committee (Medical Sciences)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice*.

Details of this approval are as follows:

Approval Date: 23 November 2017

The following documentation has been reviewed and approved by the HREC (Medical Sciences):

Documents reviewed	Version no.	Date
Correspondence responding to the issues raised by the HREC (Medical Sciences)		Received 24 Nov 2017 08 Nov 2017
Resubmitted Human Research Ethics Application (HREA)	2*	08 Nov 2017
Macquarie Participant Information and Consent Form (PICF)	2	30 Oct 2017
Advertisement	2	02 Nov 2017
Measures and exercise programmes • ESSA Pre-Exercise Screening Tool • Rating of perceived exertion scale (RPE) Scale • Workout Load • Workout	2*	08 Nov 2017

***If the document has no version date listed one will be created for you. Please ensure the footer of these documents are updated to include this version date to ensure ongoing version control.**

Appendix 5. Study 2 Advertisement

Please see next page for a copy of the advertisement leaflet used for recruitment purposes in study 2.

We are conducting a research study you may be eligible for!

MACQUARIE University
SYDNEY · AUSTRALIA

Sex-specific adaptive responses to load-carriage specific training programs

If you are:

- A healthy **female 18-30** years old
- Have a current body mass **≥55** kg
- Able to perform up to 70 sit-ups and 21 pushups in 2 min each
- Have a maximal oxygen uptake of ≥45 $mL.kg^{-1}\cdot min^{-1}$ (level 7.5 beep test)

Then you qualify to participate!

The requirements of the study include:

- Participating in a 10-week physical training intervention (3 x 1 hr sessions p/week, up to 2 x unsupervised sessions p/week)
- Partake in 2 laboratory data collection sessions whilst walking with load

Benefits to you include:

- Personal training three times per week
- Personalised report detailing overall performance improvements

Volunteers will be screened for eligibility before participating

If you are interested or would like some further information, please contact;

Dr Tim Doyle
E: tim.doyle@mq.edu.au

Miss Jodie Wills
M: 0424 281 314
E: jodie.wills@hdr.mq.edu.au

Load-Carriage study
jodie.wills@hdr.mq.edu.au mobile: 0424 281 314
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tim.doyle@mq.edu.au

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tim.doyle@mq.edu.au

Appendix 6. Study 2 Participant Information and Consent Form

Please see the following pages for a copy of the participant information and consent form used by investigators and participants in study 2 of this thesis.

Department of Health Professions
Faculty of Medicine and Health Sciences
MACQUARIE UNIVERSITY NSW 2109

Phone: *02 9850 9841*
Email: tim.doyle@ mq.edu.au

Chief Investigator's / Supervisor's Name & Title: Dr. Tim Doyle, Senior Lecturer.

Participant Information and Consent Form

Sex-specific adaptive responses to load-carriage specific training programs

You are invited to participate in a load-carriage research study. The purpose of the current study is to identify physical adaptations in response to a targeted load-carriage physical training program in females.

The study is being conducted by Miss Jodie Wills (T: 0424 281 314, E: jodie.wills@hdr.mq.edu.au) to meet the requirements of Doctor of Philosophy in Health Professions under the supervision of Dr Tim Doyle (T: 02 9850 9841, E: tim.doyle@mq.edu.au) of the Department of Health Professions.

Study Details

If you decide to participate, you will be required to attend one familiarisation session, two separate laboratory sessions and participate in a 10-week physical training intervention (specific strength and conditioning for loaded walking ability). Each visit is briefly detail below;

Initial / familiarisation session:

- Assessment of inclusion criteria variables (18-30 years of age, have a body mass ≥55 kg, perform up to 70 sit-ups and 21 push ups in 2 min each, have a maximal aerobic capacity ≥45 $mL.kg^{-1}.min^{-1}$ (assessed via the beep test), performance tests (strength, power and aerobic capacity) and a short duration loaded walking task for familiarisation purposes

N.B. These measures will be repeated at the end of the training intervention to assess physical performance improvements.

Laboratory visit 1 and 2:

- You will be required to complete a 5km treadmill walking task in 55 minutes whilst wearing a weighted vest (23kg)
- Several measures will be recorded during the walking task. These include; movement analysis, surface electromyography (muscle activity), force production, oxygen consumption, heart rate and perceived exertion scale rating (subjective rating)

The periodised 10-week physical training intervention will consist of three main components: resistance (weight) training, cardiovascular exercises, and walking with a weighted vest to simulate Army load-carriage tasks. The following is a brief description of the training structure:

- Supervised training session three times per week at the Macquarie University Sport and Aquatic Centre gymnasium
- Un-supervised general conditioning a maximum of twice per week

A complimentary gym membership will be provided for the duration of your participation within the study, in addition to individualised personal training. Upon completion, if you wish, a detailed report of fitness performance improvements can be provided.

Risks

It is important to remind you that there will be several risks associated with participation in this study. However, a range of safeguards have been put in place to ensure these risks are minimised.

1. You feel that you are being coerced or forced to participate in this study. To minimise the potential for coercion, you are being recruited by a person who is not your superior or employer. You are also free to withdraw at any time should you change your mind about participating in this study, this will not be reported to anyone and will not in any way affect your status as student.
2. The research activities require that you walk on a treadmill for 55 minutes. As such, you will be asked to familiarise yourself with walking on the treadmill until you feel comfortable. In the unlikely case that you do lose your balance, there are rails on either side of the treadmill that you can use to support yourself. There is also an emergency stop button that you will be familiarised with prior to any testing.
3. Surface EMG and 3D motion analysis data collection will all require the use of low-allergenic adhesive tape (for small equipment to be affix to your body). Although rare, some people do have allergies to this tape. If you have any allergies to adhesive tape that may pre-dispose you to skin irritation, please inform the research staff as you may need to be excluded from testing. The information you report will be kept in confidence.
4. For oxygen consumption you will be required to wear a mask. This mask does not interfere with breathing although there is a chance you may feel discomfort from it, this is however rare.
5. There is a small risk of blisters developing through walking on the treadmill with external load. You will be asked to wear your own athletic shoes that have been worn in, ensuring this risk is minimal.
6. The research activities require that you carry load in the form of a weighted vest for the duration of testing. While there is a risk of pain arising in your shoulder and torso from this load carriage, it is only typically observed with heavier weight and prolonged duration activities. There is specific inclusion criteria to ensure this load is not too heavy relative to body mass, therefore the likelihood of any pain greater than discomfort is low.

Various safeguards have been enforced to minimise the risk of injury.

1. You will not be able to participate if you have an injury or illness that may be made worse due to your involvement in the study. You will be asked to disclose any injury and/or illness status to a researcher where all information reported will be kept confidential. If you experience an injury during participation, you will be given first aid/medical treatment by qualified personnel.
2. You will not be asked to undertake any activities that are more physically demanding than those that you perform in your normal active lifestyle. All areas in which physical activities will be undertaken will be checked to ensure there are no unacceptable physical hazards present.
3. You may experience some discomfort throughout the physical training intervention however, it is anticipated that the physical demands associated with participating would not exceed that encountered in your normal active lifestyle.

Any information or personal details gathered during the study are confidential, except as required by law. No individual will be identified in any publication of the results, with all data obtain remaining de-identified. Only members detailed as part of the research team will be able to access collected study data. Results from this study will be used to inform future research Human Research Ethics Committee-approved projects within this area of interest.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to provide reason and without further consequence.

I,.. have read *(or, where appropriate, have had read to me)* and understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Additionally, I **do / do not** (please cross out as appropriate) provide permission for photographic content to be obtained throughout the duration of the study.

Participant's Name:____
(Block letters)

Participant's Signature: ______________________ Date:__________________

Investigator's Name:____

(Block letters)

Investigator's Signature:____________________ __ Date:__________________

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics & Integrity (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

Alternately, should you have any complaints or concerns about the way this project is conducted, please do not hesitate to contact the researchers in person, by email, or phone.

(PARTICIPANT/INVESTIGATOR COPY)

Name of Investigators

1. Dr Tim Doyle
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Macquarie University,
Sydney, NSW 2109
T: 02 9850 9841
E: tim.doyle@mq.edu.au

2. Miss Jodie Wills
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Appendix 7. Exercise and Sports Science Australia (ESSA) Exercise Pre-screening Tool

Please see next page for a copy of the ESSA exercise pre-screening tool used in both study 1 and 2 to assess participant eligibility prior to undertaking the inclusion testing session.

ESSA PRE-EXERCISE SCREENING TOOL

This screening tool does not provide advice on a particular matter, nor does it substitute for advice from an appropriately qualified medical professional. No warranty of safety should result from its use. The screening system in no way guarantees against injury or death. No responsibility or liability whatsoever can be accepted by Exercise and Sports Science Australia, Fitness Australia or Sports Medicine Australia for any loss, damage or injury that may arise from any person acting on any statement or information contained in this tool.

Name:____________ Date of Birth:_____ Male ☐ Female ☐ Date: ______

AIM: to identify those individuals with a known disease, or signs or symptoms of disease, who may be at a higher risk of an adverse event during physical activity/exercise. This stage is self administered and self evaluated.

Please circle response

1.	Has your doctor ever told you that you have a heart condition or have you ever suffered a stroke?	Yes	No
2.	Do you ever experience unexplained pains in your chest at rest or during physical activity/exercise?	Yes	No
3.	Do you ever feel faint or have spells of dizziness during physical activity/exercise that causes you to lose balance?	Yes	No
4.	Have you had an asthma attack requiring immediate medical attention at any time over the last 12 months?	Yes	No
5.	If you have diabetes (type I or type II) have you had trouble controlling your blood glucose in the last 3 months?	Yes	No
6.	Do you have any diagnosed muscle, bone or joint problems that you have been told could be made worse by participating in physical activity/exercise?	Yes	No
7.	Do you have any other medical condition(s) that may make it dangerous for you to participate in physical activity/exercise?	Yes	No

IF YOU ANSWERED 'YES' to any of the 7 questions, please seek guidance from your GP or appropriate allied health professional prior to undertaking physical activity/exercise

IF YOU ANSWERED 'NO' to all of the 7 questions, and you have no other concerns about your health, you may proceed to undertake light-moderate intensity physical activity/exercise

I believe that to the best of my knowledge, all of the information I have supplied within this tool is correct. Signature ____________________ Date ____________

Appendix 8. Example Participant Report

Please see next page for an example report provided to participants in both study 1 and 2 upon study completion.

Sex-specific adaptive responses to load carriage specific training programs

Participant: Joe Blogs
Enrolment Date: 23.04.2019
Mid-Test Date: 07.06.2019
Post-Test Date: 09.07.2019

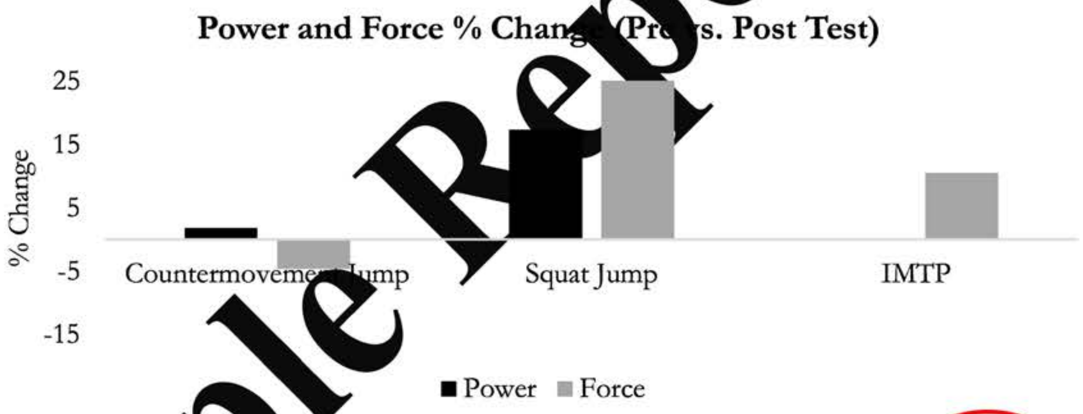
DOB: 10.03.1993
Height: 178 cm
Mass: 63 kg
Post-Test Mass: 62.2 kg

Inclusion Criteria Assessment

Australian Defence: BFA Standards		Pre	Post	% ↑
Push-Ups	21	40	48	20
Sit-Ups	70	80	72	[illegible]
Beep Test	7.5	9	9.2	[illegible]

Jumps Assessment - Maximal Power and Force Output

	Countermovement Jump		Squat Jump		IMTP	
Maximum	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Power	2367	2411	2295	2693	-	-
Force	1342	1279	1205	[illegible]	1843	1989



Week	Exercise	Weight	Set x Rep (Range)
1	Squat	40	3 x 10
	Deadlift	60	3 x 10
[illegible]	Squat	60	5 x 5
	Deadlift	65	5 x 5
7	Squat	55	5 x 5
	Deadlift	72.5	5 x 5
	Hip-Thrusts	100	5 x 5
	Stiff-legged Deadlift	45	3 x 10
10	Squat	62.5	3 x 5
	Deadlift	77.5	3 x 5
	Hip-Thrusts	115	3 x 5
	Stiff-legged Deadlift	55	3 x 5

Report provided by: Miss Jodie Wills
Department of Health Professions,
75 Talavera Road, Macquarie
University, NSW, 2109

MACQUARIE University SYDNEY-AUSTRALIA

Appendix 9. Supplementary Material

Please see following pages for supplementary materials relevant to the individual chapters of this thesis.

Appendix 9.1. Supplementary Table 1

Supplementary Table 1. Evidence-based 10-week physical training program for resistance-based training sessions.

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
1	Squat	3	8-10	120	Deadlift	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Curls	3	8-10	120	Leg Curls	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Seated Row	3	8-10	120	Bench Pull	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Bench Press	3	8-10	120	Bench Press	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	20	0	Leg Raises	1	20	0	**NA**	**NA**	**NA**	**NA**
Week	Squat	4	8-10	120	Deadlift	4	8-10	120	**NA**	**NA**	**NA**	**NA**
2	Leg Curls	4	8-10	120	Leg Curls	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Seated Row	4	8-10	120	Bench Pull	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Bench Press	4	8-10	120	Bench Press	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Face Pulls	4	8-10	120	Face Pulls	4	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	20	0	Leg Raises	1	20	0	**NA**	**NA**	**NA**	**NA**
Week	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
3	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	30	120	Upright Rows	3	8-10	120	Hyperextensions	1	30	120
	Leg Raises	1	30	0	Crunches	1	30	0	Leg Raises	1	30	0

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
4	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	40	120	Upright Rows	3	8-10	120	Hyperextensions	1	40	120
	Leg Raises	1	40	0	Crunches	1	30	0	Leg Raises	1	40	0
Week	Squat	5	5	120	Bench Pull	5	8-10	120	Squat	5	5	120
5	Deadlift	5	5	120	Bench Press	5	8-10	120	Deadlift	5	5	120
	Nordic Lowers	3	6	120	Face Pulls	5	8-10	120	Nordic Lowers	3	6	120
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	KB Step-ups (alternating)	5	10*	120
	Hyperextensions	1	50	120	Upright Rows	3	8-10	120	Hyperextensions	1	50	120
	Leg Raises	1	50	0	Crunches	1	50	0	Leg Raises	1	50	0
Week	Hip Thrusts	3	5	120	Bench Pull	3	8-10	120	**NA**	**NA**	**NA**	**NA**
6	Deadlift	3	5	120	Bench Press	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Curls	3	8-10	120	Face Pulls	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	KB Step-ups (alternating)	5	10*	120	¾ Lat Pulldowns	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Hyperextensions	1	50	120	Upright Rows	3	8-10	120	**NA**	**NA**	**NA**	**NA**
	Leg Raises	1	50	0	Crunches	1	50	0	**NA**	**NA**	**NA**	**NA**

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
7	Squats	5	5	120	Bent-over Rows	5	6-8	120	Deadlift	5	5	120
	Hip Thrusts	5	5	120	45-degree TRX Flyes	3	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	3	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	3	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0
Week	Squats	5	5	120	Bent-over Rows	5	6-8	120	Squats	5	5	120
8	Hip Thrusts	5	5	120	45-degree TRX Flyes	4	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	4	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	4	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	4	10*	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	50	0	Bicycles	1	60 (s)	0	Roman Twists	1	50	0
Week	Squats	5	5	120	Bent-over Rows	5	5	120	Squats	5	5	120
9	Hip Thrusts	5	5	120	45-degree TRX Flyes	5	10	120	Hip Thrusts	5	5	120
	Stiff-leg Deadlift	5	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	5	10	120
	Overhead Plates Walks	5	10-15	120	Chin Ups	4	10	120	Overhead Plates Walks	5	10-15	120
	Hyperextensions	1	50	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	50	120
	Roman Twists	1	50	0	Bicycles	1	60 (s)	0	Roman Twists	1	50	0

	Session 1				Session 2				Session 3			
Week	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)	Exercise	Sets	Repetitions	Rest (s)
10	Squats	3	5	120	Bent-over Rows	5	5	120	Squats	3	5	120
	Hip Thrusts	3	5	120	45-degree TRX Flyes	5	10	120	Hip Thrusts	3	5	120
	Stiff-leg Deadlift	3	10	120	Cable Shoulder Retract	5	10	120	Stiff-leg Deadlift	3	10	120
	Overhead Plates Walks	3	10-15	120	Chin Ups	5	10(5)**	120	Overhead Plates Walks	3	10-15	120
	Hyperextensions	1	40	120	Dumbbell Shrugs	5	8-10	120	Hyperextensions	1	40	120
	Roman Twists	1	40	0	Bicycles	1	60 (s)	0	Roman Twists	1	40	0

Reps, repetitions**; s,** seconds of recovery; **KB,** Kettlebell**. NA**, no session implemented; *Indicates 5 repetitions per leg were completed, **indicates the number of repetitions completed during the final set only.

Appendix 9.2. Supplementary Table 2

Supplementary Table 2. Evidence-based 10-week physical training program for load carriage training sessions.

Week	Session	Acute Variables		
		Distance (km)	Speed (5.5 km·h-1)	Load (kg)
1	1	3	4	0
	2	0	0	0
2	1	4	4	0
	2	3	4	0
3	1	4	5	0
	2	4	4	5
4	1	5	5	5
	2	5	5	5
5	1	5	6	5
	2	0	0	0
6	1	5	6	10
	2	5	6	12.5
7	1	5	6	15
	2	5	6	17.5
8	1	6	6	20
	2	0	0	0
9	1	6	6	20
	2	5	6	25
10	1	6	6	25
	2	0	0	0

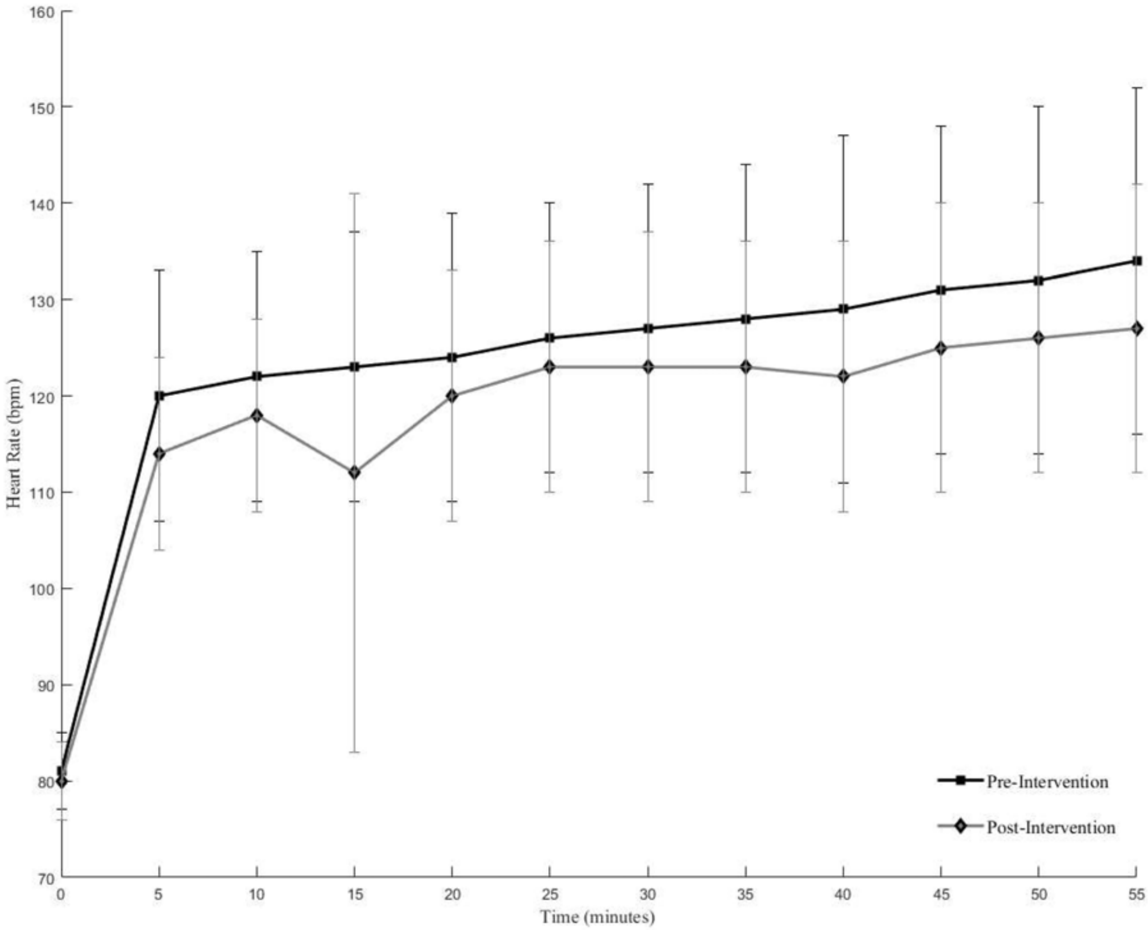
km, kilometres; **km·h-1**, kilometres per hour; **kg**, kilograms.

Appendix 9.3. Supplementary Table 3

Supplementary Table 3. Mean ± standard deviation magnitudes for three-dimensional kinematic variables. *Indicates a significant main effect of distance, #indicates a significant main effect of training, ‡indicates a significant interaction effect ($p < 0.05$).

Variable	Pre-Training Intervention				Post-Training Intervention				Effect Size (η_2)	
	Pre-March		Post-March		Pre-March		Post-March			
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	Training	Distanc
Hip										
Adduction Peak Angle	-2.15 ± 0.55	-2.49, -1.82	-2.23 ± 0.60	-2.59, -1.87	-2.23 ± 0.60	-2.59, -1.87	-2.23 ± 0.60	-2.59, -1.87	0.02	0.08
Abduction Peak Angle	0.38 ± 0.51	0.80, 0.69	0.38 ± 0.51	0.80, 0.69	0.31 ± 0.48	0.17, 0.60	0.46 ± 0.52	0.15, 0.78	0.00	0.05
External Rotation Peak Angle	0.46 ± 0.52	0.15, 0.78	0.62 ± 0.51	0.31, 0.92	0.54 ± 0.52	0.23, 0.85	0.54 ± 0.52	0.23, 0.85	0.00	0.08
Excursion	49.54 ± 4.63	46.7, 52.34	50.85 ± 3.74	48.59, 53.11	48.31 ± 3.86	45.98, 50.64	49.54 ± 3.92	47.16, 51.91	0.2	0.59
Knee										
Excursion	75 ± 6.16	71.28, 78.73	75.8 ± 5.89	72.29, 79.40	73.46 ± 5.17	70.34, 76.59	74.00 ± 4.85	71.07, 76.93	0.14	0.24
Ankle										
Excursion	30 ± 6.16	26.28, 33.73	32.15 ± 6.34	28.33, 35.98	30.92 ± 4.65	28.12, 33.73	31.38 ± 4.87	28.44, 34.33	0.00	0.15

Appendix 9.4. Supplementary Figure 1



Supplementary Figure 1. Heart rate response changes during a load carriage task before and after a 10-week training program. Data are presented as mean±standard deviation.

Appendix 10. Conference Material

Please see following pages providing copies of accepted conference abstracts, poster presentations, and oral presentations delivering research findings from this thesis.

Appendix 10.1. International Society of Biomechanics in Sport (ISBS 2018)

A TARGETED LOAD CARRIAGE TRAINING PROGRAM ELICITS POSITIVE ADAPTATIONS AFTER 10-WEEKS

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The purpose of this study was to identify and characterise physical performance responses to a targeted 10-week load carriage physical training intervention in males. Performance measures of maximal strength, heart rate, rating of perceived exertion, and basic fitness from nine male civilians before and after the 10-week training intervention are presented. There were significant increases in maximal force (~200 N) and aerobic performance (Level. Shuttle 8.9 vs 9,4 variables). Small-to-large effect sizes were shown for basic fitness and perceptual responses. The 10-week load carriage physical training intervention elicited physical performance improvements and may facilitate load carriage task performance.

KEYWORDS: **Strength, Fitness, Military**

INTRODUCTION: Load carriage is a requirement of many military occupational roles and is commonly used as an assessment standard of recruits. However, the type and volume of the physical load experienced by recruits is often greater than the individual's capacity (Friedl et al., 2015). Failure to adapt to increases in musculoskeletal demands and physiological stresses result in decreased soldiering performance (Groeller et al., 2015).

Progressive resistance training is known to improve occupational performance, and reduce cumulative demands of physical training (Kraemer et al., 2001). Repeated task exposure (i.e., simulated loaded walking tasks) decrease physical stress responses that result in improved occupational task performance. (Szivak & Kraemer, 2015). (Lenton et al., 2017) identified specific demands of load carriage and found the hip to be the critical lower limb joint, contributing ~60% power, followed by the ankle (~25%), and then the knee (~15%). A physical training program targeting the hip joint musculature may improve Australian soldier's load carriage capacity through performance and neuromuscular adaptations. The purpose of this study was to identify and characterise physical performance responses to a targeted 10-week load carriage training program.

METHODS: Sixteen male civilians have been recruited; nine of these have completed all testing (age 22.1±1.3 years, height 1.80±0.06 m, body mass 83.7±7.3 kg (Mean ± SD)); the remainder are currently completing the training. At the time of testing, no participants had acute or chronic injuries. No former experience with load carriage was required. Participants gave their written informed consent and the Macquarie University Human Research Ethics Committee approved the study (protocol number: 5201700406). Participants were required to meet or exceed the Army Basic Fitness Assessment (BFA) standards for male soldiers ≤ 25 years old (Mullins et al., 2015) (70 sit-ups and 40 push ups in 2 minutes each), body mass ≥ 73 kg, and have a maximal aerobic capacity ≥45 $mL\cdot kg^{-1}\cdot min^{-1}$ (Flouris, Metsios, & Koutedakis, 2005; Ramsbottom et al., 1988).

Participants completed maximal strength tests (isometric mid-thigh pull (IMTP), countermovement (CMJ), and squat jumps (SJ) using a portable force plate (Fitness Technology, Adelaide, Australia), and Ballistic Measurement Software (Innervations, Perth, Australia). These and BFA tests were repeated upon completion of the 10-week training program. Eccentric utilisation ratio (EUR) was calculated using results from the CMJ and SJ (McGuigan et al., 2006).

In two separate laboratory sessions, a single load carriage task representative of the minimum physical employment requirement for Australian Army All Corps Standard (5 km at 5.5 $km\cdot h^{-1}$, wearing a 23 kg vest) was completed before and after the 10-week training program. Heart rate (HR) and rating of perceived exertion (RPE) were measured every 5 minutes during the load carriage task.

The 10-week physical training program consisted of resistance training three times per week and walking with a weighted vest twice per week. Sessions were delivered to participants by an accredited strength and conditioning coach, with resistance tailored to individual abilities. Loaded walking sessions were self-directed on a separate day to weight training sessions, with load incrementally increasing over the 10-week program ranging from 0 kg to 25 kg.

Paired t-tests were conducted on IMTP, CMJ, SJ, EUR, BFA measures, RPE, and cardiovascular response (HR). Effect sizes were calculated using difference in means (d) and were interpreted as trivial, small, moderate, and large effects for values of d equal to 0.0, 0.2, 0.6, and 1.2, respectively (Hopkins, 2016).

RESULTS: Results are presented for nine participants; the remaining seven participants are currently completing the 10-week training program.

Significant main effects were found for maximal force output for SJ (t(8) = -5.014, $p = 0.001$, $d = 0.52$), but not for CMJ (t(8) = 0.018, $p = 0.986$, $d = -0.005$). There was a small-to-moderate effect size for squat jump, and a trivial effect size for countermovement jump. No significant main effects were shown for the IMTP maximal force values with small to moderate effect sizes ranged from (t(8) = -1.548, $p = 0.160$, $d = 0.36$). EUR calculations for maximal force demonstrated significant effects (t(8) = 2.409, $p = 0.043$, $d = -0.78$) with a moderate to large effect size.

BFA results demonstrated significant effects for beep test scores only (t(8) = -2.63, $p = 0.030$, $d = 0.32$). A small to moderate effect size was shown for push up ($d = 0.54$) and sit-up scores ($d = 0.49$) (Table 1).

Table 1: Physical performance measures pre and post the targeted physical training intervention. Values are means (±SD) *Indicates significant difference pre-post training ($p < 0.05$).

Performance Measure	Variable	Pre	Post	Significance	Effect Size
SJ	Maximal Force (N)	1920 (358)	2103 (347)	0.001*	Small-Modaerate
CMJ		1888 (213)	1887 (245)	0.986	Trivial
IMTP		2982 (450)	3033 (509)	0.160	Small-Moderate
CMJ / SJ	Eccentric Utilization Ratio (AU)	1.00 (0.14)	0.91 (0.10)	0.043*	Moderate-Large
Basic Fitness Assessment	Push-Ups (#)	49 (8)	55 (15)	0.055	Small-Moderate
	Sit-Ups (#)	76 (5)	79 (9)	0.196	Small-Moderate
	Beep Test (Level Shuttle)	8.9 (1.4)	9.4 (1.6)	0.030*	Small-Moderate

SJ, squat jump; **CMJ**, countermovement jump; **IMTP**, isometric mid-thigh pull. * Indicates significantly different at $p < 0.05$. **N** = Newtons, **AU** = Arbitrary Units.

HR decreased on average by 6 beats as a result of the training program. Similarly, RPE values decreased on average by two points after the training program compared to pre-values (Figure 1). Although differences were not significant, they demonstrated up to large effect sizes ($d = -0.19$ to -0.75).

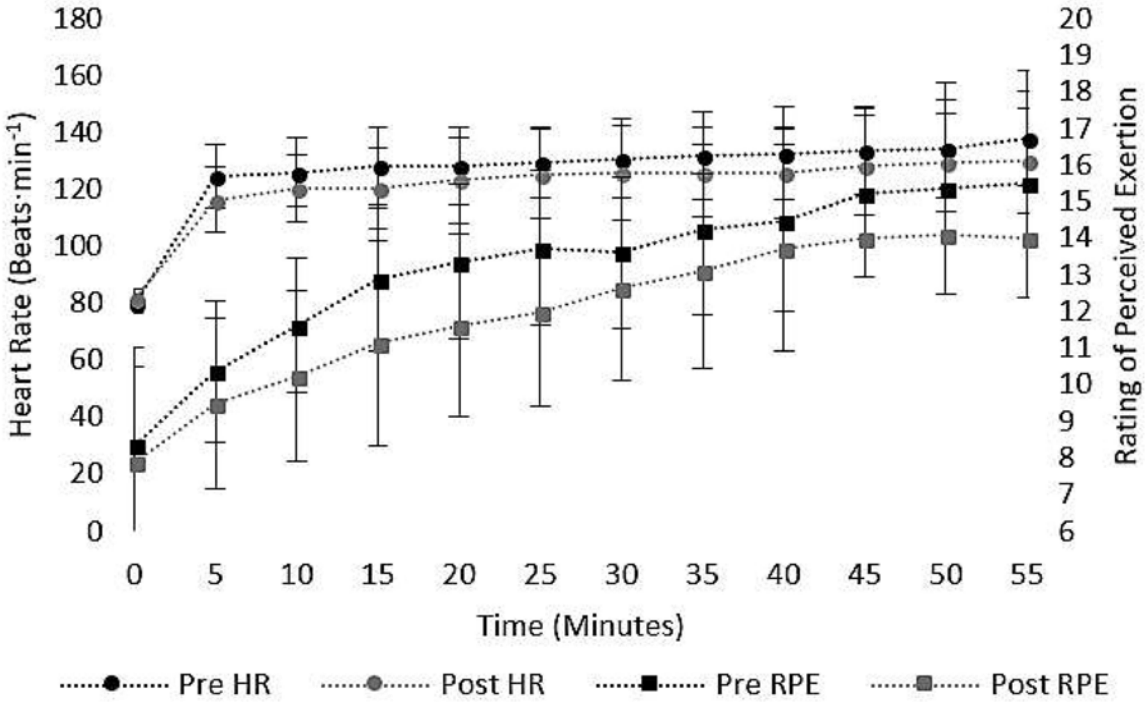

Figure 1: Heart rate and perceptual responses during the 5 km load carriage walking task. Values are means (±SD).

DISCUSSION: The purpose of this study to identify and characterise physical performance responses to a periodised progressive 10-week resistance training program. Significant main effects for pre-post physical performance measure values were observed. Some measures were not statistically significant, however, effect size values indicated differences in pre-post means.

The SJ performance improved following the training program, but CMJ did not. This indicates enhanced capacity of the lower limb to produce concentric strength (McGuigan et al., 2006), which was a goal of the current training program. An increased capacity of the hip extensors to produce force during a predominantly concentric only contraction may account for the increase in force production during the SJ. The EUR supports this speculation, as there was a decrease between pre- and post-intervention (pre: 1.00(0.14), post: 0.91(0.10)).

Statistically significant differences for beep test scores indicate an improvement in maximal aerobic capacity of 5.6% as a result of the training program. This is an interesting finding given the aerobic capacity per se was not a goal of the program. Results however, are supported by previous findings where strength training increased aerobic capacity 13% after a 12-week program (Kraemer et al., 2004). These responses may be due to specific loaded walking tasks within our 10-week training program (Häkkinen et al., 2003) or possibly an improvement in lower body strength and therefore economy of movement (Beattie, Kenny, Lyons, & Carson, 2014). The push-ups and sit-ups performance did not achieve statistical significance, though improvements were observed pre-post (PU, 13%; SU, 5%, respectively), similarly to previous research (PU, 32%; SU, 8%, respectively) (Harman et al., 2008b).

Reductions in HR suggest participants experienced less physiological strain during testing as a result of the training program (Mullins et al., 2015). RPE was similar to previous reports (Birrell et al., 2007; Mullins et al., 2015), and increased throughout the duration of the loaded walking task. Pre-post values revealed no significant differences, however, post training RPE decreased by at least 2 points per time interval, indicating reductions in overall perceived exertion.

CONCLUSION: The current study was the first to investigate physical performance responses to a 10-week targeted load carriage training program. Results demonstrate that an evidence-based resistance training program can induce physical performance improvements and physiological adaptations in males. Military organisations could utilise such a program to effectively train soldiers over a decreased duration to facilitate improvements in overall task capacity. Further insight into training responses will follow upon completion of the 10-week program by remaining participants. Additionally, sex-specific responses should be investigated to understand any training adaptations that are specific to males and females.

ACKNOWLEDGEMENTS: The authors acknowledge all participants who volunteered their time to participate and Macquarie University Sport and Aquatics Centre. Australian Army Research Scheme and The International Society of Biomechanics contributed funding to support this research.

Appendix 10.2. Australian Strength and Conditioning Association (ASCA 2018) International Conference on Applied Strength & Conditioning

10-WEEK LOAD-CARRIAGE TRAINING PROGRAM REDUCES PERCEIVED TASK DEMANDS

MACQUARIE University SYDNEY·AUSTRALIA

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Griffith UNIVERSITY

Military Load-Carriage

Load-carriage demands often exceed individual's physical capacity

Failure to adapt to task demands results in detrimental physical and task specific performance[1,2]

Hip joint is predominant contributor to torque production during load-carriage; training program targeting hip joint musculature may improve load-carriage capacity[3]

>>

Study Aim

Identify and quantify psycho-physical and physical performance responses to an evidence-based 10-week training program

TSAC AUSTRALIA
Evidence Based · Tactically Tested · Operationally Proven

To see where this research is heading load up the QR code reader

@JodieAWills
@DavidJohnSaxby1
@D_Glassbrook
@tladoyle

Key Findings

First study linking evidence-based physical training responses to load-carriage performance in males

Load-carriage specific conditioning ↓ perceived task demands and ↑ lower-limb strength[4]

Hip-focussed training program elicited physical performance adaptations and improvements [5]

Evidence-based training programs could optimise overall load-carriage capacity and performance

METHODS

10-Week Training Program:

x3 per week >> Coach delivered (ASCA) >> x2 per week >> 97% total program compliance

♂ 15 healthy civilians ≤25 years (body mass ≥73 kg)

Initial testing:

- 70 sit-ups and 40 push ups in 2 minutes each
- Level 7.5 on the beep test
- Completed countermovement (CMJ) and squat jump (SJ) tests (surrogate measures of lower-limb power and strength)

V
V

SJ max force ↑ after training (p=0.01), CMJ did not (p>0.05) (Table 1)

SJ max power and CMJ (p>0.05) did not improve

Physical performance ↑ after training for:

- Sit-ups (p<0.05)
- Push-ups (p<0.05)
- Estimated maximal oxygen uptake (p<0.05)

Table 1. Physical performance pre and post testing (mean±SD)
*Paired samples t-test significant difference pre-post (p<0.05)

Test	Pre	Post	Effect Size
SJ Force (N)	1958±315	2082±245*	Small
SJ Power (W)	4172±729	4270±887	Trivial
CMJ Force (N)	1899±182	1930±214	Trivial
CMJ Power (W)	4291±718	4363±635	Trivial
Sit-ups (n)	76±4	81±9*	Moderate
Push-ups (n)	51±8	57±13*	Moderate
Maximal O_2 uptake (ml·kg^{-1}·min^{-1})†	43±5	45±5*	Small

†Estimated from beep test performance

Load-carriage Task

Participants completed treadmill walk for 5 km at 5.5 km·h^{-1} wearing 23 kg torso-borne vest (week 0, week 11)

Rating of perceived exertion (RPE) measured at 5-minute intervals

V
V

RPE values significantly ↓ (p<0.05) during the post-training load-carriage task compared to pre-training (Figure 1)

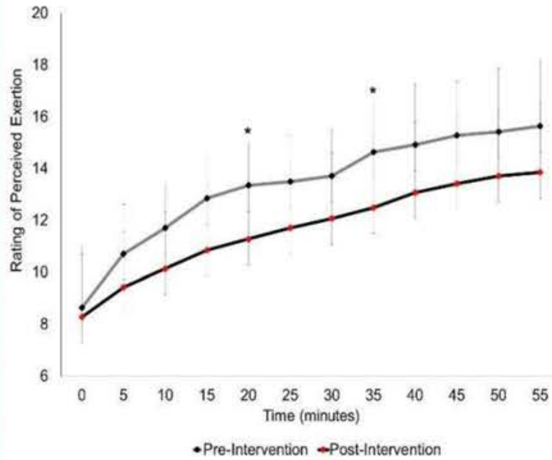

Figure 1. Rating of perceived exertion (mean±SD) before and after training program
*Significant difference found for One-way Analysis of Variance test (p<0.05)

ACKNOWLEDGEMENTS

Army Research Scheme (AARC 013/17) and the International Society of Biomechanics for financial support of this research. Macquarie University Sport and Aquatics Centre Gym for in-kind support.

Army
International Society of Biomechanics

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10-WEEK LOAD-CARRIAGE TRAINING PROGRAM REDUCES PERCEIEVED TASK DEMANDS

Jodie A. Wills[1], David J. Saxby[2], Daniel J. Glassbrook[1], Tim L. A Doyle[1]

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[2]Menzies Health Institute Queensland, Griffith University, Gold Coast, Australia

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BLUF: A 10-week resistance training program decreases perceived task demands of a loaded walk and could be utilised by Military organisations to elicit positive training responses to improve load-carriage capacity.

INTRODUCTION: Load-carriage is a common Military task. The hip is a primary contributor for load-carriage tasks; a training program targeting hip joint musculature may improve load-carriage capacity. This study aimed to identify physical performance responses to a 10-week load-carriage program.

METHODS: Fifteen male civilians (22.6±1.5 yr, 1.82±0.06 m, 84.1±6.9 kg) provided informed consent. Participants met or exceeded the Australian Army Fitness standards for male soldiers ≤25 years: body mass ≥73 kg, 70 sit-ups (SU) and 40 push ups (PU) in 2 minutes, and a minimum of 7.5 on the beep test. Tests were completed before and after the training intervention.

Participants completed 5 km at 5.5 $km \cdot h^{-1}$, wearing a 23 kg torso-borne vest. Rating of perceived exertion (RPE) was measured at 5-minute intervals. After a 10-week training program consisting of resistance training and loaded walking, participants repeated testing. Additionally, countermovement (CMJ) and squat jump (SJ) tests were completed prior to and upon completion of the program. They completed up to three resistance training and two weighted walking per week. Resistance training sessions were delivered by a Level 1 Australia Strength and Conditioning Association coach.

Paired samples t-tests were conducted on CMJ, SJ, SU, PU, and beep test. Repeated measures one-way analysis of variance were conducted for HR and RPE values. Effect sizes were calculated using difference in means (d).

RESULTS: Significant main effects were found for maximal force output for SJ ($t(14) = -3.44$, $p = 0.01$, $d = 0.44$), but not for CMJ ($t(14) = -0.74$, $p = -0.74$, $d = 0.16$). Fitness tests demonstrated significant differences for PU ($t(14)$, $p < 0.01$, $d = 0.60$), SU ($t(14)$, $p < 0.05$, d = 0.74), and beep test (t(14), $p < 0.001$, d = 0.48). RPE values significantly decreased at numerous timepoints (figure 1) after training ($p < 0.05$).

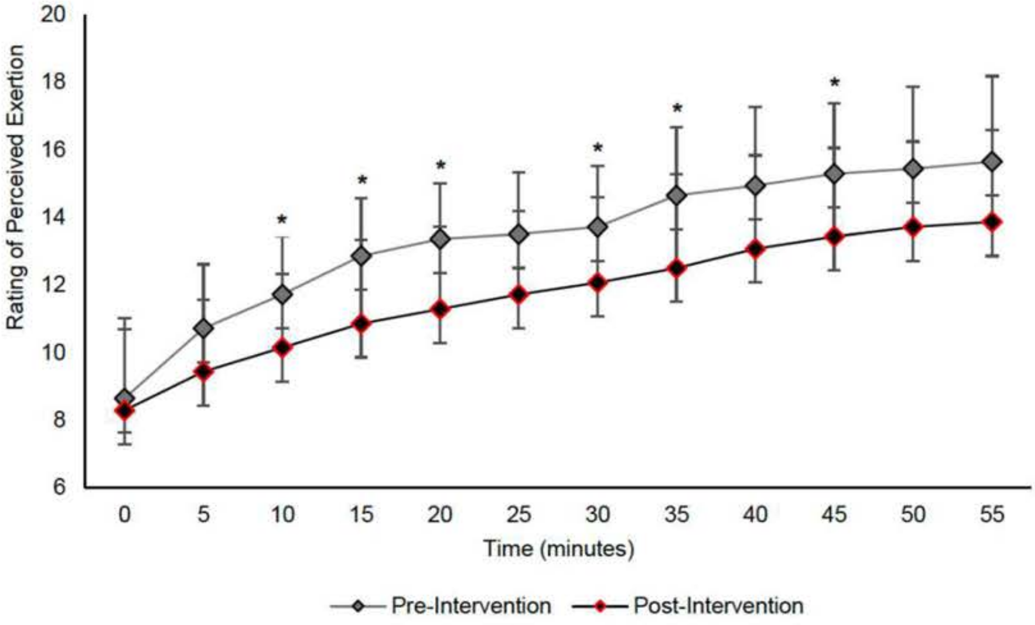

Figure 1. Rating of perceived exertion values (mean±SD) before and after training program. *significant difference ($p <0.05$).

DISCUSSION: SJ performance improved following the training program, which indicates an increased capacity of the hip extensors to produce force during a predominantly concentric only contraction. Improvement in estimated $\dot{V}O_2$ max may indicate adaptations specific to loaded walking as a result of training and in improvement in gait economy. RPE values significantly decreased during the loaded walk, demonstrating perceptions of task demands decreased after training. Task demands did not change, which suggests the targeted program successfully conditioned individuals for a specific load-carriage task through increasing lower-limb strength.

PRACTICAL APPLICATIONS: Results demonstrate that an evidence-based resistance training program induces physical performance improvements and physiological adaptations in males. Military organisations could utilise such a program to effectively train soldiers to facilitate improvements in overall task capacity.

ACKNOWLEDGEMENTS: Army Research Scheme, International Society of Biomechanics, and Macquarie University Sport and Aquatics Centre Gym for financial and in-kind support.

Appendix 10.3. Australasian Biomechanics Conference 11 (ABC11)

TIME-COURSE CHANGES OF LOWER LIMB KINEMATICS DURING MILITARY LOAD-CARRIAGE

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INTRODUCTION

Occupational physical employment performance standards require soldiers to carry loads >20kg. Increased physical demands of loaded walking result in variations of lower limb kinematics and mechanical work [1]. To efficiently meet task demands, hip joint contributions increase to assist forward progression [2]. Quantification of lower-limb kinematics over an extended duration loaded walking task will help provide further understanding of how task demands are met. This study examined how lower-limb gait kinematics differed before and after a loaded walking task.

METHOD

Fifteen male civilians participated within this study (age 22.4±1.6 years, height 1.82±0.06 m, body mass 83.8±6.7 kg). At the time of testing, no participants had acute or chronic injuries. No former experience with load-carriage was required. Participants gave written informed consent to the protocol and Macquarie University Human Research Ethics Committee approved the study (protocol number: 5201700406). Participants were required to meet or exceed the Army Basic Fitness Assessment (BFA) standards for male soldiers ≤25 years old [3] (70 situps and 40 push-ups in 2 minutes each), body mass
≥73 kg, and have a maximal aerobic capacity ≥45 $mL \cdot kg^{-1} \cdot min^{-1}$.

A single treadmill load-carriage task representative of the minimum Australian Army All Corps physical employment standard (5 km at 5.5 $km \cdot h^{-1}$, wearing a 23 kg vest) was completed. Three-dimensional motion capture and over-ground force plate data were acquired for ten successful over-ground loaded walking trials pre and post the 5 km task (defined as: 1) the participant strikes the force plate cleanly, 2) walking speed equates to 5.5 $km \cdot h^{-1}$ ± 0.1%). A scaled fullbody OpenSim model was used to estimate hip, knee, and ankle joint angles from inverse kinematics. Data was compared before and after the assigned loaded walking task.

Paired samples t-tests were conducted on all variables. Significance was set at $p < 0.05$. Effect sizes were calculated using difference in means (d) and were interpreted as trivial, small, moderate, and large effects for values of d equal to 0.0, 0.2, 0.6, and 1.2, respectively [4].

RESULTS

Results are presented for eight participants; the remaining seven participants data are currently being analysed. Significant increases in peak hip extension ($t(7) = 3.805$, $p = 0.007$, $d = -0.56$), hip abduction ($t(7) = -2.864$, $p = 0.024$, $d = 0.51$) and knee flexion angle ($t(7) = -4.496$, $p = 0.003$, $d = 0.03$) values were demonstrated after the loaded walking task. Peak knee extension angle significantly decreased ($t(7) = 2.603$, $p = 0.035$, $d = -0.21$). Trivial-to-moderate effect sizes were shown for peak joint variables.

Table 1. Mean ± standard deviation of gait kinematics. * indicates a significant difference between pre-post walking variable values *(p < 0.05)*.

Variable	Walking Condition		Significance	Effect Size
	Pre	Post	*P*-value	*d*
Stride length	1.62 ± 0.04	1.62 ± 0.03	.963	0.02
Step width	0.07 ± 0.03	0.06 ± 0.023	.240	-0.26
Peak hip extension angle	-19.36 ± 2.70	-20.95 ± 3.01	.010*	-0.56
Peak hip flexion angle	34.23 ± 6.64	33.20 ± 6.16	.166	-0.16
Peak hip abduction angle	11.72 ± 2.49	12.88 ± 2.02	.024*	0.51
Peak hip adduction angle	-15.44 ± 4.99	-15.27 ± 5.24	.737	0.03
Hip angle at heel strike	32.55 ± 6.41	31.55 ± 6.00	.114	-0.16
Peak knee extension angle	2.75 ± 2.90	2.18 ± 2.55	.035*	-0.21
Peak knee flexion angle	70.26 ± 4.39	71.53± 4.12	.003*	0.30
Knee angle at heel strike	9.38 ± 2.09	9.91 ± 2.60	.320	0.22
Peak ankle dorsiflexion angle	9.49 ± 3.51	7.96 ± 4.02	.354	-0.41
Peak ankle plantarflexion angle	-20.66 ± 7.89	-22.35 ± 5.86	.324	-0.24
Ankle angle at heel strike	2.99 ± 2.87	1.63 ± 4.63	.331	-0.35

CONCLUSIONS

Current findings support previous results reported within load-carriage literature. Investigating the effects of an evidence-based physical training intervention will enable further understanding of time-course changes in lower-limb kinematics.

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SPEAKER INFORMATION

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TIME-COURSE CHANGES OF LOWER LIMB KINEMATICS DURING MILITARY LOAD-CARRIAGE

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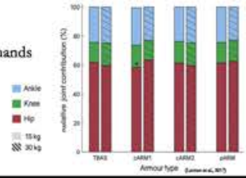
Task Demands and Impact on Performance

Soldiers regularly carry heavy loads during training and operations

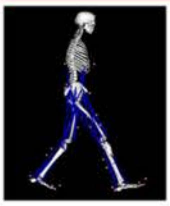
Increased physical demands during load-carriage tasks result in kinematic variations

Hip joint contributions ↑ to effectively meet task demands



Aim

To quantify time-course changes in lower-limb kinematics to assist in understanding how task demands are met



Study Inclusion Criteria

16 healthy civilians (22.4 ± 1.7 years, 1.82 ± 0.06 m, 83.8 ± 6.7 kg)

No recent injury / No former experience of load-carriage required

Meet or exceed Australian Defence Basic Fitness Standards

- 40 push-ups in 2-min
- 70 sit-ups in 2-min
- Minimum of level 7.5 completed for beep test

Testing Protocol

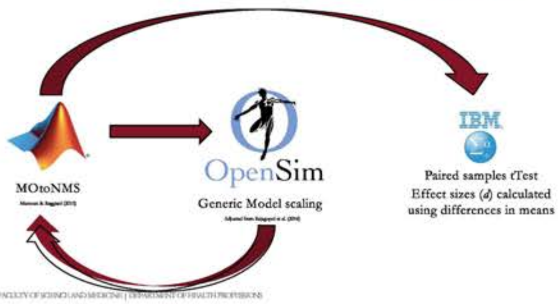
Walk for 5km at 5.5km·h^{-1} wearing a 23kg torso-borne vest

10 successful over-ground trials using an in-ground force plate on a 13m walkway:

✓ Clean force plate foot strike
✓ No gait pattern alterations on approach
✓ Met target speed of 1.5m·s^{-2} ± 5% (5.5km·h^{-1} ± 0.1%)

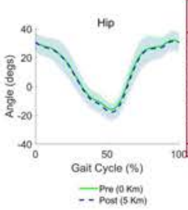
VICON → Kinematic data sampled at 100Hz
Kinetic and EMG data sampled at 1000Hz

Data Workflow



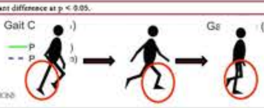
Results

KINEMATIC VARIABLES



Variable	Walking Condition		P	Effect Size	95% CI (lower, upper)
	Pre (0 Km)	Post (5 Km)			
Knee					
Internal Rotation Peak	-0.2 ± 0.1	-0.14 ± 0.1	0.02*	Small	-0.03, -0.01
Extension Peak Angle	1.6 ± 3.1	0.9 ± 3.6	0.02*	Small	0.10, 1.19
Flexion Peak Angle	71.1 ± 5.3	72.2 ± 4.8	0.04*	Small	-2.18, -0.08
ROM	74.3 ± 6.3	75.7 ± 5.8	0.03*	Small	-2.69, -0.15

*Indicates a significant difference at $p < 0.05$.



Results

SPATIOTEMPORAL VARIABLES

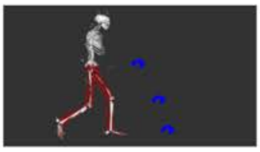
Variable	Walking Condition		P	Effect Size	95% CI (lower, upper)
	Pre (0 Km)	Post (5 Km)			
Stride Length	1.6 ± 0.05	1.6 ± 0.06	0.58	Trivial	-0.02, 0.02
Stride Time	1.06 ± 0.05	1.07 ± 0.6	0.55	Moderate	-0.02, 0.01
Step Width	0.06 ± 0.03	0.05 ± 0.03	0.00*	Trivial	0.00, 0.02
Walk Speed	5.4 ± 0.2	5.4 ± 0.2	0.97	Large	-0.12, 0.11

*Indicates a significant difference at $p < 0.05$.

Discussion

Kinematic variations occurred at the hip and knee joints

Adaptive kinematic strategy appears to be adopted over time



Position after 5 km load-carriage task

- Extended hip at toe off
- Flexed knee at heel strike
- Extended knee at toe off
- ↓ Step width

So What's Next?

[illegible] POPULATION FOCUS

Acknowledgements

Co-authors:
Gavin K. Lenton
David J. Saxby
Tim L. A. Doyle

Army
International Society of Biomechanics

FY 2017-2018 Australian Army Research Scheme and The International Society of Biomechanics for financial support of this research

MACQUARIE University

Macquarie University for PhD (iMRTP) Scholarship

Macquarie University Sport and Aquatic Centre for in-kind support

@JodieAWills

TIME-COURSE CHANGES OF LOWER LIMB KINEMATICS DURING MILITARY LOAD-CARRIAGE

JODIE A. WILLS[1], DAVID J. SAXBY[2], GAVIN K. LENTON[2], TIM L. A. DOYLE[1]
[1]MACQUARIE UNIVERSITY, AUSTRALIA
[2]GRIFFITH UNIVERSITY, AUSTRALIA

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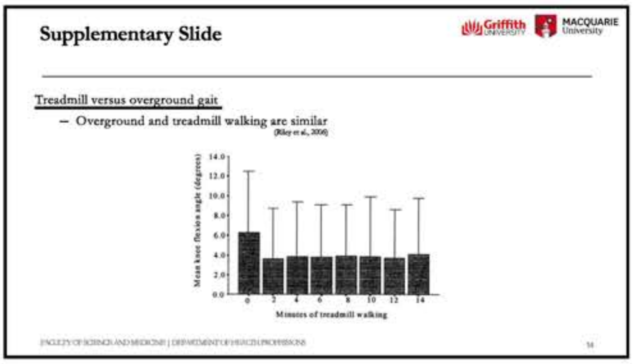

Appendix 10.4. International Society of Biomechanics and American Society of Biomechanics (ISB/ASB 2019)

Lower-limb joint moment and power adaptations elicited through load-carriage strength training

Jodie A. Wills[1], David J. Saxby[2], Gavin K. Lenton[2], Tim L.A. Doyle[1]

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Background

Occupational load-carriage tasks elicit increased physical demands in soldiers. Failure to adapt to increased task demands increase injury risk and decrease performance. Implementing evidence-based physical training could help reduce risks and enhance physical capacity [1]. Neuromuscular demands move proximally from the ankle to the hip during load-carriage tasks to meet demands of external loading [2].

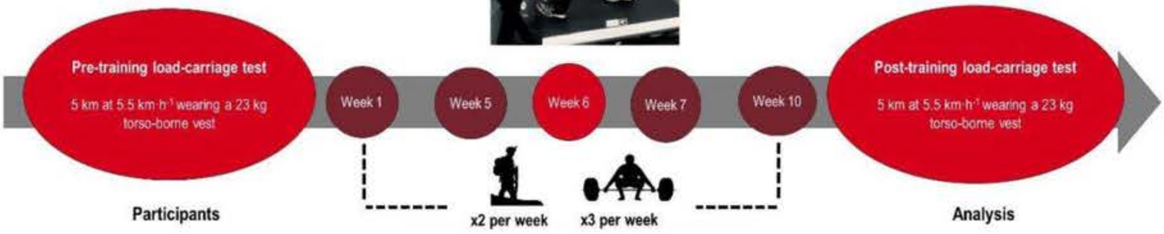
Aim

Identify changes in lower-limb joint biomechanics during a 5-km load carriage task in response to a 10-week physical training program.

Hypotheses

a) Before training, knee joint moments will increase more pre-to-post during the load-carriage task compared to after training.

b) Lower-limb net joint powers will be maintained during the load-carriage task after training compared to before.



Participants

Age: 22.4±1.7 years, height: 1.82±0.06 m, mass 83.91±6.5 kg

Inclusion Criteria	
Push-ups (reps)	40
Sit-ups (reps)	70
Beep Test (shuttle)	7.5

Analysis

- Generic OpenSim Model estimated inverse kinematics and inverse dynamics [3]
- Joint power and work calculated using Matlab
- Over-ground GRF and motion capture measurements taken at pre- and post-march (0 km and 5 km) distances in pre- and post-training load carriage tests

	Pre-March	Post-March
HIP		
Flexion Moment Peak (Nm·Kg⁻¹)		
Pre-Training	-2.07 ± 0.31	-2.03 ± 0.37
Post Training	-2.26 ± 0.33	-2.19 ± 0.31*‡
Positive Joint Work (J·Kg⁻¹)		
Pre-Training	0.34 ± 0.06	0.34 ± 0.08
Post Training	0.37 ± 0.44	0.34 ± 0.06*/**‡
KNEE		
Flexion Moment Peak (Nm·Kg⁻¹)		
Pre-Training	-0.52 ± 0.67	-0.48 ± 0.36
Post Training	-0.53 ± 0.69	-0.47 ± 0.60γ
Positive Joint Work (J·Kg⁻¹)		
Pre-Training	0.19 ± 0.05	0.19 ± 0.03
Post Training	0.21 ± 0.06	0.20 ± 0.05‡
ANKLE		
Percentage Positive Power Contribution (%)		
Pre-Training	44.04 ± 4.12	40.82 ± 4.25
Post Training	44.10 ± 4.70	43.63 ± 4.69**/***‡

*Indicates a main effect of training; **main effect of distance; ***interaction effect. ǂ Indicates a small, γ medium, and ‡ large effect size.

Key Findings

- Significant increases in hip flexion moment peak over the duration of the 5 km load carriage task after training suggests an enhanced capacity of the hip joint to assist with forward progression under load.
- Positive joint power and work at the knee joint decreased from pre-march to post-march (0 km to 5 km) after training.
- An increased ability to maintain the ankle joint contributions towards percentage of positive power from pre-to-post-march after training was indicated by a significant interaction effect.
- A 10-week periodised resistance training program elicits lower-limb joint neuromuscular adaptations which increases individual's capacity to sustain performance during a load-carriage task.

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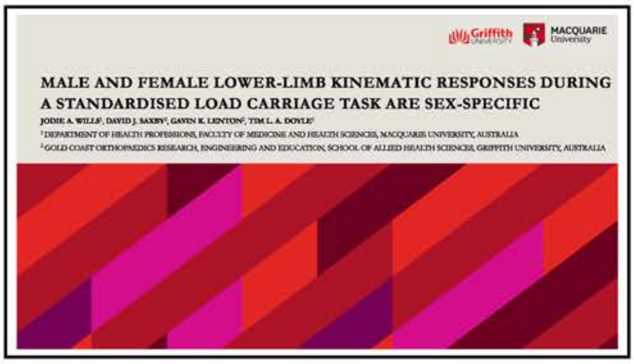
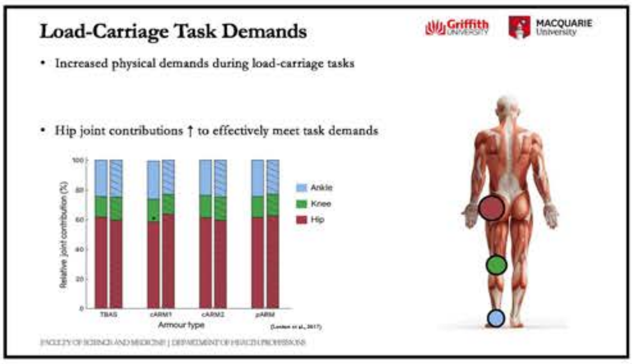
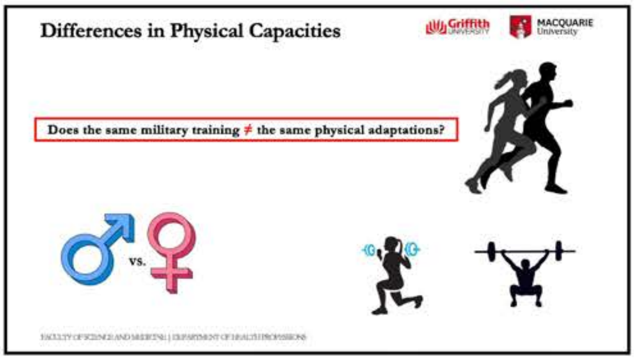
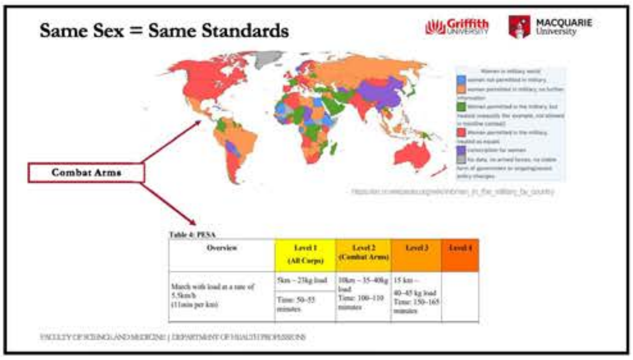
[3] Rajagopal, A et al. (2016). IEEE Trans Biomed Eng 63: p. 2068-79.

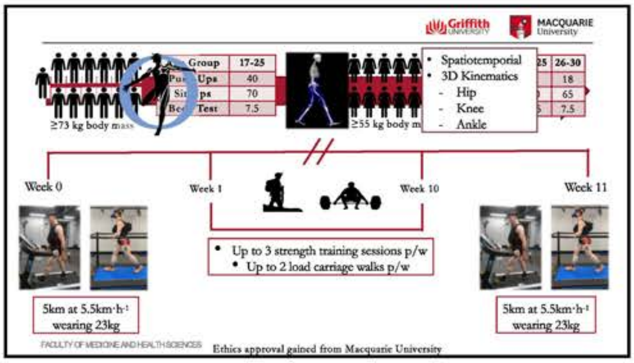
The Australian Army Research Scheme (AARC 013/17) and the International Society of Biomechanics for funding. Macquarie University for providing PhD scholarship (iMRTP). Macquarie University Sport and Aquatic Centre for in-kind support.

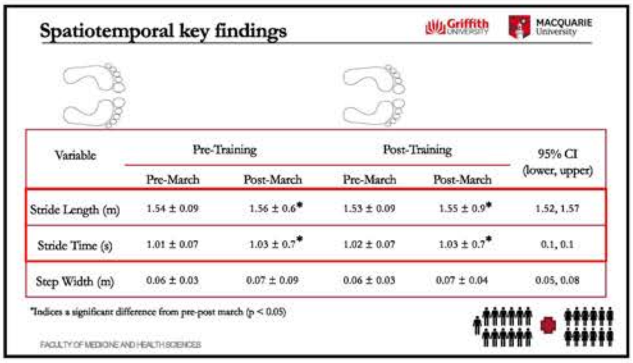






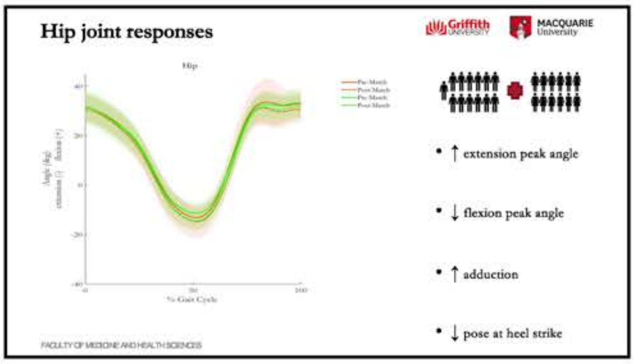






Variable	Pre-Training		Post-Training		95% CI (lower, upper)
	Pre-March	Post-March	Pre-March	Post-March	
Stride Length (m)	1.54 ± 0.09	1.56 ± 0.6*	1.53 ± 0.09	1.55 ± 0.9*	1.52, 1.57
Stride Time (s)	1.01 ± 0.07	1.03 ± 0.7*	1.02 ± 0.07	1.03 ± 0.7*	0.1, 0.1
Step Width (m)	0.06 ± 0.03	0.07 ± 0.09	0.06 ± 0.03	0.07 ± 0.04	0.05, 0.08

*Indices a significant difference from pre-post march ($p < 0.05$)


Hip joint responses
Griffith UNIVERSITY
MACQUARIE University
Hip
Pre-March
Post-March
Pre-March
Post-March
% Gait Cycle
↑ extension peak angle
↓ flexion peak angle
↑ adduction
↓ pose at heel strike
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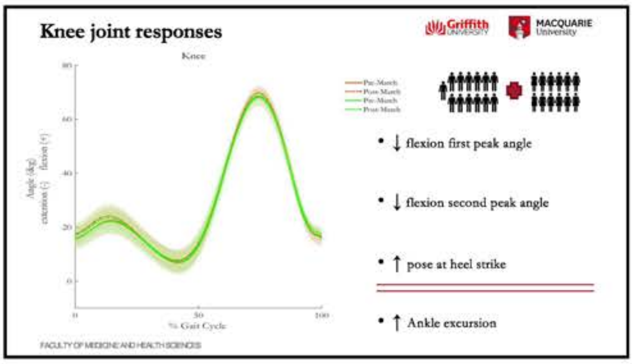
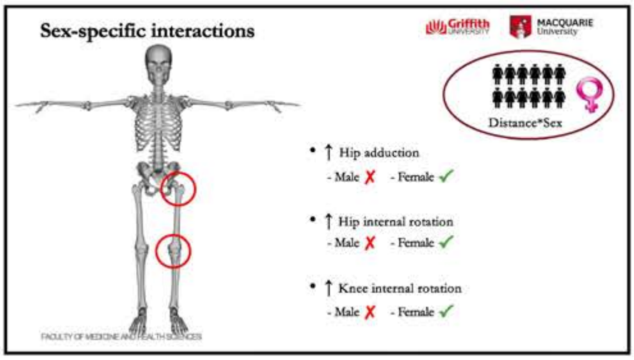
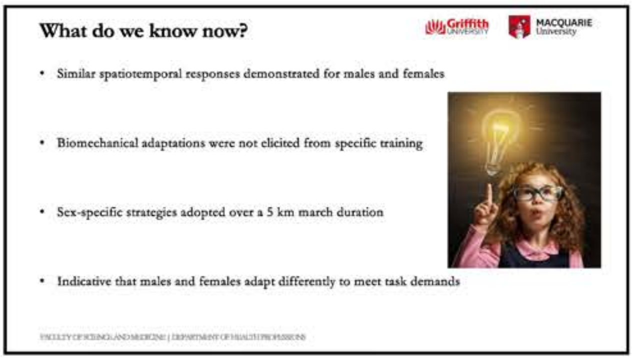
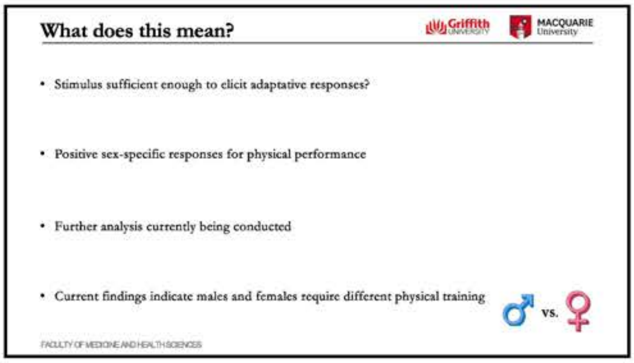
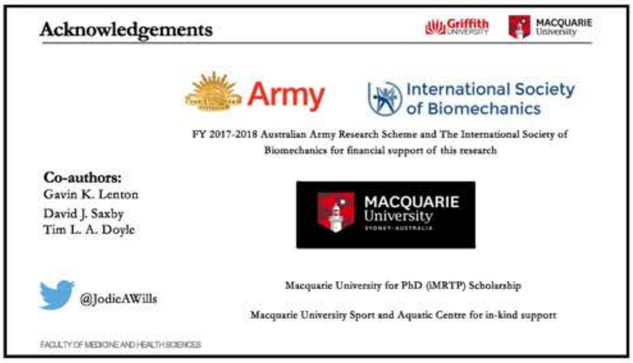

Knee joint responses
Griffith UNIVERSITY
MACQUARIE University
Knee
Pre-March
Post-March
Pre-March
Post-March
% Gait Cycle
↓ flexion first peak angle
↓ flexion second peak angle
↑ pose at heel strike
↑ Ankle excursion
FACULTY OF MEDICINE AND HEALTH SCIENCES


Sex-specific interactions
Griffith UNIVERSITY
MACQUARIE University
Distance*Sex
↑ Hip adduction
- Male ✗ - Female ✓
↑ Hip internal rotation
- Male ✗ - Female ✓
↑ Knee internal rotation
- Male ✗ - Female ✓
FACULTY OF MEDICINE AND HEALTH SCIENCES


What do we know now?
Griffith UNIVERSITY
MACQUARIE University
Similar spatiotemporal responses demonstrated for males and females
Biomechanical adaptations were not elicited from specific training
Sex-specific strategies adopted over a 5 km march duration
Indicative that males and females adapt differently to meet task demands


What does this mean?
Griffith UNIVERSITY
MACQUARIE University
Stimulus sufficient enough to elicit adaptative responses?
Positive sex-specific responses for physical performance
Further analysis currently being conducted
Current findings indicate males and females require different physical training
♂ vs. ♀
FACULTY OF MEDICINE AND HEALTH SCIENCES


Acknowledgements
Griffith UNIVERSITY
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FY 2017-2018 Australian Army Research Scheme and The International Society of Biomechanics for financial support of this research
Co-authors:
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@JodieAWills
Macquarie University for PhD (iMRTP) Scholarship
Macquarie University Sport and Aquatic Centre for in-kind support
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MALE AND FEMALE LOWER-LIMB KINEMATIC RESPONSES DURING A STANDARDISED LOAD CARRIAGE TASK ARE SEX-SPECIFIC

JODIE A. WILLS[1], DAVID J. SAXBY[2], GAVIN K. LENTON[2], TIM L. A. DOYLE[1]
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[2] GOLD COAST ORTHOPAEDICS RESEARCH, ENGINEERING AND EDUCATION, SCHOOL OF ALLIED HEALTH SCIENCES, GRIFFITH UNIVERSITY, AUSTRALIA

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Supplementary Data

Variable	Pre-Training		Post-Training	
	Pre-March	Post-March	Pre-March	Post-March
HIP				
Extension Peak Angle (°)	-14.5 ± 6.0	-16.38 ± 6.4	-14.0 ± 5.8	-16.7 ± 5.6
Flexion Peak Angle (°)	34.8 ± 7.8	33.1 ± 5.8	33.3 ± 5.8	34.0 ± 5.8
Pose at Heel Strike (°)	31.7 ± 5.8	32.4 ± 5.8	31.7± 5.9	30.2 ± 6.6
KNEE				
Flexion 1st Peak Angle (°)	23.6 ± 5.1	25.1 ± 4.9	25.1 ± 10.7	26.2 ± 11.2
Flexion 2nd Peak Angle (°)	70.2 ± 4.9	71.3 ± 4.1	64.7 ± 17.7	65.4 ± 17.6
Pose at Heel Strike (°)	11.6 ± 5.5	12.9 ± 5.8	11.3 ± 5.7	12.0 ± 6.2
ANKLE				
Excursion (°)	0.06 ± 0.03	0.07 ± 0.09	0.06 ± 0.03	0.07 ± 0.04

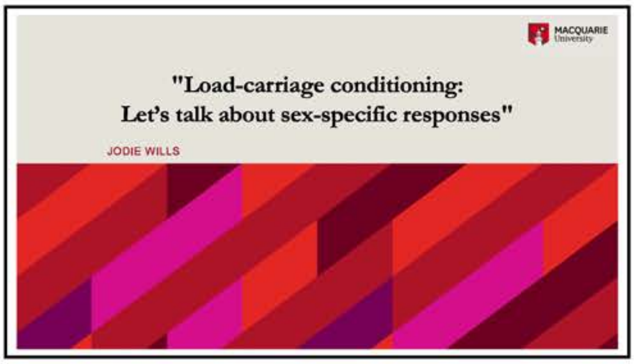
Pooled data means for males and females.

Supplementary Data

Variable	Pre-Training				Post-Training			
	Pre-March		Post-March		Pre-March		Post-March	
	Male	Female	Male	Female	Male	Female	Male	Female
HIP								
Adduction Peak Angle (°)	-17.3 ± 4.8	-14.71 ± 2.9	-16.9 ± 4.1	-17.5 ± 3.0*	-17.3 ± 4.4	-16.4 ± 2.8	-18.3 ± 4.8	-19.1 ± 2.5*
Internal Rotation Peak Angle (°)	-18.0 ± 6.5	-16.3 ± 6.0	-17.4 ± 6.2	-17.8 ± 6.4*	-18.1 ± 6.5	-14.7 ± 5.5	-17.6 ± 8.0	-16.4 ± 6.6*
KNEE								
Internal Rotation Peak Angle (°)	-0.16 ± 0.8	-0.11 ± 0.9	-0.14 ± 0.6	-0.10± 0.7*	-0.14 ± 066	-0.10 ± 0.7	-0.12 ± 0.6	-0.15 ± 0.7*

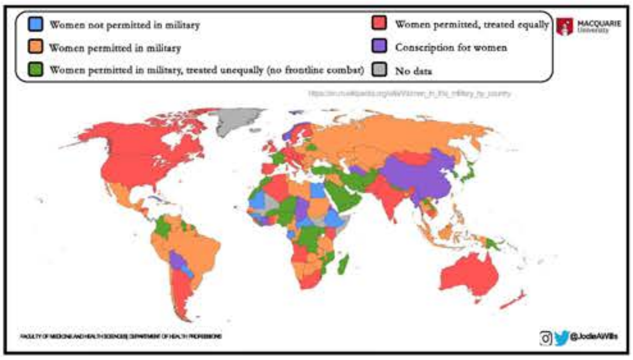
*Indices a significant difference ($p < 0.05$) for females from pre-post march values.

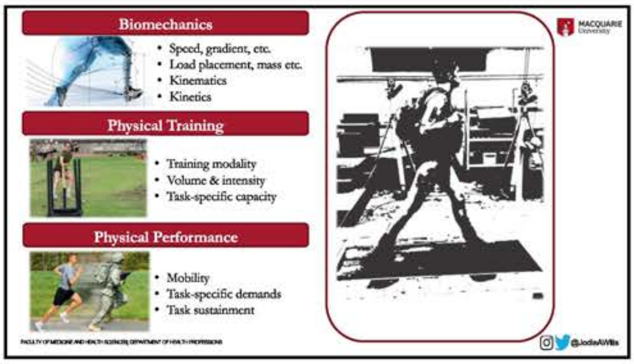
Appendix 10.5. Australian Strength and Conditioning Association (ASCA 2019) International Conference on Applied Strength & Conditioning

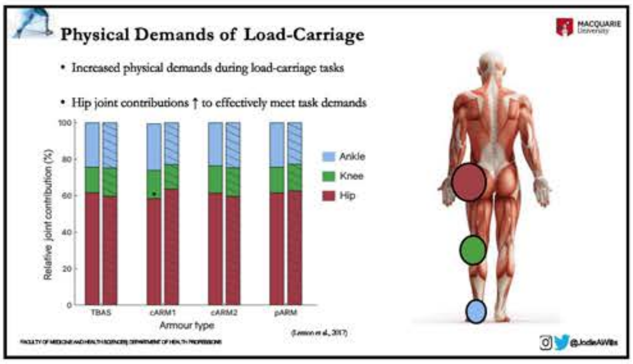

MACQUARIE University
"Load-carriage conditioning:
Let's talk about sex-specific responses"
JODIE WILLS

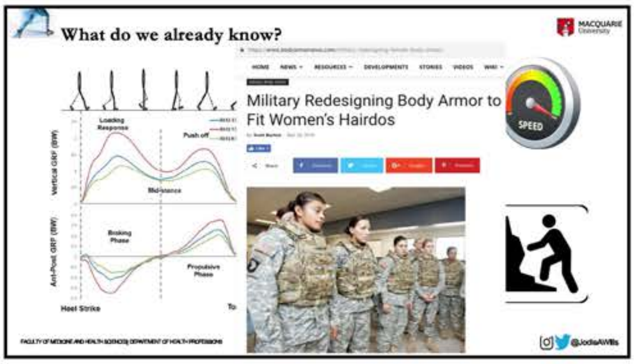

The Overweight Infantryman
MACQUARIE University
@JodieAWills


Training vs. Operational Loads
MACQUARIE University
Training
Load range: 5-23kg
Task time: Varied
Recent conflicts
Load: ≥45kg
THE LONGEST WAR
THE AUSTRALIAN ARMY IN AFGHANISTAN
@JodieAWills


Women not permitted in military
Women permitted in military
Women permitted in military, treated unequally (no frontline combat)
Women permitted, treated equally
Conscription for women
No data
MACQUARIE University
@JodieAWills

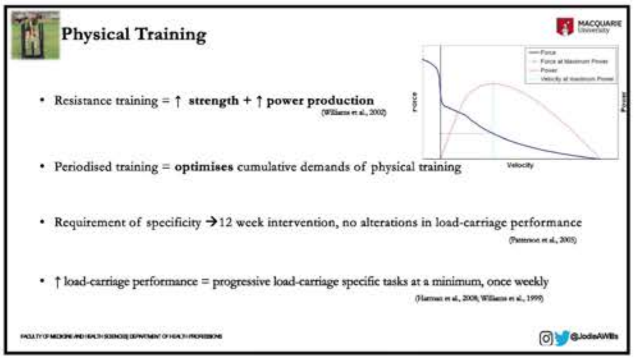

Biomechanics
Speed, gradient, etc.
Load placement, mass etc.
Kinematics
Kinetics
Physical Training
Training modality
Volume & intensity
Task-specific capacity
Physical Performance
Mobility
Task-specific demands
Task sustainment
MACQUARIE University
@JodieAWills


Physical Demands of Load-Carriage
MACQUARIE University
Increased physical demands during load-carriage tasks
Hip joint contributions ↑ to effectively meet task demands
Relative joint contribution (%)
100
80
60
40
20
0
TBAS
cARM1
cARM2
pARM
Armour type
Ankle
Knee
Hip
(Lenton et al., 2017)
@JodieAWills



What do we already know?
MACQUARIE University
Loading Response
Push off
Mid-stance
Vertical GRF (BW)
Braking Phase
Propulsive Phase
Ant-Post GRF (BW)
Heel Strike
Military Redesigning Body Armor to Fit Women's Hairdos
SPEED
FACULTY OF MEDICINE AND HEALTH SCIENCES| DEPARTMENT OF HEALTH PROFESSIONS
@JodieAWills

What do we already know?
MACQUARIE University
• Limited changes in gait parameters during loaded walking
(Krupenevich et al., 2015; Silder et al., 2013)
• No changes in gait parameters during loaded walking
Combined data reported
Limitations
Standardised loads
ABS vs. %BW
FACULTY OF MEDICINE AND HEALTH SCIENCES| DEPARTMENT OF HEALTH PROFESSIONS
@JodieAWills



Physical Training
MACQUARIE University
• Resistance training = ↑ strength + ↑ power production
(Williams et al., 2002)
• Periodised training = optimises cumulative demands of physical training
• Requirement of specificity → 12 week intervention, no alterations in load-carriage performance
(Patterson et al., 2005)
• ↑ load-carriage performance = progressive load-carriage specific tasks at a minimum, once weekly
(Harman et al., 2008; Williams et al., 1999)
Force
Power
Velocity
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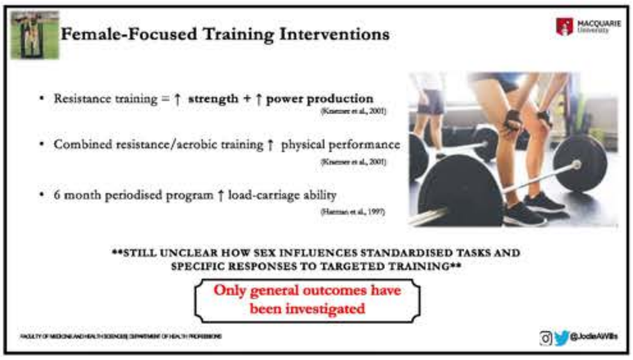
@JodieAWills



Female-Focused Training Interventions
MACQUARIE University
• Resistance training = ↑ strength + ↑ power production
(Kraemer et al., 2001)
• Combined resistance/aerobic training ↑ physical performance
(Kraemer et al., 2001)
• 6 month periodised program ↑ load-carriage ability
(Harman et al., 1997)
STILL UNCLEAR HOW SEX INFLUENCES STANDARDISED TASKS AND SPECIFIC RESPONSES TO TARGETED TRAINING
Only general outcomes have been investigated
FACULTY OF MEDICINE AND HEALTH SCIENCES| DEPARTMENT OF HEALTH PROFESSIONS
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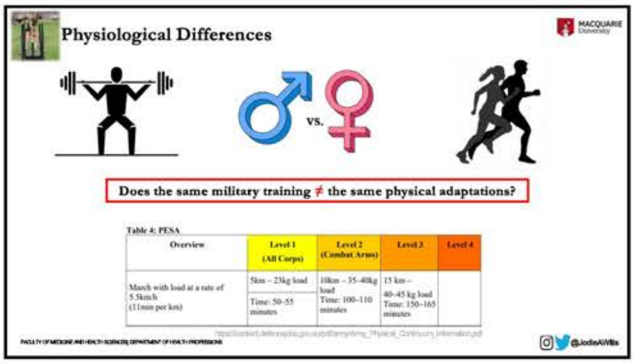

Physiological Differences
MACQUARIE University
vs.
Does the same military training ≠ the same physical adaptations?
Table 4: PESA
Overview
Level 1 (All Corps)
Level 2 (Combat Arms)
Level 3
Level 4
March with load at a rate of 5.5km/h (11min per km)
5km – 23kg load
Time: 50-55 minutes
10km – 35-40kg load
Time: 100-110 minutes
15 km – 40-45 kg load
Time: 150-165 minutes
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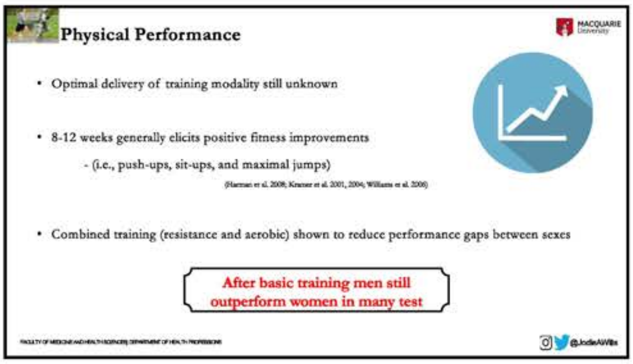

Physical Performance
MACQUARIE University
• Optimal delivery of training modality still unknown
• 8-12 weeks generally elicits positive fitness improvements
- (i.e., push-ups, sit-ups, and maximal jumps)
(Harman et al. 2008; Kraemer et al. 2001, 2004; Williams et al. 2006)
• Combined training (resistance and aerobic) shown to reduce performance gaps between sexes
After basic training men still outperform women in many test
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Physical Performance

- Physical and physiological burden associated with load-carriage
- Typically results in degraded soldier performance
  - i.e. task capacity or sustainment (Drain et al. 2016)
- March performance improved through combined, periodised training (Kraemer et al. 2004; Harman et al. 2008)
- Specific training may be required to optimise task-specific performance

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Application: PhD Research

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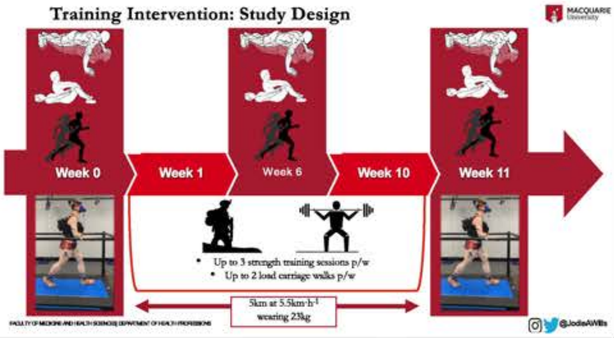
Training Intervention: Study Design



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Training Intervention: Participants

- No previous load-carriage experience
- Recreationally active civilians

Inclusion Criteria

Sex	Age Range (years)	Sit-ups (reps)	Push-ups (reps)	Beep Test (level, shuttle)
Female	18-25	70	21	7.5
	26-30	65	18	7.5
Male	18-25	70	40	7.5

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Weeks 1 & 2

Week	Session 1	Session 2
1	Squat - 3 x 8-10 Leg Curls - 3 x 8-10 Seated Row - 3 x 8-10 Bench Press - 3 x 8-10 Hyperextensions - 20 total	Squat - 4 x 8-10 Leg Curls - 4 x 8-10 Seated Row - 4 x 8-10 Bench Press - 4 x 8-10 Face pulls - 4 x 8-10 Hyperextensions - 20 total
2	Deadlift - 3 x 8-10 Leg Curls - 3 x 8-10 Bench Pull - 3 x 8-10 Bench Press - 3 x 8-10 Leg raises - 20 total	Deadlift - 4 x 8-10 Leg Curls - 4 x 8-10 Bench Pull - 4 x 8-10 Bench Press - 4 x 8-10 Face pulls - 4 x 8-10 Leg raises - 20 total

Generic	Loading	Taper	Loading	Taper
2 weeks	3 weeks	1 week	3 weeks	1 week

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Weeks 3 - 5

Week	Session 1	Session 2	Session 3
3	Squat - 5 x 5 Deadlift - 5 x 5 Nordic lowers - 3 x 6 KB Step Ups - 5 x 10 (alternating) Hyperextensions - 30 total Leg Raises - 30 total	Bench Pulls - 5 x 8-10 Bench Press - 5 x 8-10 Face Pulls - 5 x 8-10 3/4 Lat Pulldowns - 5 x 8-10 Upright Rows - 3 x 8-10 Crunches - 30 total	Repeat Session 1
4	Squat - 5 x 5 Deadlift - 5 x 5 Nordic lowers - 3 x 6 KB Step Ups - 5 x 10 (alternating) Hyperextensions - 40 total Leg Raises - 40 total	Bench Pulls - 5 x 8-10 Bench Press - 5 x 8-10 Face Pulls - 5 x 10 3/4 Lat Pulldowns - 5 x 8-10 Upright Rows - 3 x 8-10 Crunches - 40 total	
5	Squat - 5 x 5 Deadlift - 5 x 5 Nordic lowers - 3 x 6 KB Step Ups - 5 x 10 (alternating) Hyperextensions - 50 total Leg Raises - 50 total	Bench Pulls - 5 x 8-10 Bench Press - 5 x 8-10 Face Pulls - 5 x 10 3/4 Lat Pulldowns - 5 x 8-10 Upright Rows - 3 x 8-10 Crunches - 50 total	

Generic	Loading	Taper	Loading	Taper
2 weeks	3 weeks	1 week	3 weeks	1 week

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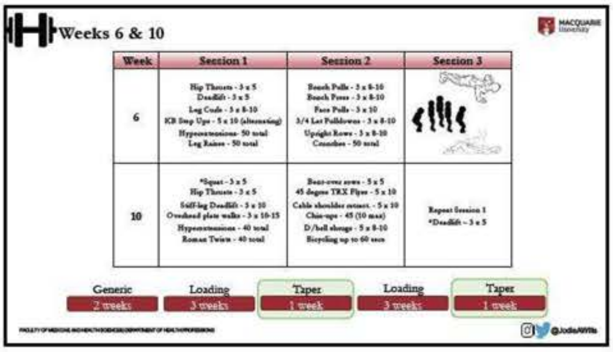
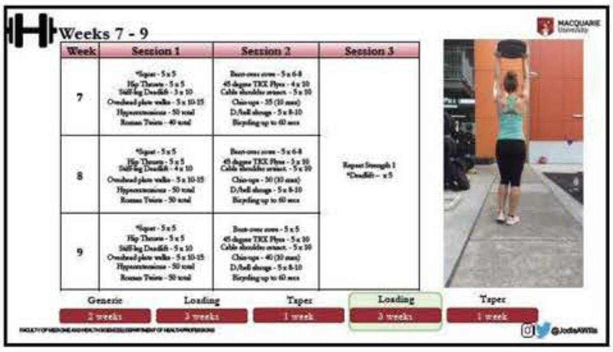
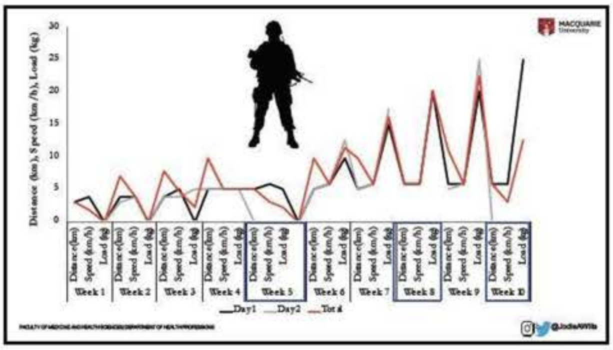
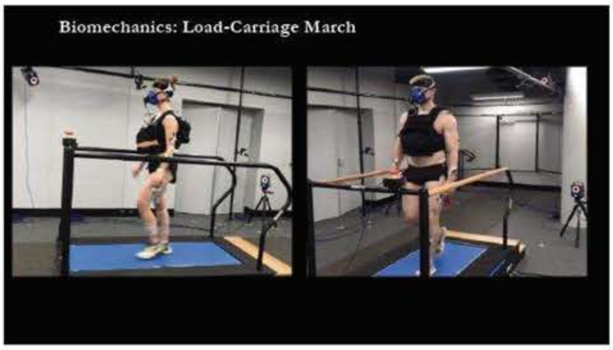


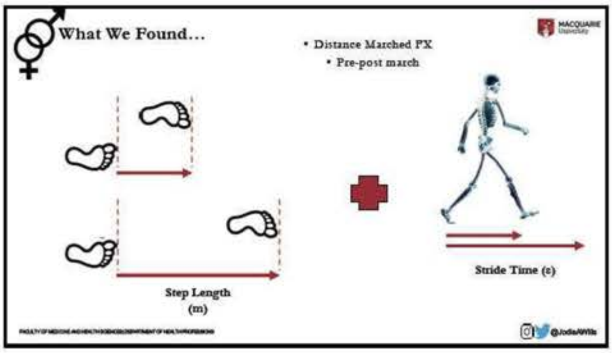
Week	Session 1	Session 2	Session 3
6	Hip Thrusts - 3 x 5 Deadlift - 3 x 5 Leg Curls - 3 x 8-10 KB Step Ups - 5 x 10 (alternating) Hyperextensions- 50 total Leg Raises - 50 total	Bench Pulls - 3 x 8-10 Bench Press - 3 x 8-10 Face Pulls - 3 x 10 3/4 Lat Pulldowns - 3 x 8-10 Upright Rows - 3 x 8-10 Crunches - 50 total	
10	*Squat - 3 x 5 Hip Thrusts - 3 x 5 Stiff-leg Deadlift - 5 x 10 Overhead plate walks - 3 x 10-15 Hyperextensions - 40 total Roman Twists - 40 total	Bent-over rows - 5 x 5 45 degree TRX Flyes - 5 x 10 Cable shoulder retract. - 5 x 10 Chin-ups - 45 (10 max) D/bell shrugs - 5 x 8-10 Bicycling up to 60 secs	Repeat Session 1 *Deadlift – 3 x 5

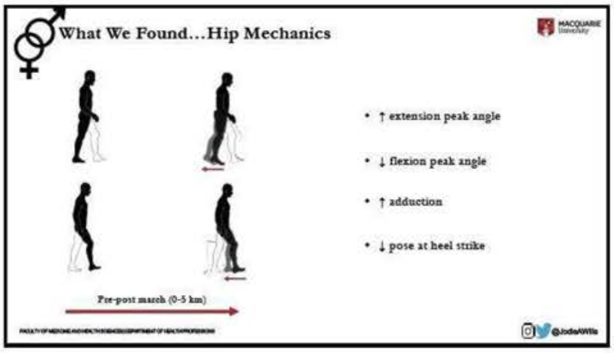


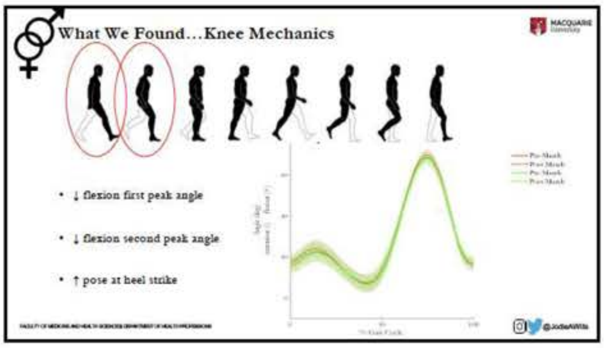
Week	Session 1	Session 2	Session 3
7	*Squat - 5 x 5 Hip Thrusts - 5 x 5 Stiff-leg Deadlift - 3 x 10 Overhead plate walks - 5 x 10-15 Hyperextensions - 50 total Roman Twists - 40 total	Bent-over rows - 5 x 6-8 45 degree TRX Flyes - 4 x 10 Cable shoulder retract. - 5 x 10 Chin-ups - 35 (10 max) D/bell shrugs - 5 x 8-10 Bicycling up to 60 secs	Repeat Strength 1 *Deadlift – x 5
8	*Squat - 5 x 5 Hip Thrusts - 5 x 5 Stiff-leg Deadlift - 4 x 10 Overhead plate walks - 5 x 10-15 Hyperextensions - 50 total Roman Twists - 50 total	Bent-over rows - 5 x 6-8 45 degree TRX Flyes - 5 x 10 Cable shoulder retract. - 5 x 10 Chin-ups - 30 (10 max) D/bell shrugs - 5 x 8-10 Bicycling up to 60 secs	
9	*Squat - 5 x 5 Hip Thrusts - 5 x 5 Stiff-leg Deadlift - 5 x 10 Overhead plate walks - 5 x 10-15 Hyperextensions - 50 total Roman Twists - 50 total	Bent-over rows - 5 x 5 45 degree TRX Flyes - 5 x 10 Cable shoulder retract. - 5 x 10 Chin-ups - 40 (10 max) D/bell shrugs - 5 x 8-10 Bicycling up to 60 secs	










What We Found…Knee Mechanics
MACQUARIE
↓ flexion first peak angle
↓ flexion second peak angle
↑ pose at heel strike
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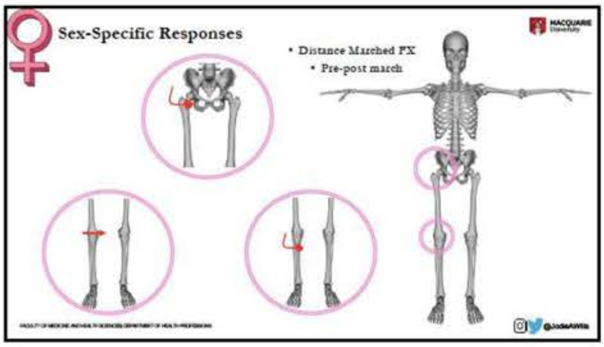
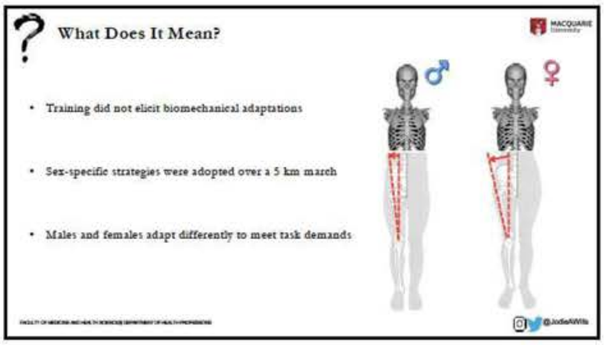

Sex-Specific Responses
MACQUARIE
Distance Marched FX
Pre-post march
@JodieAWills


What Does It Mean?
MACQUARIE
Training did not elicit biomechanical adaptations
Sex-specific strategies were adopted over a 5 km march
Males and females adapt differently to meet task demands
@JodieAWills


What We Found…
MACQUARIE
♂ > ♀
Power, Force, Velocity
No training FX
No interaction
♂ > ♀
Power, Force, Velocity
Training FX for force
No interaction
♂ > ♀
RPE, HR, VO2max*
Training FX
RPE
VO2max (men)
CMJ
SJ
Load Carriage
0 week
6 week
11 week
Power (W)
Force (N)
Velocity (m/sec)
Male
Female
RPE (AU)
Heart Rate (bpm)
VO2max (ml/min/kg)
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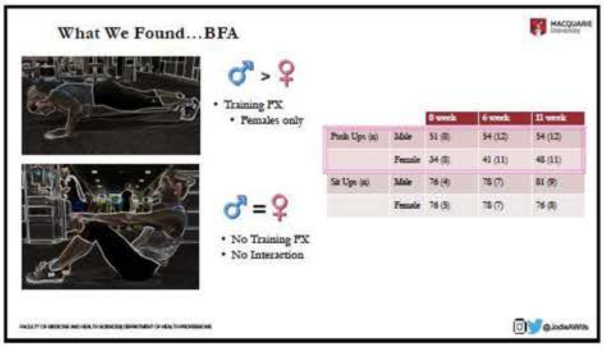
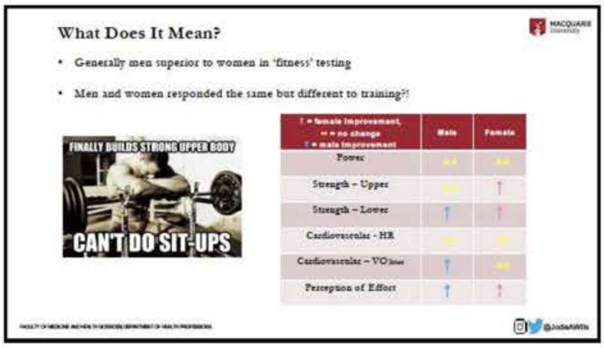
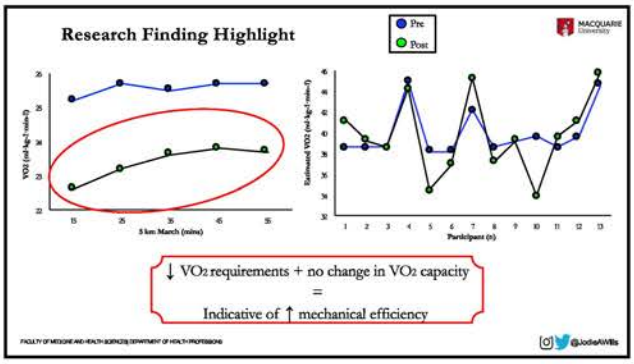
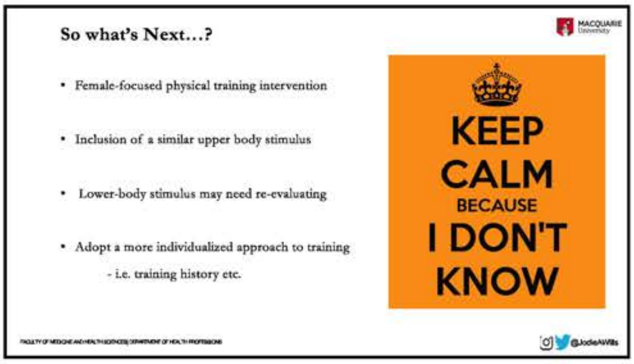
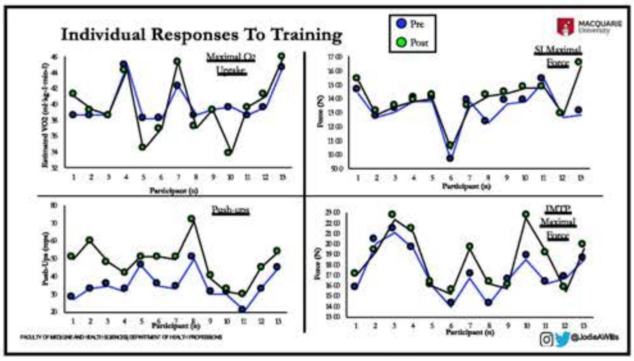

What We Found…BFA
MACQUARIE
♂ > ♀
Training FX
Females only
♂ = ♀
No Training FX
No Interaction
0 week
6 week
11 week
Push Ups (n) Male 51 (8) 54 (12) 54 (12)
Female 34 (8) 41 (11) 48 (11)
Sit Ups (n) Male 76 (4) 75 (7) 81 (9)
Female 76 (5) 78 (7) 76 (8)
@JodieAWills

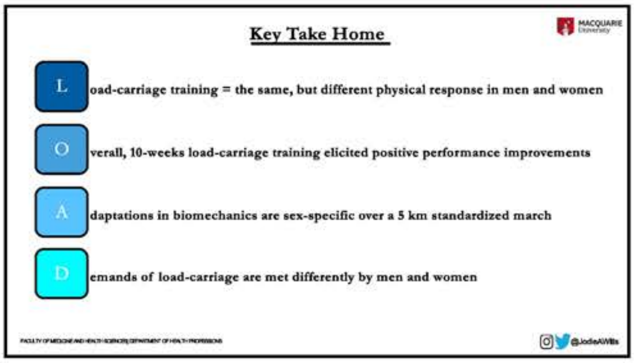

What Does It Mean?
MACQUARIE
Generally men superior to women in 'fitness' testing
Men and women responded the same but different to training?!
FINALLY BUILDS STRONG UPPER BODY
CAN'T DO SIT-UPS
↑ = female improvement,
↔ = no change
↑ = male improvement
Male
Female
Power
Strength – Upper
Strength – Lower
Cardiovascular - HR
Cardiovascular – VO2max
Perception of Effort
@JodieAWills


Research Finding Highlight
Pre
Post
MACQUARIE University
5 km March (mins)
Participant (n)
↓ VO2 requirements + no change in VO2 capacity
=
Indicative of ↑ mechanical efficiency
@JodieAWills


So what's Next…?
MACQUARIE University
• Female-focused physical training intervention
• Inclusion of a similar upper body stimulus
• Lower-body stimulus may need re-evaluating
• Adopt a more individualized approach to training
- i.e. training history etc.
KEEP
CALM
BECAUSE
I DON'T
KNOW
@JodieAWills


Individual Responses To Training
Pre
Post
MACQUARIE University
Maximal O2 Uptake
SJ Maximal Force
Push-ups
IMTP Maximal Force
Participant (n)
@JodieAWills


Soldering On…
MACQUARIE University
"Train like a girl"
Overall findings strongly indicate that physical conditioning must be tailored to meet specific requirements of each sex
@JodieAWills


Key Take Home
MACQUARIE University
L oad-carriage training = the same, but different physical response in men and women
O verall, 10-weeks load-carriage training elicited positive performance improvements
A daptations in biomechanics are sex-specific over a 5 km standardized march
D emands of load-carriage are met differently by men and women
@JodieAWills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ASCA
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Dr. Jace Drain
Dr. David J. Saxby
Dr. Tim L. A. Doyle
@JodieAWills

Appendix 11. External Scientific Engagement

Please see the following pages for content relevant to scientific communication events that I have participated in throughout the duration of this thesis. These events have enabled me to engage with the wider community to disseminate scientific content and key research findings highlighted within this thesis.

Appendix 11.1. Three-minute Thesis (3MT)

MACQUARIE
University
SYDNEY·AUSTRALIA

3MT® THREE MINUTE THESIS
FOUNDED BY THE UNIVERSITY OF QUEENSLAND

Faculty of Medicine and Health Sciences

Three Minute Thesis Competition

First Prize Award

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2019 MACQUARIE UNIVERSITY FINAL

Finalist

Jodie Wills

MACQUARIE University SYDNEY·AUSTRALIA

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Appendix 11.2. FameLab

Application video link:

https://www.youtube.com/watch?v=Q3x4umfGTA&feature=youtu.be

Subject: Congratulations - 2019 FameLab Semi-Final - New South Wales
Date: Friday, 15 March 2019 at 7:36:28 pm Australian Eastern Daylight Time
From: Melissa Callanan
To: Melissa Callanan
Attachments: image001.png, image002.jpg, 2019FameLabTermsAndConditions.pdf

Congratulations – we'd love to invite you to take part in the FameLab 2019 competition.

We were impressed with the quality of your research as well as the passion that you have shown for communicating your science. On behalf of the Foundation for the WA Museum and the British Council, it is with great pleasure that we invite you to participate in the **New South Wales** semi-final.

DATE AND TIMES

The **New South Wales semi-final** will be held on the **Wednesday 10 April 2019** at the **Powerhouse Museum, Sydney**.

FameLab is a full day commitment as it involves communications training during the day and the public event during the evening.

This training session will be held at the **Powerhouse Museum** from 10:00 to 16:00.
The public event will be held in the **Museum's Turbine Hall** from 18.00 to 20.30.

A schedule and run order for these events will be circulated in the coming weeks. Please contact me as soon as possible if any of the above timing is of issue.

You have automatically been registered for this event, but we are asking all other guests to RSVP for the free evening event. You can pass on the following link to your networks to registers for the FREE event here. Please note that the FameLab event books out quickly, so book early to avoid disappointment.

TRAVEL ARRANGEMENTS AND REQUIREMENTS

If you live outside of the Sydney area, we will work with you to arrange your travel requirements. If you require arrangements to be made, please contact me (mcallanan@fwam.com.au) as soon as possible.

Please contact me with any food intolerances, allergies or access requirements prior to the day so that we can take this into consideration in our planning.

We will be sharing some further information about the event over the coming week, including what to expect on the day.

In the meantime, please do start thinking about your three-minute presentation, remembering the cardinal rules of FameLab: **No jargon and No Powerpoint. Props, costumes, music, and humor are all encouraged.**

For your reference, attached are the FameLab – Eligibility Criteria (Terms and Conditions). Please note that should you become a finalist, you would be required to travel to Perth 6-8 May and the UK in 4-9 June . If these dates become a challenge for you, it is important that we are advised quickly.

I look forward to working with you on FameLab 2019. If you have any questions at all, please don't hesitate to get in contact with me. My details are below.

Thanks,

Melissa Callanan

Melissa Callanan
Project Director FameLab

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