Physiological and Biomechanical Analysis of Prolonged and Repeated Bouts of Load Carriage

by

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Abstract

Previous work has attempted to define the physiological determinants of load carriage over a single day of load carriage, primary aims of this thesis were to determine the physiological and biomechanical changes as a result of load carriage and to explore the causes of these changes during load carriage and to explore these changes over multiple days of activity. A secondary aim was to explore individual differences in performance and possible mechanisms for this.

Chapter 4 observed acute changes in vertical ground reaction force, supported by effect sizes which suggests individual differences in performances (loading peak d_{Cohens}=1.66 and d_{Glass} 4.49). These findings were supported by no change in first negative rate which suggests increased knee flexion is occurring to mitigate the effect of the load. Differences in anteroposterior ground reaction force variables suggest that changes in gait may affect movement economy. Energy expenditure was shown to be correlated to a number of strength variables, such as ankle plantarflexion (r=-0.47) and knee extensors(r=-0.46).

Similar variables were studied as a result of 2 hours treadmill load carriage in chapter 5. An additional variable was the study of torque at specific joint angles in addition to peak torque. Drift was observed for $\dot{V}O_2$ (68.93%). The torque curves showed significant reduction for load carriage, around the optimum muscle lengths for force (Knee extension at 180°s^{-1}: 95°-125°, knee flexion at 180°s^{-1}: 95°-125°) with findings supported by the peak torque values, suggesting there is no shift in muscle function. These findings were supported by associations between knee extension neuromuscular function scores, ankle plantarflexion neuromuscular function scores and energy cost variables which suggest that reductions in neuromuscular function may account for the increased energy cost.

Chapter 6 observed load carriage on repeated days. The chapter observed that energy cost did not recover to baseline 24 hours post day one (4.41%). Further increases in energy cost and $\dot{V}O_2$ were observed post day two for energy expenditure and $\dot{V}O_2$ which suggest that a cumulative increase in energy cost as a result of load carriage occurred. Knee extension at $60^{\circ}s^{-1}$ and $0^{\circ}s^{-1}$ was shown to not recover 24 hours post day one, these variables were shown to show increased reduction for post day two and day three. Similar findings were observed within the ankle plantarflexors but no significant changes were observed for knee flexion and ankle dorsiflexion.

Variables were also studied in a field setting during a >12hour load carriage task by Greek Special Forces soldiers. This study observed increased Medial and lateral deviations of the centre of pressure which suggests ankle instability even during unloaded walking as a result of load carriage. Large reductions were observed in vertical jump height and power as a result of the task, however this did not correlate to any biomechanical findings.

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Abbreviations

AP	Anteroposterior
APGRF	Anteroposterior Ground Reaction Force
BM	Body Mass
BW	Body Weight
Ca^{2+}	Calcium
CI	Confidence Interval
CFT	Combat Fitness Test (2hours load carriage)
CK	Creatine Kinase
CoM	Center of Mass
CoP	Center of Pressure
CV	Coefficient of Variance
D_{Cohens}	Cohen's D (Effect Size)
D_{Glass}	Glass's D (Effect Size)
ELI	External Load Index
EMG	Electromyography
GPS	Global Positioning System
GRF	Ground Reaction Force
HR	Heart Rate
HR_{max}	Maximum Heart Rate
HRR	Heart Rate Reserve
LCS	Load Carriage System
MAP	Mean Arterial Pressure
ML	Mediolateral
MLGRF	Mediolateral Ground Reaction Force
MOLLE	Modular Lightweight Load-carrying Equipment
MVC	Maximal Voluntary Contraction

NM	Neuromuscular
NMF	Neuromuscular Function
PL	Peronious Longus
PLCE	Personal Load Carriage Equipment
RER	Respiratory Exchange Ratio ($\dot{V}$CO2/ $\dot{V}$O2)
RPE	Rating of Percieved Exertion
SD	Standard Deviation
$\dot{V}CO_2$	Volume of Carbon Dioxide Expired
Ve	Ventilation
VE	Variance Explained
VGRF	Vertical Ground Reaction Force
VJT	Vertical Jump Test
$\dot{V}O_2$	Volume of Oxygen
$\dot{V}O_{2Drift}$	Drift in Oxygen Uptake Over Time
$\dot{V}O_{2max}$	Maximum Rate of Oxygen Uptake
20:50 Hz	Electrical Stimulation at 20 and 50 Hertz

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1.1 Introduction

A variety of recreational and occupational activities require the carriage of external loads (Knapik et al., 1996, Taylor et al., 2016, Simpson et al., 2011a). The most common manner of transporting these loads is through the use of a backpack (Knapik et al., 2012). In an occupational setting, the absolute mass of these loads can vary between 20kg to >50kg depending on the demands of the activity (Taylor et al., 2015), and although rare, these loads can be greater than the carrier's body mass (BM). The forces exerted onto the musculoskeletal system have been shown to increase substantially (Birrell et al., 2007, Lloyd and Cooke, 2000b) and have been deemed to increase both the risk (Rice et al., 2016) and incidence of injury (Rice et al., 2013b).

Occupational and recreational load carriage share commonalities, in that the load carriage task itself is seldom completed in isolation; usually it is a means by which equipment is transported to facilitate the completion of the primary objective e.g. fighting a fire or setting up a military position. As such, a person undertaking load carriage needs to be physically capable once they have finished the load carriage task to ensure effective completion of a separate primary objective.

During military basic training recruits undergo many military training tasks which include load carriage. Work within military cohorts suggest substantial physiological change as a result of load carriage (Fallowfield et al., 2012) which could possibly influence the increased injury risk (Rice et al., 2016). Understanding the mechanisms behind these injuries would help develop preventative protocols within training programmes. It has been reported that 16% of the annual intake of Royal Marine recruits are admitted to hunter company for injury rehabilitation, where the median recovery time has been reported to be 14.30 weeks (Munnoch, 2008). Furthermore, other work has observed that 58% of 1810 recruits self reported that they sustained at least one injury during army basic training, with overuse injuries (65%) being more prevalent than traumatic injuries(35%)(Robinson et al., 2016). This incidence of injury has resulted in a substantial loss of training time and associated costs (Ross, 2002).

A number of research groups have examined physiological and, infrequently, biomechanical changes as a result of broader military exercise (Hill et al., 2015, Nindl et al., 2002, McCaig and Gooderson, 1986). More frequently, studies have attempted to define physiological and biomechanical changes specific to load carriage (Sagiv et al., 1994, Lloyd and Cooke, 2000b, Hinde et al., 2017, Hudson et al., 2017, Dames and Smith, 2016, Dames and Smith, 2015), however the papers tend to focus on short duration activities (<20minutes). It is probable that this time frame does not sufficiently reflect the duration of most load carriage tasks, which have been documented to be from two to 10 hours over consecutive days (Knapik et al., 2012), meaning that much of the currently published work can only partially explore the research problem. Recently researchers have started to address this short coming, with some studies assessing load carriage over a prolonged (≥2hours) duration through both physiological (Margolis et al., 2016, Dewhurst et al., 2014) and biomechanical (Rice et al., 2016) methods. These have provided valuable insight to the changes which occur to during load carriage. However, the requirements for these studies to answer specific questions (defined by the funding bodies) have resulted in broader mechanistic questions remaining unanswered. Therefore, this thesis is well placed to investigate both, physiological and biomechanical changes as a result of load carriage concurrently enabling basic and applied study of load carriage.

As previously noted the duration of the load carriage task is not the only issue not fully considered, as soldiers are expected to complete these bouts of prolonged load carriage over repeated days (Knapik et al., 2012). During both training and during training and operations (Orr, 2010); during operations loads can also be far greater than those carried in training (Brown, 2009) and repetitive bouts of physical activity are fundamental to operational success. It has previously been demonstrated that neuromuscular function (NMF) is reduced up to 72 hours after a single bout of prolonged load carriage (Blacker et al., 2010), meaning that participants commencing any bout of load carriage in this time could be starting from a sub-optimal condition. To date, very little research has explored consecutive days physical activity, while no published research has explored consecutive day bouts of prolonged load carriage or the individual differences in recovery from multiple day exercise; and no published research has considered individual variability between participants.

The experimental studies reported in this thesis (chapters 4-7) investigate the responses to load carriage, with particular reference to NMF, movement economy and ground reaction force (GRF). Acute changes as a result of military load carriage are compared to unloaded walking in chapter 4. chapter 5 explores relationships between NMF and GRF as a result of a prolonged military load carriage task. An array of biomechanical and physiological measures were applied to a two-day load carriage task in chapter 6, exploring participants capacity to recover from exercise and the demands of exercise over repeated days. Finally, chapter 7 explores NMF and plantar pressure variables in an occupational environment as a result of an extreme duration (>12 hours) field based load carriage by Greek Special Forces soldiers.

2.1 Literature Review

The primary purpose of this literature review is to evaluate the demands of load carriage. A secondary purpose is to explore how this previously established knowledge can inform the subsequent experimental studies within this thesis. This literature review will focus on load carriage in the form of backpack carriage in either occupational or recreational settings. For the purpose of this review, a load carriage system (LCS) will refer to all aspects of the load that is carried, e.g. personal protection equipment, weapon, webbing and backpack.

2.2 Occupational Load Carriage Tasks

Individuals engaged in occupational tasks may carry loads using a variety of LCS. Fire fighters and other emergency personnel carry oxygen tanks and breathing apparatus in addition to other lifesaving equipment (Smolander et al., 1985, Taylor et al., 2015). Recreationally, hikers commonly carry loads of up to 40%BM for sustenance and comfort for durations of over two hours or even over consecutive days (Simpson et al., 2012).

Infantry soldiers often carry extremely heavy backpack loads, often between 78kg and 108kg (Orr, 2010) and walk longer distances than most of their civilian counterparts (Kobus et al., 2010). As part of their annual performance evaluation, British soldiers complete a Combat Fitness Test (CFT) which comprises of carrying a backpack weighing 25kg and a rifle (7kg) for eight miles in two hours.

The challenge of load carriage on a soldier has changed dramatically over the last 30 years, with an increase in the magnitude of loads carried (Knapik et al., 1996), changes in doctrine and changes to the enemy threat mean that soldiers are carrying more personal protection equipment than in previous decades (Knapik et al., 2012). There have been changes in backpack design from a single pack to a modular design where loads are now spread across webbing, body armour, weapons and backpacks with multiple partitions (Pal et al., 2014). These differences suggest that while research focusing on a civilian population does have merit, transferring the findings from civilian LCS to military LCS must be considered with caution. As such, in order for any experimental study to be applied in the real world, all aspects of the load (personal protection equipment, weapon, webbing and backpack) should be considered (Birrell et al., 2007).

The biomechanical responses to load carriage have been examined principally in laboratory conditions over distances of less than 20meters(m) (Lloyd and Cooke, 2011, Birrell and Haslam, 2010, Kinoshita, 1985, Kinoshita and Bates, 1981, Singh and Koh, 2009) with a few notable exceptions (Rice et al., 2016, Harman et al., 2000, Simpson et al., 2011a, Simpson et al., 2011b). Most research in this context considers the acute effect of the load carriage system but it is unable to explore the effect of load carriage as a result of prolonged occupationally relevant load carriage. A range of acute protective mechanisms have been observed to occur, such as increased ground contact time to increase the time which the external load can be decelerated (Kinoshita, 1985), forward lean to maintain the mass within the base of support (Lloyd and Cooke, 2011) and increased knee flexion to increase the distance over which the vertical force of the load is halted (Polcyn et al., 2002).

While more recent work has attempted to explore biomechanical and physiological parameters concurrently (Rice, Fallowfield et al. 2016), most work observing prolonged load carriage does still tend to apply physiological methods of investigation (Brown, 2009), with most testing using single index values, such as heart rate (HR) (Grenier et al., 2012a) and heart rate reserve (HRR) (Fallowfield et al., 2012) due to the difficulty of data collection in an occupational setting (Notley et al., 2015). This research has yielded valuable information on load carriage by providing an insight into load carriage from a field based perspective. However, these methods have not been able to adequately observe a link between NMF reduction and injury risk. Laboratory simulation of load carriage has allowed for further data collection methods and observations of load carriage through direct measures of force output which has been used previously (Blacker et al., 2013, Clarke et al., 1955).

The purpose of the following section is to explore the literature which identifies current measures and avenues to explore possible mechanisms behind any observed degradation in performance, in order to understand why such changes occur. The review will explore possible links between parameters during load carriage and use supporting research from animal studies or from studies using physiologically similar protocol to provide pathways for future research when there is little empirical research in the load carriage field.

2.3 Predictors of Load Carriage Performance

Research to predict load carriage performance is driven by a real world requirement for militaries, to select and train recruits in an economical manner without placing them at undue injury risk (Rayson et al., 2002). This was principally done by participants completing a battery of tests, the findings of which were then correlated to completion times during maximum effort load carriage tasks. Most research was completed by the U.S. Army Research Institute of Environmental Medicine at the Natick Institute, or through various institutions observing British soldiers undergoing various tasks; therefore participants wear military clothing and carry weapons and packs and completed occupationally relevant testing protocols.

Studies have explored $\dot{V}O_{2max}$ (Mello et al., 1988, Dziados et al., 1987, Rayson et al., 1993), leg strength (Rayson et al., 1993) maximal lift capacity (Mello et al., 1988), body anthropometry (Mello et al., 1988, Frykman and Harman, 1995, Williams and Rayson, 2006), aerobic capacity (Dziados et al., 1987, Brown, 2009), occupational tests (Knapik et al., 1990, Rayson et al., 2000), mood states (Knapik et al., 1990), marksmanship tests (Knapik et al., 1990) and military experience (Knapik et al., 1990). Broadly speaking these studies have found that higher body mass and $\dot{V}O_{2max}$ values were associated with faster road march times when carrying a load of 46kg over 20km (Knapik et al., 1990). Hamstring strength and $\dot{V}O_{2max}$ was found to be a significant influence on 10km performance time. Moreover, Mello et al. (1988) observed that both strength and endurance ability of the hamstrings and quadriceps were significant predictors of performance times over distances up to 8km and 12km. Additionally, shoulder diameter (Frykman and Harman, 1995) and stature (Rayson et al., 1993) have been amongst the best predictors of performance, despite many more measurements being taken (Knapik et al., 1990).

Measures of isometric and isokinetic strength have been used to predict load carriage performance, considering amongst others; leg extension, leg flexion, hand grip and trunk flexion strength (Knapik et al., 1990). The strongest strength based determinants have consistently been isometric hamstring strength (Dziados et al., 1987, Mello et al., 1988) and repeated squat scores (Frykman and Harman, 1995). It is interesting to note that despite the clear importance of aerobic measurements as predictors, muscular strength scores have been shown to be superior to muscular endurance values for performance time prediction (Rayson et al., 2000). It is likely that such a phenomenon occurs as a result of the large loads carried.

Overall the strongest predictors tend to be measurements of central aerobic fitness, the principal measure of which has been $\dot{V}O_{2max}$. The highest recorded association between $\dot{V}O_{2max}$ and loaded march performance was r=0.84 (Frykman and Harman, 1995). However, it must be noted that this occurred during a loaded march of only 3km, which is considerably shorter than the other distances covered and not completed at a load (20%BM) which is occupationally relevant to a military cohort and therefore is likely to have an aerobic component which is at a higher percentage of $\dot{V}0_{2max}$ than a slower more laden march.

Research has been conducted by the British military, which observed that aerobic fitness tests dominated single item regression models for 15kg, 20kg and 25kg loads carried over eight miles. The strongest predictor was the multistage fitness test score for the 15kg condition and 20kg load carriage tasks (Rayson, 1998, Rayson et al., 2000). As with the previous studies, the authors observed that muscle strength; in this case demonstrated by an upright pull and static lift power and muscular endurance (dynamic and static arm flexion and press-ups) were amongst the strongest predictors of performance.

When multiple markers were subjectively selected to produce regression models to predict performance. The most successful models included measures of strength, aerobic fitness and body composition. Generally, the models more accurately predicted performance at the lighter load classifications (Rayson et al., 2000, Rayson et al., 2002). The strongest model for the 25kg condition used $\dot{V}O_{2max}$, body mass and static arm flexion endurance to account for 40% of the variance, while the multistage fitness test score and gender were the strongest predictors of performance for the 20kg condition accounting for 55% of the variance. The multistage fitness test, static arm flexion endurance and percentage body fat accounted for 77% of the variance in the 15kg condition (Rayson et al., 2000).

It is important to note that task failure rates of 2% and 5% for men were much lower than for females (35%) at the 20kg load carriage task and 16% for the 15kg load carriage tasks. This principally occurred by most of the male participants completing the load carriage tasking comfortably within the allotted 120min while most of the females times distributed more heavily around the 120min point, with many more failures recorded.

Due to the specific military requirements of the research projects, the research tends to examine occupational or easily administered predictor variables. The variables therefore provide a general insight into load carriage ability to military users but they may not provide the strongest predictor variables available or provide specific mechanistic explanation of the changes. Key issues with the models were missing data from participant drop out (Knapik et al., 1990) only using a single measure (Dziados et al., 1987) and lack of relevance to the subject task (Rayson et al., 1993).

Broadly, the regression models with the strongest correlation with load carriage times were observed in models which included measures of aerobic fitness, muscle strength and body composition (Brown, 2009).

The above studies explore factors which predict load carriage performance are important to this thesis, the studies highlight that load carriage performance is influenced by a number of parameters which may not have been observed concurrently within previous research. It is clear that load carriage performance depends on aerobic capacity and an ability to resist fatigue both aerobically and through muscular strength and endurance measures. This suggests that the mechanisms behind reduced load carriage performance are likely to be multifaceted. Therefore the study of such parameters needs to occur concurrently to examine the interplay between measures; as such the next section will focus on exploring the role which such parameters play during load carriage tasks.

2.4 Energy Cost of Load Carriage

Most load carriage research has attempted to establish the energy costs of load carriage tasks (Blacker et al., 2009b, Abe et al., 2008, Ainslie et al., 2003, Lloyd and Cooke, 2000b, Hinde et al., 2017, Grenier et al., 2012b). The two most critical determinants of energy cost during load carriage have been found to be speed and load carried by the participant (Scott and Christie, 2004). As has been previously discussed, soldiers rarely have the luxury to dictate their own speed and load. This has a profound impact on their ability to maintain physiological homeostasis.

Early papers which attempt to define energy cost at a range of load and speeds, suggest that a speed of $4\text{km}\cdot\text{h}^{-1}$ was an optimal speed for load carriage (Cathcart et al., 1920, Soule et al., 1978), such analysis is based on very short duration trials (<30min) and only considers energy expenditure as the limiting mechanism of performance. However, the work did highlight that the optimal speed is dependent on the load carried, with participants slowing down to mitigate the increase in the energy cost of carrying the load in an attempt to maintain homeostasis.

When undergoing any form of physical activity, oxygen consumption and HR rises rapidly from resting during the first three or four minutes of sub-maximal exertion before plateauing. This plateau or ‘gradual plateau’ in oxygen consumption is by convention referred to as ‘steady state’ (McArdle et al., 2010). There is debate about whether a true plateau exists (Sagiv et al., 2006) or whether the will be a gradual increase in energy cost over time, possibly due to the depletion of intramuscular fuel stores (Logan-Sprenger et al., 2012) which will occur over an extended period despite working at a constant work load (McArdle et al., 2010).

For moderately fit populations, such as those who are the topic of this thesis, the steady state threshold is normally achieved between 40%$\dot{V}O_{2max}$ and 60%$\dot{V}O_{2max}$ (Smith et al., 1998) as cited by Pompeu and Gomes (2017) although it should be acknowledged that this can vary significantly depending on circadian rhythm (Scott et al., 2015) and transient changes in acid base (Pompeu and Gomes, 2017). If participants with a moderate level of physical fitness such as those who are the topic of this thesis worked at a higher level of intensity and if it is assumed that muscle strength is not the limiting factor, their oxygen consumption would continue to increase until they reach task failure. This gradual increase in oxygen consumption and HR during prolonged sub-maximal exercise at a constant and steady pace, during an apparently constant work load, has been termed respiratory and cardiovascular drift, respectively (Gaesser and Poole, 1996). Drift can be observed after a minimum 10min of prolonged moderate-intensity exercise when in a neutral or warm environment (Coyle and Gonzalez-Alonso, 2001).

During 120min walking on a treadmill at a speed of 4.5km·h^{-1} with a +5% gradient and a 25kg load Epstein et al. (1988) observed an initial exercise intensity of 45.50±0.60%$\dot{V}O_{2max}$ (measured at 20min) but observed no change after 120min of loaded walking. However, under the same parameters but with a load of 40kg, observed a statistically significant drift of 4.10% from an intensity of 52.10±0.60%$\dot{V}O_{2max}$ at 20min which increased to 56.20±0.60%$\dot{V}O_{2max}$ at the cessation of exercise (120min). This led the authors to conclude that exercise intensity greater than

$50\%\dot{V}O_{2max}$ instigates an increase in physical fatigue causing a change in locomotion, leading to an increase in energetic cost. It must be noted that that the sample comprised of six highly trained endurance athletes, as such may not be representative of a military population, as it has been shown that elite endurance athletes may respond differently to moderately trained participants (Billat et al., 1998).

Conversely, it has been observed that a $\dot{V}O_{2drift}$ of 3.10% can occur at intensities starting as low as $26.60\pm0.80\%\dot{V}O_{2max}$ as a result of 50min of level treadmill walking, contrasted to no drift during a 5.20kg carriage condition (unloaded; weight of clothing) (Patton et al., 1991). The authors did not observe any change in blood lactate levels, which is unsurprising considering that the activity was completed at less than $50\%\dot{V}O_{2max}$ and therefore below the threshold at which lactate is likely to accumulate within the blood (O'Connell et al., 2017). However, the authors observed that $\dot{V}O_{2drift}$ occurred more rapidly when the participant was performing at a greater speed or with a greater load (Patton et al., 1991).These findings were supported by Warber et al. (2000) who observed that exercise intensity increased from 36.50±0.90% to $40.60\pm2.40\%\dot{V}O_{2max}$ during a 240min walk at $5.60km\cdot h^{-1}$. Furthermore, $\dot{V}O_{2drift}$ was observed when carrying 45.50kg loads at $4km\cdot h^{-1}$ for 230min and 225min (Reading et al., 1996) cited by Blacker (2009).

A number of studies did not observe any change in either $\dot{V}O_2$ or HR as a result of load carriage (Sagiv et al., 1994, Sagiv et al., 2006). There are a number of explanations for this, the load carriage task lasted only 30min and the authors used a predictive sub maximal protocol to calculate participants $\dot{V}O_{2max}$, in a healthy population, which may have inflated the $\dot{V}O_{2max}$ values of participants. Also, the authors stipulate that due to the calculation of work load, the work load scores did not reflect the real work load which the participants were exposed to.

The authors propose a number of arguments for the differences within the findings. They suggest the use of new backpacks with chest and hip pads, which distribute the load to the larger muscles of the hips and legs allowing the work load to be spread across a broader range of muscles, while the other studies used backpacks only. It is feasible that backpacks could cause such changes; Lloyd et al. (2010) demonstrated that it is possible to observe the difference between backpacks using solely metabolic data during only short duration activities, while it has been demonstrated that load placement (Abe et al., 2004) and distribution of the load center of mass (CoM) (Simpson et al., 2012, Birrell and Haslam, 2010) have a pronounced effect on load carriage performance. It is certainly possible over prolonged durations small differences can become more pronounced as they may cause increased local fatigue and discomfort which may potentially result in gait change as the participant tries to avoid pain, resulting in a reduction in movement economy and increasing $\dot{V}O_2$ and HR. However, more contemporary studies such as Mullins et al. (2015), still observed drift, while using modern load carriage equipment during a 2hour loaded walking treadmill (0° gradient) task at $5.5 km \cdot h^{-1}$ compared to an unloaded control. These findings suggest that the occurrence of cardiovascular drift is more than a consequence of the $\dot{V}O_2$ intensity of the activity.

The literature suggests it is generally accepted that well-trained men cannot be expected to exercise for extended periods of time at intensity over $40\%\dot{V}O_{2max}$ without considerable drift (McArdle et al., 2010). It is clear from the previously presented studies that carrying loads over 30%BM for periods greater than two hours can elicit an energy cost of over $50\%\dot{V}O_{2max}$. This is operationally significant as it is likely that increase in energy cost could be caused by a change of gait, this change of gait could indicate greater injury risk or reduced movement economy (Lloyd and Cooke, 2011).

Physiologic drift has been observed in respiratory exchange ratio (RER), $\dot{V}O_2$ and HR measures during a 40min treadmill load carriage task at loads of 15% and 30%BW (Quesada et al., 2000). Providing further support that physiological drift can occur at relatively low loads (Patton et al., 1991). These findings are further supported by Mullins et al. (2015) who observed an 11% increase in $\dot{V}O_2$ and 12% increase in HR. The authors also observed a statistically significant increase in body temperature (0.40±0.30°C). While core body temperature has been shown to attenuate physiological drift (Coyle and Gonzalez-Alonso, 2001), the authors suggest the change was likely to be of little physiological significance, as by the end of the protocol the core body temp was still within normal limits and the $\dot{V}O_2$ value was well below 40%$\dot{V}O_{2max}$. It is unlikely central nervous system was the limiting factor to load carriage performance, suggesting that the systems were comfortably able to supply both the cutaneous vasculature and working muscles.

However, as significant drift is frequently observed during load carriage, and while $\dot{V}O_2$ and HR are frequently used as measures of task intensity, it can be suggested that the drift is affected by mechanisms which may cause task failure. As such, in order to understand the mechanisms behind injury risk and task failure, effort must be placed into understanding the causal mechanisms behind cardiac and respiratory drift.

Studies which have reported self-paced tasks purport that participants self-paced at an intensity between 30-40%$\dot{V}O_{2max}$ (Levine et al., 1982). Suggesting that it is desirable to ensure a combination of pace and load which maintain an intensity that is within these boundaries. As such exploration of further variables which explain this change would enable the participants to operate at a comfortable pace for a longer percentage of the total loaded march time.

A number of studies have explored the effect of gradient on $\dot{V}O_2$ values. Over short durations, Santee et al. (2001) observed that until -8% gradient $\dot{V}O_2$ values are reduced, with -8% representing the optimum value. Decreases beyond -8% were seen to increase $\dot{V}O_2$ until the final measurement taken at -12%. These findings were also observed in early walking studies where $\dot{V}O_{2drift}$ was observed to be at its highest between -6% and -15% (Wanta et al., 1993). It is conceivable that walking on a negative gradient places greater emphasis on the eccentric component of the stretch shortening cycle in the muscles of the lower limb, which in turn leads to greater energy requirement to negate the increased braking forces. However downhill loaded walking at -8% has been shown to produce a reduced $\dot{V}O_2$ response when compared to level walking of the same load (25kg)(Blacker et al., 2009b), however when change scores were examined a greater drift was observed for the downhill load carriage, suggesting that there are biomechanical changes to gait which are advantageous to movement economy, however the increased strain to maintain this gait may reduce movement economy over time.

It is broadly accepted that during prolonged exercise muscle fibres become damaged, reducing the force they can produce (Komi, 2000, Burt et al., 2014, Heavens et al., 2014). To compensate, additional motor units are stimulated to maintain movement when walking at a dictated speed. Which generally means that there is a change from type I to type II fibres during muscle contraction, which use oxygen less economically and fatigue quickly (Heppenstall et al., 1988), therefore increasing the oxygen demand within the exercising muscles and eventually the oxygen demand of the task, which may be a factor in the upward drift in $\dot{V}O_2$. This is further supported by Davies and Baknes (1972) who observed a greater activation in supporting muscles such as the quadriceps to maintain position and reduce the impact on the treadmill during the increased eccentric phases. More recently a reduction in the mean frequency of the peroneus longus muscular has been observed as a result of 12.8km load carriage in Royal Marines (Rice et al., 2016), suggesting at muscular fatigue. When 120min load carriage was completed with downhill vs level walking conditions with both conditions involving carriage of a 25kg bergen Blacker et al. (2009b) observed that the level condition instigated greater $\dot{V}O_2$ and HR response than the downhill condition, while the downhill condition instigated greater $\dot{V}O_{2drift}$ and HR_{drift}.

It has been demonstrated that running economy reductions have been shown to be accompanied by reductions in the knee extensor output during maximal voluntary contraction (MVC) (Millet et al., 2003). The most reliable method of examining loss of NMF is through direct measurement of force output, such as isokinetic dynamometry or maximal voluntary isometric contraction. Reductions in both centrally and peripherally activated muscle contractions of knee extensors and flexors following load carriage have previously been observed (Blacker et al., 2013). These studies suggest that neuromuscular impairment may be linked to changes in $\dot{V}O_{2drift}$ and HR_{drift} during prolonged load carriage. By using a fatiguing protocol of timed box jumps, designed to dissociate locomotor muscle fatigue from metabolic stress Marcora et al. (2008) demonstrated that reduced locomotor muscle force was significantly associated with cardiorespiratory responses signified by a significant increase in HR along with a trend for increased mean arterial pressure and time to exhaustion during intensive cycling exercise. Such findings suggest that reduced muscle force may have a significant influence on cardiorespiratory regulation during prolonged steady state exercise

Another factor which is often considered in relation to cardiovascular drift is a shift in substrate oxidation (Quesada et al., 2000). While caution must be used when drawing conclusions from RER values in studies which do not control dietary intake, the studies within this review have applied limits on participants which are common within the field, as such participants commence exercise two hours post prandial and started testing in a rested state at least 24hours after any vigorous exercise and only consumed water throughout the testing. It must be considered that RER is only an indication of whole body substrate oxidation, therefore glycogen depletion may have occurred locally in individual muscle fibers, which could further contribute to $\dot{V}O_{2drift}$ which being without being observable through RER values.

Not all studies which examine metabolic changes as a result of load carriage present RER or $\dot{V}CO_2$ values. The studies which adequately reported RER values (Quesada et al., 2000) observed a significant increase in RER between 0min and 5min followed by no change thereafter until protocol completion, suggesting no change in RER was observed once steady state was achieved. While Blacker (2009) observed a reduction in RER from 5min to 120min during loaded walking compared to an unloaded condition, indicating a change from carbohydrate to fat substrates as an energy source as a result of load carriage. This suggests that glycogen stores were depleted during load carriage which may account for some of the $\dot{V}O_{2drift}$, however the authors estimate that the alterations in substrate utilisation could only account for 5% of the change in drift (Blacker et al., 2009b).

It is clear that metabolic and cardiovascular drift occurs in a number of load carriage studies, however, due to a focus only on the physiological measures in isolation it is not possible to explore in depth the mechanisms causing drift and the effects that drift has on performance. It has been suggested that military personnel have to complete load carriage on multiple days, to date there is no research exploring the timeframe required to recover metabolically from such tasks. In an effort to explain the previously observed drift in physiological parameters this study will examine changes in NMF via isokinetic and isometric dynamometry, the following section will examine key research within the area.

2.5 Dynamometry

A commonly used method of exploring changes in a muscle groups ability to produce force has been through reductions in NMF. Due to the restrictions of field based testing a range of neuromuscular performance measures have been used. These comprise of measurements of vertical jump height (Nindl et al., 2002, Welsh et al., 2008, Fallowfield et al., 2012) and functional tasks such as squat lifts (Warber et al., 2000). The gold standard and most easily controlled method of measuring NMF is isokinetic dynamometry. Which is a method that has been used to evaluate the NMF of lower limbs, trunk and shoulder muscle groups as a result of load carriage tasks (Blacker, 2009).

Findings from early field based research were not conclusive. While Ainslie et al. (2003) observed no change in vertical jump performance after a self-paced 21km hill walk carrying a load of 9.5kg. Findings may not be transferable to a military population due to the participant’s ability to self-regulate pace, meaning they could potentiate the effects of fatigue (Simpson et al., 2010). The load only weighed the equivalent to approximately 12% of the participants mean body mass. It has been suggested that biomechanical changes to gait do not occur with loads under 30%BM (Birrell and Haslam, 2009). The 9.5kg load instigated a mean HR of 132±21beats·min^{-1}. By using the reported average age (24years) of the sample it is possible to extrapolate that participants worked at approximately an average of 67% of their estimated heart rate maximum (HR$_{max}$), which if looking at the intensity alone would be enough to instigate NMF reduction. From this, it is possible to speculate that NMF is reduced more by the peripheral effects of mitigating the effect of the load as opposed to the centrally fatiguing aspects of the task.

Alternatively, a reduction in the maximum number of squat lifts (45.5kg barbell at 25reps·min^{-1}) from 52±28 to 27±10 (48%) completed by participants after 240 min of load carriage on a treadmill at 5.6km·h^{-1} and 3% gradient has been observed (Warber et al., 2000) and more recently a vertical jump height decrease of 8±9% following load carriage (0.37±0.05 vs 0.34 ± 0.06 m, which was caused by a 5±5% decrease in vertical jump power following load carriage (3821±427Watts vs. 3647±539Watts) (Fallowfield et al., 2012). This reduction in jump height suggests NMF impairment in the lower limbs, which are contrary to previous work which observed no change in jump height following load carriage (Ainslie et al., 2003, Knapik et al., 1991). This inconsistency might be explained by the best effort nature of the studies, meaning the participants were able to self-regulated speed to maintain physiological homeostasis, while the dictated speed of the latter study increased physiological strain that the participants experienced (Fallowfield et al., 2012). It is likely that this increase in physiological strain, is from the march being conducted on cross country terrain, such as long grass and gravel (Knapik et al., 2004), while the former was conducted during road marches, the inability for the soldiers to self-regulate their pace, is also likely to be a contributing factor.

Dynamometry is the gold standard method of recording NMF, able to study force reduction of each joint action while isolating non acting muscles. This process enables the researcher to draw meaningful conclusions from complex actions, however, due to the complex equipment required it cannot easily be used within a field based setting. As such most studies which use isokinetic dynamometry study load carriage conducted on a treadmill (Blacker et al., 2013, Blacker et al., 2010).

Clarke et al. (1955) observed reductions in the force producing capability of the ankle plantar flexor, pectorals, shoulder elevators, knee, hip and trunk extensors and flexors following 12.1km field based load carriage bouts carrying loads between 0kg and 27kg. The authors acknowledge that there was uncontrolled variation, generated by the data collection methods, such as the cable tension weight stack measuring on a discrete scale. As the author attempted to mitigate this by the use of statistical adjustment, the data must be viewed with some caution. However, of relevance to this thesis strength decrements were observed in all observed muscle groups, for an external load of 18kg and 27kg; with the greatest reductions in strength occurring in the trunk and hip flexors and extensors and the ankle plantar flexors. This work did not present all the data from the control group, meaning the authors are unable to draw conclusions regarding the effect of the load for all variables.

The only current research to observe NMF which employed a control condition consisted of a 120min walking task at $6.5km \cdot h^{-1}$ and compared unloaded walking to load carriage of 25kg, allowing examination of the effect of the load in isolation (Blacker et al., 2013). During this research, an interaction effect supported by a reduction in NMF during the loaded condition was observed for maximal isometric knee extension and knee extension during electrical stimulation. The electrically stimulated contractions were supported by large effect sizes, suggesting that the changes observed were due to alterations of the central nervous system and the contractile properties of the peripheral muscle. The reduction in MVC force lead the authors to postulate that the additional load, instigates greater GRFs, which in turn increases the amount of force which the muscles must absorb, therefore increasing muscle damage.

These findings were further supported by the observation of isokinetic contractions for the knee flexors and extensors at 60◦s^{-1} and 180◦s^{-1} after the same task which observed a reduction at all variables. These changes were supported by no interaction effect suggesting that the load did not have any additional effect over unloaded walking (Blacker, 2009). It must be noted in line with Clarke et al. (1955) that the authors observed large CVs (Coefficient of Variance), while the load carriage condition also had a significantly higher baseline score for knee extension. When compared to Clarke et al. (1955), Blacker (2009) observed greater reduction in knee extensor (8%) and flexor (6%) peak torque, but observed comparable changes in reduction of trunk flexors and extensors (11% from pre-test scores), which suggests that a 120min walking bout is a suitable laboratory based method of observing neuromuscular change as a result of military load carriage.

The previous work conducted analysis at 60◦s^{-1} and 180◦s^{-1} for the knee extensors and flexors. It is well known that angular velocity has a pronounced effect on the maximum torque which the muscles are able to produce (Baltzopoulos and Brodie, 1989). As such for any study to produce findings which are meaningfully comparable testing needs to have occurred at equivalent angular velocities.

Furthermore, neither Blacker (2009) nor Clarke (1955) presented data representing torque values at defined joint angles during isometric contraction. The angular position is important in the assessment of muscle function because it may provide information about the mechanical properties of the contracting muscles (Baltzopoulos and Brodie, 1989). It has been reported that during knee extensions the maximum torque occurs later in the range of movement as the joint target velocity increased (Thorstensson et al., 1976). This suggests that while no change in the peak torque achieved, the measure could overlook that the peak torque is generated differently and that the muscle is producing less force throughout the cycle as a whole. As such, analysis of maximum torque data irrespective of angular position may lead to erroneous conclusions about muscle function. Consequently, this thesis will examine both parameters which will allow best practice principals to inform the work while also meaningful conclusions can be drawn to previous work in the field.

2.6 Recovery from Neuromuscular Function Loss

One study has attempted to profile NMF up to 72hours after load carriage. After a 120min load carriage task, a reduction in NMF of the knee extensors at $60°s^{-1}$ and $180°s^{-1}$ was observed. This reduction remained below baseline values to the final measurement 72hours post activity for the $60°s^{-1}$ condition and reduced significantly until 24hours post for the $180°s^{-1}$ condition during downhill walking but statistically recovered for the level unloaded walking condition. Moreover, knee flexion at $60°s^{-1}$ was reduced at 24hours for the level loaded walking condition (Blacker, 2009).

These findings are supported by further electrically stimulated peripheral measures which suggest that greater damage occurs to knee extensors than the flexors, this is likely due to the increased role of the extensors within the gait cycle. MVC of the knee extensors showed a bimodal pattern of recovery, as they recovered at 24 hours and then dropped below a post exercise value at 48 and 72 hours. Dousset et al. (2007) suggests that this bimodal change is due to the varying effects of chemical and mechanical mechanisms for NMF loss occurring at different time scales.

After repeated contractions such as those involved in load carriage, reductions in a muscles force producing capability occur, they are often referred to as reductions in NMF or exercise induced muscle damage. Both terms refer to a neuromuscular impairment caused by the activity and can be observed by a reduction in the muscles force output (Howatson and Van Someren, 2008). It is convention which dictates that reference to neuromuscular fatigue usually refers to change in neuromuscular output immediately post exercise, and as such displays a short recovery period. Alternatively exercise induced muscle damage refers to the changes in muscle performance in the ensuing days, and assumes slow recovery, due to damage to the muscle tissue. While some markers of muscular damage can be observed experimentally (for example, the presence of blood urea, myofibril proteins and most commonly creatine kinase (CK) (Kobayashi et al., 2005), these methods of investigation are not without issues such as the lack of assay detection range in healthy participants, and assay specificity (Shave et al., 2010).

The initial events are thought to occur either by mechanical or metabolic stress (Tee et al., 2007). It has been proposed that mechanical stress is more prevalent during human locomotion due to the high tension within muscle fibers which do not contract uniformly causing an imbalance in tension (Armstrong, 1990, Friden and Lieber, 1992, Lieber and Friden, 1993). This imbalance can disrupt the myofibrillar structures, creating damage to the cross bridges resulting in damage to certain fibers meaning a reduction in the force producing potential of the muscle (Tee et al., 2007). Experiments on mice models have suggested that the magnitude of muscle damage is related to a combination of speed of lengthening of the muscle, peak forces and exercise duration (Kuipers, 1994).

The mechanical overload is believed to cause increases in intracellular calcium concentration resulting in a loss of cellular Ca^{2+} homeostasis, which ultimately can trigger a chain of events after the exercise task prompting the secondary loss of force 1-3 days after exercise, which is observed as the secondary reduction in NMF (Armstrong, 1990). This could be evidence of simultaneous chemical and mechanical muscle damage.

Metabolic events such as increased temperature, altered pH, reduced mitochondrial respiration and oxygen free radical production, can weaken the muscle fibre which in turn potentiates mechanical fatigue (Tee et al., 2007). The extent of the involvement of metabolic and mechanical stress factors and the resultant process is still debated. However, it is likely that a number of mechanistic and metabolic factors will be involved in reducing the function of a muscle fibre all of which occur over a range of timeframes over a number of days following physical activity. This suggests that research conducted over a single day of activity may not be able to be transferred to physical activity conducted on consecutive days as participants may be starting performance in a state different to the initial baseline.

2.7 Cumulative Day Exercise and Load Carriage

Work has observed performance during two exhaustive running bouts at 70%$\dot{V}O_{2max}$ separated by four hours (Alghannam et al., 2016). This study observed that time to completion during the second task was longer than for the first task. However the timeline for these treadmill runs are not indicative of the load carriage demands which are the topic of this thesis, where changes are observed on a timeline between one and three days.

Some studies have explored physical activity over consecutive days. Fell et al. (2006) explored the effect of three days' time trial laboratory cycling. The study observed a reduction of counter movement jump height between day 1 and day 3; this is further supported by an observed increase in creatine kinase between day 1 and day 3 suggesting a possible increase in muscle damage. While the study also observed a simple effect reduction in knee extension MVC, between pre and post testing each day, however observed no change between days. These findings suggest that the may be a functional change in NMF as a result of multiple day activity, however the lack of specificity of the tests to the fatigue protocol make it hard to draw conclusions, also the best effort nature of the testing is not reflective of the occupational setting of this thesis.

A study which used high intensity cycling bouts over three days observed elevations in plasma total antioxidant status once corrected for changes in plasma volume, and urinary allatoin excretion, suggests that while exercise does elevate markers of oxidative stress, there is no cumulative effect of successive days of high intensity exercise (Shing et al., 2007), however again the high intensity and short duration model of exercise makes transferring findings to an occupational model difficult.

Stewart et al. (2008) conducted a study observing NMF recovery after three days of cycling at 60%$\dot{V}O_{2peak}$; an intensity which approximates that of load carriage. The authors observed NMF output of the knee extensors through both MVC and electrical stimulation. Interestingly, while the authors observed a recovery of MVC to baseline after day 1 and day 2 from day 3, the MVC output was shown to remain reduced for 72hours after day 3, suggesting that there is a cumulative effect of NMF reduction during exercise.

Squat jump mean power has been shown to be reduced (9%) in 10 soldiers following 72hours of sustained exercise. While no change in bench press output or marksmanship scores were observed (Nindl et al., 2002). The authors suggest that this decrement in performance occurred in muscles which were over used, and are not allowed adequate recovery. Further analysis shows that there was a gradual decline in squat jump performance with difference between days (d1-3=5.85% and d3-d4=41.96%) suggesting that the lower limb was not provided with adequate recovery time even when load carriage was not the only task observed.

Interestingly, the authors observed an increase in SEM between each day, suggesting that the may be notable individual differences in the participants capacity to complete the tasks. This is worthy of note, considering participants are expected to complete the same operational tasks, but may be exposed to differing leveling of fatigue and as such injury. This is further supported by Welsh et al. (2008) who observed small but notable increases in standard deviation (SD) for vertical jump scores after an eight day military exercise.

2.8 Neuromuscular Function and Injury

Animal models have shown that when a muscles force producing ability is reduced there is a reduction in the amount of energy a muscle can absorb, this, in turn, suggests the is a greater risk of muscle strain (Mair et al., 1996). It is accepted that skeletal muscle provides protection to the skeletal system, by gradually absorbing and attenuating the force from the external loads as they are transmitted along the proximal chain (Warren et al., 2002). When a muscle is fatigued or damaged, its ability to absorb force is impaired. This impairment would increase loading on the skeletal structure, therefore, increasing the risk of stress fracture (Arendt, 2000). It is known that stress fractures occur from repetitive and excessive stress on a bone (Arendt, 2000), prompted by the bones inability to withstand repetitive load, which results in structural fatigue. Stress fractures occur along a pathological continuum, which begins with a stress reaction, and localized pain and ends with a complete bone fracture. It is believed that stress fractures occur after a buildup of microdamage caused by a consistent application of above optimum loads (Warden et al., 2014).

The mechanisms which cause this increased injury risk have been unclear. During walking, movement predominantly occurs by the ankle plantar flexors and knee extensor muscles (Kepple et al., 1997). When a load is carried there is an increase in ankle dorsiflexion (Harman et al., 2000, Kinoshita, 1985) and knee flexion angles (Birrell and Haslam, 2009), which could be an action to lower center CoM in order to maintain postural stability, or an action to increase the distance over which the load is attenuated. All of these movements which occur predominantly in the sagittal plane and bending movements in the sagittal plane are believed to have a significant role in the development of tibial stress fractures (Phuah et al., 2010).

Previous studies have suggested that plantar flexor muscle fatigue has been associated with both tibial and metatarsal stress fractures (Arndt et al., 2002, Sharkey et al., 1995) due to increased bone strain. Additionally, the peroneus longus muscle which acts as a plantar flexor and rear foot evertor also stabilizes the ankle thus preventing ankle inversion injuries. Reduced function of this muscle may increase the risk of ankle inversion injuries, a prevalent injury in military recruits (Milgrom et al., 1991). Research using electromyography (EMG) measurements before and after a 12.8km load carriage task by Royal Marine recruits has shown that PL fatigue does occur (Rice et al., 2016).

Research has attempted to explore such parameters by using EMG to provide mechanistic explanation of injury risks. Such research while valuable is unable to assess the forces exerted through the skeletal system as a result of the neuromuscular output reductions. The following section will explore studies which have observed changes in ground reaction force and plantar pressures as a result of load carriage.

2.9 Gait Cycle

This thesis will follow the broad naming conventions which exist within biomechanics for the gait cycle. It is acknowledged that these may not be comprehensive, nor without fault, however it does provide a recognisable terminology base which can be used as the foundation of discussion. In the first instance the gait cycle is broken down in to a stance and swing phase, the stance phase pertains to the total duration of time a foot is in contact with the ground, as this is where all the impact forces occur, this will be the focus of this thesis. It is broadly accepted that human locomotion can be split in to three components, which are used to subdivide the stance phase. The stance phase is considered to contain all GRF components from heel contact (the first time the foot touches the ground) through to toe off, which is the point at which the foot is observed to be no longer in contact with the ground. The first subcomponent of the stance phase can be considered to be the load phase, which is considered the period where all vertical force of the human body (and external loads such as bergen) is impacting with the ground. This phase will contain loading variables, such as loading peak, which is an indicator of total force through the system. First positive rate (also referred to as loading rate in the literature) which is a description of the speed at which force is loaded to the system, which as this thesis will discuss later, can be observed as markers of injury risk.

During this phase mediolateral (ML) variables can be seen to fluctuate, if maximal ML variables are observed during the loading phase or particularly over a shortened duration it is an indication that a lack of ankle stability exists (Gefen, 2002). This period is also likely to contain the commencement of the breaking phase, which is an anteroposterior ground reaction force (APGRF) variable, pertaining to the reduction in momentum of the system to mid stance. This literature review will broach that there is some debate whether AP variables correlate to movement economy (Saunders et al., 2004). However, it is broadly accepted and certainly logical that any increase in breaking force, needs to be overcome in order to propel the system forward.

Mid stance is the second phase which follows the loading phase. This phase comprises of the forward swing of the body, and includes knee flexion (Birrell et al., 2007). In GRF terminology this phase will contain the force minimum, which is the lowest observed vertical variable between the two peaks, this position can be further characterised by two vertical rates. The first negative rate is a marker of the speed for which the vertical force is reduced, and will pertain to the speed of knee flexion and the amount of time which is required to decelerate the vertical load. Mid stance leads into the forward thrust movement, defined by the upward trend in the vertical ground reaction force (VGRF) parameters. The final phase can be defined as the push off phase, which pertains to the point where the body works to propel the system forward. This can be defined by the thrust maximum point, which relates to the maximum amount of force exerted down on to the ground. It is broadly accepted that increased thrust maximum will propel the body forward more effectively (Saunders et al., 2004). The rate between force minimum and thrust maximum, this is a seldom reported variable. However it is logical that it relates to how quickly force can be applied to the ground during the push of phase, which is strongly dominated by the ankle plantarflexors pushing downwards in to the ground, as such it is likely that any change to this rate could be indicative of ankle plantarflexor change.

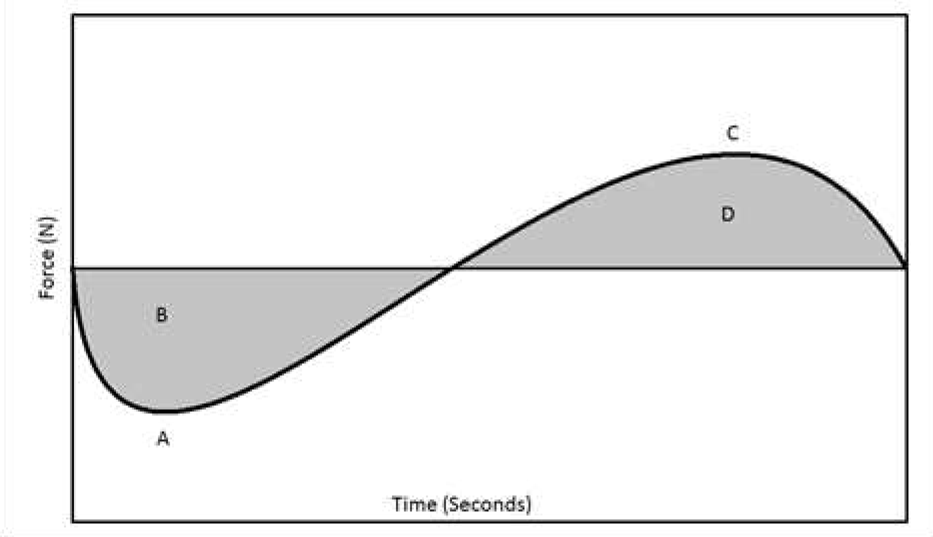
In terms of APGRFs the propulsive maximum occurs during this phase, which is the explanation of the forward advancement of the body, and is a measure of how much force is applied propelling the body forward. However, pertinently to this thesis, there is a body of thought which colloquially, but concisely defines walking through the phrase ‘walking is falling’, which suggests that during walking forward lean of the trunk prompts forward movement of the body, for which the legs move to keep pace with the moving CoM. If this is the case, then it may be possible for the body to advance more economically, despite no apparent change in propulsive maximum.

2.10 Ground Reaction Forces

Ground reaction forces have previously been used as measures of the interaction forces applied to the carriers system (Birrell et al., 2007, Crossley et al., 1999, Cavanagh and Lafortune, 1980, Gottschall and Kram, 2005). While a number of experimental methods, such as 3D analysis and EMG can define changes, that may affect gait and the corresponding impact forces, GRF is the only measure which can directly examine the forces exerted on the body. Some variation in terms used to describe GRF variables exists in the literature, as such this section will clarify the variables used within this thesis.

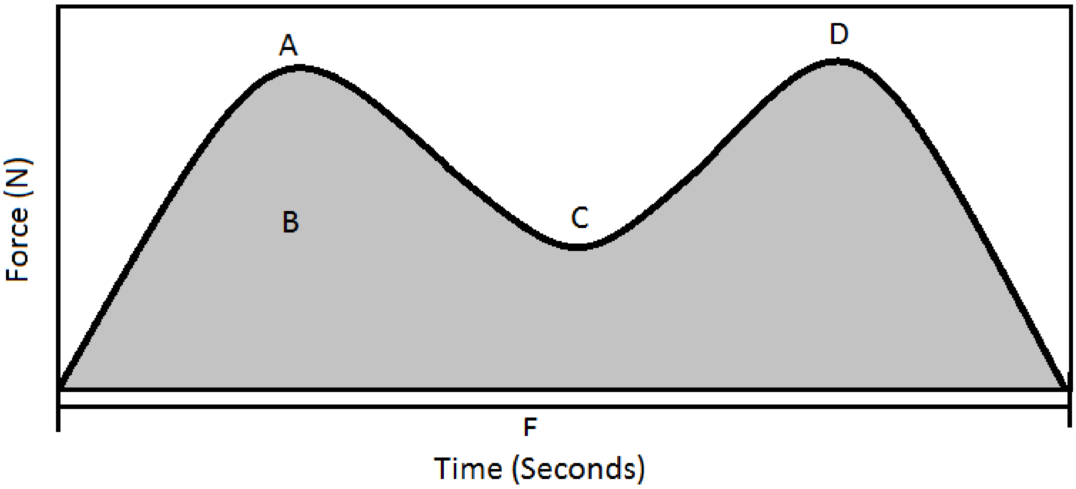
GRFs are measured along three axes. GRF data is usually analysed by plotting it against time; data is then presented graphically for each axis. There are many definitions used in the literature for the different GRF parameters. The figures below clarify the definitions and parameters that will be considered and referred to in this thesis.

Figure 2.1 Simplified representation of typical AP forces with key parameters



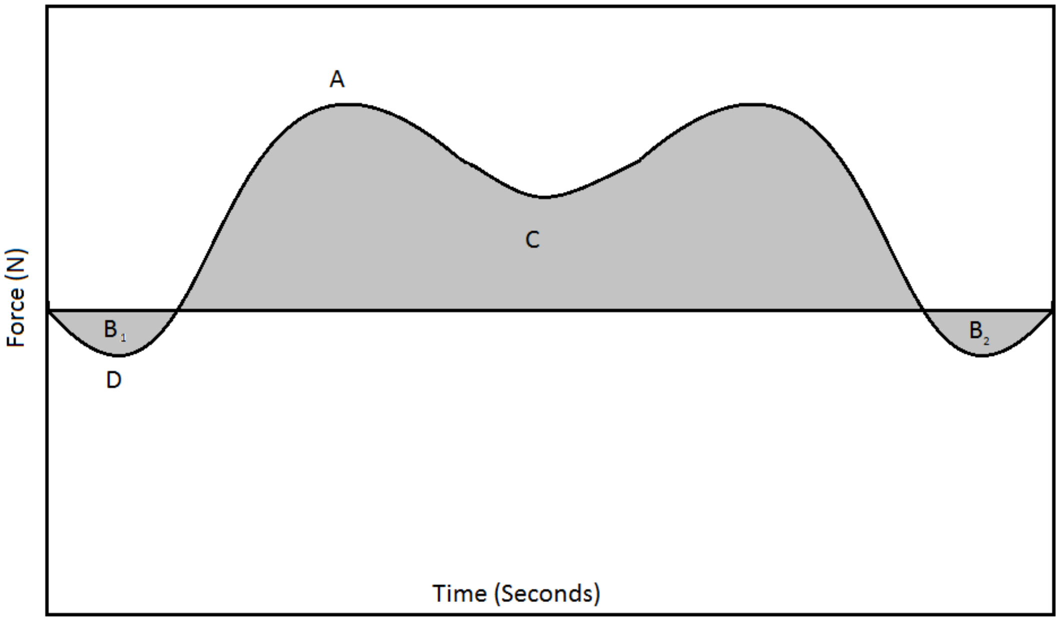
A: Maximum Braking Force, B: Braking Impulse, C: Maximum Propulsive Force, D: Propulsive Impulse

Figure 2.2 Simplified representation of typical Vertical forces with key parameters



A: Loading Peak, B: Total Vertical Impulse, C: Force Minimum, D: Thrust Maximum, E: Stance Time, F: First Positive Rate, G: First Negative Rate, H: Second Positive Rate, I: Second Negative Rate

Figure 2.3 Simplified representations of typical ML forces with key parameters



A: Lateral Maximum, $B_1 + B_2$: Medial Impulse, C: Lateral Impulse, ΣBC: Mediolateral Impulse, D: Medial Maximum.

2.11 GRFs of Load Carriage

There are a number of different methods of measuring changes in gait such as 2D and 3D kinematics. GRFs are the most sensitive measures for studying small changes in gait (Winter et al., 1974), which is particularly useful when trying to observe the small but repeated changes which occur during load carriage. When the same action is completed over a prolonged duration, it is likely that a high frequency of minor but repeated impacts can have an accumulated effect on bone structure over time.

The first papers to explore GRF markers in relation to load carriage used the same protocols over a 20m walkway but with different sample groups (Kinoshita, 1985, Kinoshita and Bates, 1981). In both studies, once the data had been normalised to total mass the authors observed increases in all vertical and anterior posterior GRF parameters for 20kg and 40kg load conditions. Additionally, the authors observed the same increase in double pack conditions with the load spread more evenly across the body. This leads the authors to the conclusion that GRF parameters are altered principally as a function of the static load as opposed to the placement or momentum forces, that have been shown to have an effect on joint kinematics (Rice et al., 2016). Support for this static load effect postulation can be found in previous work (Harman et al., 2000, Lloyd and Cooke, 2011, Birrell et al., 2007) However, examination of the presented data in these paper does not lend support to these statements as when the calculated weight of the load carriage systems is removed from the presented data there is a significant discrepancy between the loaded and unloaded conditions for the force minimum measures. Suggesting that while the postulation holds true for the loading peak and thrust maximum not all VGRF changes are in proportion to the load.

Kinoshita observed a lengthening of stance time and shortening of stride length as a result of load carriage, this has been supported by further studies on the topic (Birrell et al., 2007, Dames and Smith, 2015, Lloyd and Cooke, 2000a), the majority of the findings are expected, presumably in an effort to maintain the load within the body’s base of support. This is further supported by an increase in time to a number of vertical parameters in the first half of the stance phase, during the loaded protocol which suggests that the participants were over-striding. These findings suggest that by self-regulating gait the participant is able to mitigate the effect of the load (Tilbury-Davis and Hooper, 1999). Such findings are in agreement with the physiological studies discussed earlier in this chapter.

A varied range of outcomes have been observed for mediolateral variables, with a number of studies reporting only minimal or no changes (Kinoshita, 1985, Kinoshita and Bates, 1981, Tilbury-Davis and Hooper, 1999) and others not reporting the data at all (Castro et al., 2015, Dames and Smith, 2016, Lloyd and Cooke, 2000a). A change in ML force in the former papers would suggest a slight decrease in stability, possibly due to a greater load magnitude carried by the participants (Pau et al., 2012), however the number of studies which have chosen not to present the ML data would suggest that they observed no change in the MLGRF parameters.

Further studies have observed short duration load carriage using load carriage systems which more accurately reflect those that would be carried by a soldier such as carriage of bergen webbing and rifle exercise (Birrell et al., 2007). The military loads involved broadly represented the previously discussed studies. As such the authors report that vertical and AP impulses increase proportionally to the load (Kinoshita, 1985, Kinoshita and Bates, 1981, Harman et al., 2000, Lloyd and Cooke, 2000a). However, contrary to the previously discussed studies the authors observed an increase in ML impulse (Birrell et al., 2007). The findings suggest that military LCS may have a greater effect on stability than that of civilian hiking loads, potentially due to the LCS greater physical size requiring greater energy to change the direction of the motion, which in turns requires greater mediolateral movement, and possibly because of the distribution of the load in the pack being further away from the body’s natural CoM. In a follow-up study exploring the effects of weapon carriage specifically, the author observed small but statistically significant changes in impact peak, maximum propulsive force, mediolateral impulse, as well as a reduction in the force minimum in the vertical axis (Birrell and Haslam, 2009). Research has shown that natural arm swing modulates the CoM (Wagenaar and van Emmerik, 1994), therefore restricted arm swing will impede this modulation and the CoM may be less stable. It is possible that greater range of motion of the CoM in the vertical direction whilst walking will lead to a greater downward acceleration of the body prior to heel strike, which may be a factor as to why rifle carriage caused a greater impact force. The change in mediolateral impulse as a result of rifle load carriage alongside load suggests that an increased loss of stability while walking could increase the likelihood and severity of potential falls.

It is also possible that the natural arm swing during walking increases momentum produced by the upper body which in turns aids forward momentum (Birrell et al., 2007), subsequently reducing the amount of work required of the body to achieve forward locomotion. When this is considered with physiological variables over greater distance, it is possible that the rifles effect on the walking parameters is greater than simply the static effect of the load itself.

It is important to consider that while the observed changes are comparatively small, these alterations occur over every stride taken during load carriage and therefore the real world ramifications could be significant. For example, the average participant completing the study had a mass of 83.3kg which means as a direct result of the load carriage the supporting leg needed to absorb an extra 29.42N per stride. Soldiers frequently cover over 15km a day which would equate to 14,000 impacts (Jones et al., 1989).

2.12 GRFs During Prolonged Load Carriage

One study has examined load carriage over an outdoor prolonged obstacle course at a self-selected pace (Simpson et al., 2012) where the participants completed a simulated hiking trail, which consisted of a 2km route comprised of five 400m laps containing hiking obstacles such as a single log bridge, low branches and steps. No changes in AP or ML variables were observed, and only observed a change in the impact peak of the vertical GRF as a result of the simple effect of load. This is in line with the studies discussed in the last section. As previously discussed, the authors observed very little change in a range of parameters, leading to the postulation by the authors, that this is due to the participants ability to self-regulate the intensity, by reducing their pace in accordance with their perceptions of discomfort, this is supported by the statistically significant reduction in speed which has been reported (Simpson et al., 2011b). Soldiers do not have the capacity to regulate their speed, as the speed of the load carriage task is dictated by the military requirements of the task meaning that while such studies serve a heuristic purpose, research needs to be completed at controlled paces to be relevant to a military population.

More recently research has been conducted by the Institute of Navel Medicine (INM) studying biomechanical changes in Royal Marine Recruits undergoing prolonged load carriage tasks. While two studies have been published in peer review journals (Rice et al., 2016, Rice et al., 2013b) a number of studies have been presented as internal reports, and as such have not been peer reviewed and as such should be treated in the same manner.

The INM examined a load carriage task involving a 12.8km cross country march with an external load of 35.50kg, and observed that when running unshod post load carriage participants tended to adopt a more rear or midfoot strike pattern compared to pre load carriage and experienced a greater range of motion for dorsiflexion. The authors cited this as an indication of reduced plantarflexor muscle activity and a reduced control of lower limb flexion. Caution should be exerted when translating PL fatigue to reduced plantar flexion force as the authors observed no change in Gastrocnemius frequency which is the primary actor for plantar flexors (Arampatzis et al., 2006).

A follow-on study of the same load and distance parameters showed an increase in knee extensor moments again hinting at a proximal shift along the kinetic chain. Indeed the authors observed a shift in PL frequency suggesting possible plantarflexor fatigue (Rice et al., 2016). The authors propose that this is a function of the increased rear foot loading suggesting greater force being placed through the heel, causing an increase in injury risk through stress fractures and reduced movement economy due to a greater amount of force required to slow the impact (Rice et al., 2016, Rice et al., 2015). This does provide further support for the postulation that change in GRF, possibly from reduced NMF can instigate a less economical movement.

A number of studies have highlighted that during fatigue a participant is likely to become more unstable, normally signified by greater mediolateral movement (Gefen, 2002), the INM report reports an increase in eversion rate post load carriage, while the authors omit this in the peer reviewed journal article. The authors classify the PL as a primary plantarflexor which is in contrast to general opinion considering the lateral placement of the muscle, it is broadly accepted that the PL muscle acts to reduce eversion of the ankle during contact (Gefen, 2002, Hunt et al., 2001), while the gastrocnemius is the primary plantarflexor, as such it is worthy of note that no evidence of fatigue was observed in the gastrocnemius. As such it is likely that the shift in EMG frequency of the PL is having further lateral effects which were not observed by the authors. Support for this can be found in research which uses a fatiguing protocol to fatigue the peronious longus (PL) (defined by a shift in EMG frequency) which was shown to correlate to an increase in mediolateral deviations (Gefen, 2002).

It should be considered that while it is likely that the participants experienced fatigue as a result of load carriage in the previous studies, fatigue was not considered a controlled variable within the studies. Two studies have examined the effect of fatigue on load carriage, after fatigue has been induced (defined as 80% of vertical jump test [VJT] height) by repeated heel raises. Wang et al. (2013) observed increased pelvic tilt- probably in accordance with the forward lean which has been exhibited in the laboratory based studies, and increased knee flexion during mid-stance and ankle dorsiflexion, in line with the findings of Rice et al. (2016) and Harman et al. (2000). Again the authors suggest these changes occur to reduce the height of the bodies CoM and as such increasing stability. As both the knee and ankle are responsible for shock absorption during weight acceptance it is likely that these changes are occurring to attenuate GRFs, however these changes may elevate mechanical stresses of the knee extensors and ankle dorsiflexors (Wang et al., 2013).

Meanwhile as previously discussed Gefen (2002) observed increased ML Center of Pressure (CoP) variations as a result of a fatiguing protocol indicating a loss of stability. Peak stresses in the foot skeleton were shown to rise in relation to muscle fatigue during heel strike via computer model analysis. The authors use this to suggest that fatigue during load carriage is likely to increase injury through repeated impact injury.

2.13 Summary and Aims of the Thesis

Load carriage has been shown to increase energy cost, cardiovascular strain and muscle recruitment, during steady state activity compared to walking unloaded, however little research has attempted to explore the mechanisms behind this. Understanding the mechanisms for drift is critical to preventing undue drift, and therefore injury risk.

Neuromuscular function impairment has been observed as a result of load carriage, taken by field and laboratory based measures, these acute reductions in NMF have been shown to last up to 72hours after the completion of load carriage. Most military load carriage is completed over numerous days meaning soldiers will be commencing load carriage in a pre-fatigued state. It is known that reductions in NMF increase metabolic and cardiovascular drift during performance, however, no research has explored what impact this has on participants starting state during repeated days activity.

Research has been conducted exploring the loss of muscular performance and has estimated the impact on injury these changes may have. However, no study to date has explored the effect that such reductions have on the forces experienced by the participants at the foot ground contact. Therefore, GRF measures will be investigated to determine if these may be used to understand the mechanistic causes of injuries resulting from load carriage.

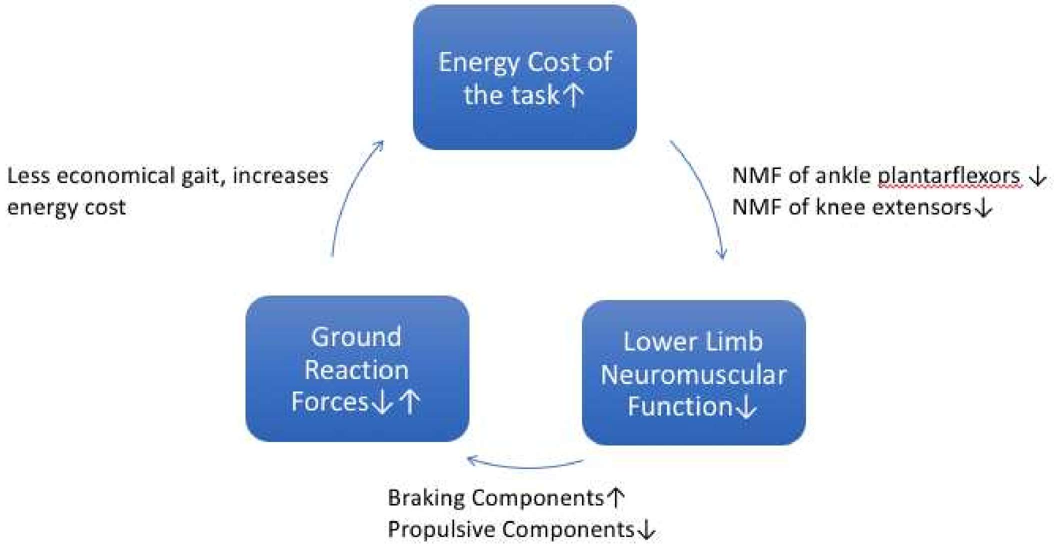
To date, few studies have explored the GRF results of prolonged load carriage at a forced march pace, while studies which have used fatiguing protocols prior to GRF measurement of short duration load carriage have used fatiguing protocols which are not transferable, in terms of muscle groups, contraction type and load magnitude.

The purpose of this thesis is to investigate participant responses to load carriage, using GRF, respiratory gas analysis NMF as principal measures. The aims of the experimental work will be to consider load carriage performance across multiple consecutive day performance. This will be achieved by using GRF, respiratory gas and NMF measures of performance.

Main thesis hypothesis

The aim of this thesis is to explore the link between the increase in energy cost of load carriage and reductions in neuromuscular function of the lower limbs. In order to do this, the main hypotheses for this thesis are that (1) prolonged load carriage instigates reductions in NMF, (2) reductions in NMF change gait (as observed by GRF), and (3) changes in GRF increases the energy cost of the task. This is presented graphically below, these hypotheses will be examined in the experimental chapters of this thesis.

Figure2.4. Graphical representation of thesis hypothesis.



3.1 General Methods

During the course of this thesis, both field and laboratory methods of data collection were utilised. In order to maintain clarity, this section will concern the laboratory based testing, discussed within chapters, 4, 5 and 6. While the field based methods employed in chapter 7 will be discussed in depth in that chapter.

All studies discussed were conducted from a post positivist perspective by employing an experimental design of randomised parallel groups supported by an unloaded walking control group. Observational study was conducted in the form of independent and repeated measures correlations. All studies in this thesis were conducted concurrently, with the data analysed in the order that the experimental chapters are presented.

3.2 Military Load Carriage Systems, loads and Rifle

The load Carriage System (LCS) used for the laboratory based studies in this research was the standard issue LCS ('90 Pattern). The '90 Pattern LCS comprises of a separate bergen (Military term for a large backpack) and webbing system. This was developed after the Falklands War where the previous LCS ('58 Pattern) was deemed inadequate, due to being uncomfortable and heavy. The '90 pattern was first issued in 1988 and has been in use ever since. More recently, changes to the original design have included MOLLE (Modular Lightweight Load-carrying Equipment) strap to allow a customisable design.

Other changes to military load carriage systems have occurred in the form of Osprey body armour which was created to the specific threats posed to soldiers in Afghanistan. However, as these are not on issue to the whole military, this thesis will focus on just the standard '90 Pattern LCS.

3.3 ’90 Pattern LCS

The standard LCS consists of two components, a bergen and the Personal Load Carriage Equipment (PLCE) waist webbing. The webbing is supported by the shoulder with a yoke and on the hips by a belt. The yoke is attached by straps to the webbing belt at six points. The webbing typically consists of three utility or water bottle pouches and two pouches for ammunition, however, personnel can and do modify the equipment to their individual requirements. The webbing contents consist of items needed to fight and survive, specifically, basic first aid kit, food, water and ammunition. Webbing can typically weigh 16kg when loaded with the necessary contents.

This study used the short-back bergen which is a backpack designed so that the base of the bergen sits on top of the webbing. The short back bergen hold a total volume of 120litres when the side pouches are attached and have an internal aluminium A-frame. The bergen has a hip belt to distribute the load from the shoulders on to the hips.

Standard operating procedures usually means that a ‘grab-sack’ commonly in the form of a day sack is kept at the top of the bergen, which contains mission essential items that the soldier would need to take in a hurry, such items as ammunition, radios and optics are heavy, making the bergen top heavy, an important consideration for exploring the ecological validity of studies in to load carriage.

3.4 Loads

During the laboratory based studies, the participants carried a load of 32kg which comprised of 15kg in a bergen, 10kg in webbing and a 7kg rifle, and were packed to reflect loads that would be carried during a military exercise. The load in the bergen was comprised of: Main compartment (bottom to top): trainers, socks (5) underwear (5), base layer top, base layer bottom, shirt, trousers spare mid-layer top, spare gloves and hat, 24hours rations, sleeping bag. Grab sack (Northern Ireland daysack) containing: warm layer (soft shell jacket), water .2l, bivvy bag, 5kg plate (representing ammunition), 1kg bar (representing weapon ancillaries, spare battery)24 hours rations. Left-hand pouch: towel (hand), wash kit, water 1l, poncho. Right-hand pouch: Gortex suit, gloves and hat. Outside: roll matt, bivvy poles. Any further changes to the total load were made by modifying the rations contained within the main compartment.

Figure 3.1 Short-back bergen contents carried by loaded participants, with webbing lower right

In terms of the load included in the webbing: 2kg weights were placed in the pouches to reflect having four loaded magazines, this means that the webbing was unbalanced with the left pouches being heavier than the right. The other webbing pouches consist of, 24hour rations and mess tins, two one-litre water bottle and tin mug, first aid kit, 20m para cord, weapons cleaning kit, 500ml thermos filled with water. This is a load that reflects what military personnel would carry in a temperate climate such as the UK. This load in conjunction with a rifle is the focus of this thesis.

Figure 3.2 The webbing with external load, three water bottles were filled with water

3.5 Backpack Fitting (Initial study to inform methods)

Introduction

Previous work has shown that lung function can be effected by backpack fit (Bygrave et al., 2004). However the paper used an absolute method of determining backpack fit which would have increased variance between the participants, furthermore the study examined differences in change scores which can over estimate changes. This study will examine whether backpack fit calculated relative to the participants body shape will affect lung function, as measured by forced voluntary contraction (FVC) and forced expiratory volume (FEV_1). Four variables of comfort fit, tight fit, lose fit and unloaded control will be assessed. Findings will be able to dictate whether participants should undergo the experimental studies with a standardised fit of the backpack or with a more ecologically valid approach of allowing the participants to fit their own backpacks accordingly.

Methods

Participants

Fourteen healthy volunteers took part in the study (8 male and 6 female (mean: range) 176.32:18.25cm, 75.45:31.23kg and 22:8 yrs). All participants gave consent before beginning the study, as part of the ethical process as approved by Canterbury Christ Church University research ethics committee. A screening questionnaire was completed by the participants, who were not able to take part in the study if they did not satisfactorily complete the questionnaire.

To participate in the study participants were required to meet the following inclusion criteria to ensure findings were based on a sample group comparable to the experimental chapters within this thesis:

- Participants must be between 18-32years old
- Participants must sufficiently complete a pre exercise physical activity questionnaire
- Participants must be taller than 163cm
- Participants must weigh more than 50kg

Procedures

Participants were given the opportunity to familiarise themselves to both the backpack and the spirometry testing through an unlimited number of trials prior to testing. Assessment was conducted using a spirometer (Vitalograph, UK) and consisted of four conditions in a randomised cross over design, by participants blindly drawing lots. Protocol followed methods previously employed by Cotes and Irvin (1994). Lung function measurements were made with the participants standing in an upright and relaxed position. In the first instance the participants were instructed to void all air from their lungs, as soon their lungs appear to be empty they are instructed to “breathe in quickly” and then to “blow out as hard and fast as you can”, they were instructed to stop when a steady decline in measures was observed, during which participants were given loud and continuous encouragement. The participants provide three breaths per condition and were given a minimum of two minutes recovery time before repeating the process. Anthropometric measurements were taken with a tape measure and segmometer (SECA, Germany).

Data analysis

Once data was checked for normality, a repeated measures ANOVA was used to identify significant differences between conditions for each of the lung function measurements. Statistically significant differences were accepted at an alpha value of 0.05. Pairwise post-hoc tests were carried out to establish specific differences between conditions and Bonferroni adjustments were used for multiple comparisons. G*Power was used to calculate a required sample size of 12 based on means and SDs taken from FEV^1 variables presented in previous research (Bygrave et al., 2004)

Bergen fitting

While the hip belt was fastened to sit comfortably over the participants clothing without pinching, the following equation was used to determine the strap lengths (cm):

$$cm = (C \times T) \times Y \tag{1}$$

Equation 3.1 Equation used to calculate backpack fit where C is the diameter in cm (under armpit) of the shoulder in line with the backpack strap, T is the length in cm between the suprailiac and the armpit and Y is the coefficient which determines fit (2.5, lose fit; 2 comfort fit; 1.5, tight fit).

Results

Table 3.1 Means and standard deviations of the lung function variables with significance

Variable	n	Unloaded	Tight	Loose	Comfort	p-Value
FEV1 ($L \cdot S^{-1}$)	14	4.30 (0.70)	4.06 (0.76)	4.32 (0.78)	4.23 (0.82)	0.109
FVC (L)	14	5.04 (0.75)	4.75 (0.71)	4.97 (0.76)	4.75 (0.99)	0.086

No significant differences were observed between conditions in Table 3.1 suggesting that when the fit is standardised to participants' anthropometric measurements there is no effect on lung function. As such within the laboratory based studies in this thesis, participants will be able to select their own backpack fit. This will increase the ecological validity of the work as anecdotally soldiers frequently change the positions of the fit during load carriage to mitigate sore and perceived tiredness and discomfort.

3.6 Boots and Clothes

Participants wore their own sports clothing, of shorts, shirt and trainers. It is acknowledged that the use of trainers may encourage different gait changes compared to boots, however, the use of trainers familiar to the participant reduces the risk of blisters developing. Participants were also instructed to wear natural wool socks, to again reduce the risk of blisters and a shirt with a collar to reduce any rubbing from the rifle strap. Participants were also offered zink-oxide tape and grannuflex.

Figure 3.3 A typically loaded participant

3.7 Participants Recruitment and Ethics

A verbal and written explanation was given to all the volunteer participants, at which time participants were invited to ask questions. Once participants satisfactorily completed health screening questionnaires to ensure that participants were fit and healthy to participate in the task and additionally ensuring that participants had no known musculoskeletal or neurological conditions that may have impaired their ability to undertake the testing, they were then invited to sign a consent form. Examples of the information sheet, and consent form can be seen in the appendix (1 and 2).

Participants were informed and reminded that they had the right to withdraw from the trial without needing to give a reason; they were also informed that they have a right to have their data removed at a later date. Ethical clearance was granted by Canterbury Christ Church University Ethics Committee for all pilot and experimental work undertaken (References: 15/SAS/243, 16/SAS/261, 16/SAS/264).

All work, planning, data collection, processing and analysis was conducted by the author and was conducted in line with the declaration of Helsinki (2013) and BASES guidelines (Winter et al., 2006) while the experimental chapters were presented in accordance with CONSORT guidelines (Schulz et al., 2010) where possible.

To participate in all the laboratory studies the participants were required to meet the following inclusion criteria in order to ensure participants were reflective of a recruit starting British military training(Allsopp and Shariff, 2003):

- Participants must be between 18-32 years old
- Participants must be free from musculoskeletal injury
- Participants must be free from musculoskeletal; disorder which may obviously alter gait
- Participants must sufficiently complete a pre exercise Physical Activity Readiness Questionnaire (PAR-Q)
- Participants must be taller than 163cm
- Participants must weigh more than 50kg

Participants were instructed to refrain from any vigorous physical activity, caffeine and energy drinks 24 hours prior to testing, and avoid food two hours prior to the commencement of exercise.

3.8 Sample Size Calculations

For each chapter initial sample size was based on subjective assessment of previous work within the field. Once the initial sample size was attained, sample sizes were calculated again using G*Power (G*Power; Germany). Using means and standard deviations drawn from the live data to confirm the studies were sufficiently powered, if they were not, further recruitment was conducted until sufficient sample size was achieved.

Sample Size: Chapter 4

In the first instance the sample size estimation was based on subjective assessment of acute GRFs based previous work (n=9 (Lloyd and Cooke, 2000a) and n=15 (Birrell et al., 2007)).

Follow on analysis used key variables taken from a review of the literature. Data collection was stopped when statistical power (+10%) was achieved for loading peak (6 participants per group), force minimum (12 Participants per group) and thrust maximum (6 participants per group).

Sample Size: Chapter 5

Initial sample sizes (n=10) were taken from a review of the literature, which demonstrated that sample sizes in load carriage research, tends to be between 10 and 32 participants (Fallowfield et al., 2012, Lloyd and Cooke, 2011, Rice et al., 2016).

Once the sample of n=10 was attained, follow on analysis used key variables to revaluate the sample size, and the likelihood of sufficient statistical power. Variables of focus were drawn from the previous chapters. Recruitment was stopped when sufficient sample size was met for the variables of knee extension 60◦s^{-1} maximum torque (n=9 participants per group) and knee extension 60◦s^{-1} average torque (n=11 participants per group).

Sample Size: Chapter 6

An initial sample of n=10 was assigned in line with previously reported studies which have reported metabolic variables during treadmill based load carriage (Blacker et al., 2009b).

Once this target was achieved metabolic variables were chosen for follow on power assessment as no research has examined the recovery profile of metabolic variables after one day of load carriage. The power of observing changes at d2 was observed to be achieved at n=7 or 10 participants before additional recruitment to account for drop out.

3.9 Participants and Training Effect

All civilians had experience of backpacking and had self-reported to be at least moderately active and moderately fit. Previous work which used similar recruitment methods (Blacker, 2009, Birrell, 2007) have noted that these participants are reflective of military recruits who would be in the early weeks of recruit training.

In the studies which involve prolonged load carriage during recruitment the physical demand of carrying a weighted bergen and webbing was highlighted to the participants, as such it is possible that this may have introduced bias, given that people undergoing load carriage may be stronger than a general population pool, however, military recruits will also have made a conscious effort to enter military training. Indeed, they will have trained to meet minimum physical requirements and as such may be more inclined towards being able to deal with physical discomfort.

3.10 Walking Speed

A walking speed of 6.5km·h^{-1} (1.78m·s^{-1} or 3.98mile·h^{-1}) was selected as the target speed for the treadmill based studies, as this represents the speed used in previous literature (Harman et al., 2000, Martin and Nelson, 1986, Blacker, 2009). This is the pace which is required to achieve 12.8km in 2hours whilst carrying 32kg to complete a combat fitness test (CFT; 25kg in a daysack or bergen, and 7kg rifle) which is a tool used to assess the basic combat readiness of British troops. It must also be acknowledged that an average of 6.5km·h^{-1} may not be a true reflection of the pace at which a CFT is completed with troops often walking slower on flat and up-hill gradients but increasing the pace to a jog on the down hill. Such coping strategies are not possible during the treadmill protocol.

A constant march pace was used during the treadmill protocol in order to maintain steady state performance while maintaining ecological validity, as during exercises soldiers walk at a pace dictated by the instructing staff. Other options for inducing fatigue were non-specific protocol such as unloaded vertical jumps (Gefen, 2002) which may have fatigued systems and muscles not used during load carriage. The second method, is a best effort loaded march, where participants attempt to complete the trial in the shortest possible time (Polcyn et al., 2002), it is likely that this would provide greater than normal stress on central systems and would again not be reflective of a field based environment, while precluding the ability to observe steady state exercise.

3.11 Treadmill

All laboratory tests were undertaken on a motorised, belt treadmill (Woodway ELG: USA). The treadmill user system controlled the speed of the treadmill to the nearest 0.1km·h^{-1} and the gradient was kept at 0% for all testing in keeping with the previously discussed literature. The belt width was 70cm with a level walking surface length of 244cm. Speed calibrations were conducted prior to the data collection phase and the gradient was confirmed to be 0% by the use of a spirit level.

3.12 Treadmill Speed Calibration

Speed calibrations were performed at speeds of 4.7, 5.4, 5.7, and 6.5km·h^{-1}. These speeds reflect the speed of the treadmill in the laboratory based studies.

In order to calibrate the treadmill an identifiable mark of retroflective tape was placed on the treadmill in order for a whole revolution of the treadmill belt to be observed by a 2D camera at 32Hz (Olympus TG3, JA).

Measurements were taken with a participant on the treadmill, loaded with a bergen representing 32kg (loaded condition), with the participant with no bergen on (unloaded condition) and with no participant on the treadmill (empty condition). Quintic software (Quintic V21, UK) was used to measure the time for the treadmill to complete 20 full revolutions, from which belt speed was calculated using the equation below:

$$Belt\ Speed\ \left(km.\hbar^{-1}\right) = \frac{\left(\left(\left(\frac{R*BL}{T}\right)*60\right)*60\right)}{1000} \tag{2}$$

Equation 3.2 Equation used to calculate treadmill speed where R represents the number of rotations, BL represents the belt length in cm and T represents time.

Table 3.2 Treadmill speeds for calibration

Display speed ($km{\cdot}h^{-1}$)	Loaded Actual Speed ($km{\cdot}h^{-1}$)	Unloaded Actual Speed ($km{\cdot}h^{-1}$)	Empty Actual Speed ($km{\cdot}h^{-1}$)
4.70	4.71	4.75	4.72
5.50	5.50	5.53	5.51
5.70	5.73	5.71	5.72
6.50	6.51	6.52	6.53
6.70	6.72	6.72	6.73

Visual inspection of the data summarized in table 3.2 showed the treadmill to be accurate with the largest deviation shown to be $0.05km{\cdot}h^{-1}$.

3.13 Preliminary Measures

Stature (Seca, Seca Ltd., Birmingham, UK) (± 0.005m) and body mass (Seca Model 880, Seca Ltd., Birmingham, UK) (± 0.01 kg) were measured whilst wearing underwear.

3.14 Dynamometry

In order to achieve accurate knee assessment participants were seated in the test chair of a Biodex System 3 Pro (Biodex: New York: USA), seatbelt-like straps were used to ensure that the participants hip and knee were secured at 90° confirmed by goniometer measurement. During all measurements the right limb was tested. The Biodex knee attachment arm was attached to the dynamometers point of rotation. The dynamometers point of rotation was lined to the participant's lateral femoral epicondyle. The right leg was chosen for all measurement to ensure comparison to previous research (Blacker, 2009) and to maintain consistency with the GRF measurements. The dynomometer has previously been shown to be reliable in similar testing (Drouin et al., 2004).

The set up followed BASES guidelines, with the exception of placing the left leg behind a restraining webbing strap to limit a countermovement swing. The participants were instructed to place their arms across their chest. The participant's range of motion was restricted by mechanical stops at self-selected limits.


[redacted]

Figure 3.4 The setup position for all knee extension and flexion measurements

Participants were instructed to undergo the entire protocol at a submaximal pace (self-perceived 30% effort) to familiarise the participant with the speed and feel of the test protocol. In order to achieve accurate ankle assessment participants were seated in the chair and secured with straps. The thigh supporting attachment was used to ensure a hip angle of approximately 80° and a knee angle of approximately 170°, again the right limb was used at all points with the lateral malleolus aligned to the dynamometers axis of rotation.

The test protocol consisted of maximal voluntary isometric knee extension and flexion and then one set of eight maximal contractions of the knee extensors and flexors at speeds of $60°s^{-1}$ and $180°s^{-1}$. These angular velocities were chosen to allow comparison to previous studies (Blacker, 2009).

The ankle placement was set in accordance with BASES guidelines, the ankle test protocol consisted of maximal voluntary isometric dorsi and plantarflexion followed by one set of eight maximal contractions of the ankle during dorsi and plantar flexion at speeds of 60°s^{-1} and 120°s^{-1}. The 120°s^{-1} velocity was chosen as pilot work showed participants were not able to achieve higher velocities during the isokinetic contractions, while the 60°s^{-1} was again chosen to be comparable to previous work (Clarke et al., 1955).

A rest of 60 or 30 seconds occurred between each exercise parameter and a rest of 120seconds occurred between knee and ankle contractions. The protocol is explained in the figures below.

Figure 3.5 Testing order for knee dynamometry testing

Knee Flexion/Extension
(0° s^{-1}) Isometric Flexion
30s Rest
(0° s^{-1}) Isometric Extension
60 Sec Rest
(8x60° s^{-1}) Isokinetic Knee Flexion and Extension
30s Rest
(8x180° s^{-1}) Isokinetic Knee Flexion and Extension

Figure 3.6 Testing order for ankle dynamometry testing

Ankle Dorsiflexion and Plantarflexion
(0° s^{-1}) Isometric Dorsiflexion
30s Rest
(0° s^{-1}) Isometric Plantarflexion
60 Sec Rest
(8x60° s^{-1}) Isokinetic Ankle Dorsiflexion and Plantarflexion
30s Rest
(8x120° s^{-1}) Isokinetic Ankle Dorsiflexion and Plantarflexion

The testing order was chosen as it has been observed that when participants who have a limited experience of isokinetic and isometric dynamometry are tested, higher reliability scores are observed when lower rotation speeds are used first (Wilhite et al., 1992).

3.15 Data Treatment and Analysis

MVC score force isometric contractions were considered the single highest recorded value taken from exported from raw .txt files.

For the isokinetic contractions, VBA code was used to highlight the start and end of each repetition, then for each repetition the highest torque value registered was extracted from each of the eight repetitions on the condition that the target velocity was attained. The highest of the eight values were presented as the “maximum” score, while the highest five out of eight values were averaged to be presented as the “average” score. This method of averaging was chosen as it was frequently observed that participants took three trials to present accurate and reliable results, however during data analysis it was highlighted that a small number of participants achieved higher velocities early in the first three repetitions, this method allowed for both events to be accurately portrayed.

Joint angle specific torques were calculated, as they more accurately define any change in torque in relation to muscle length (Baltzopoulos and Brodie, 1989). These were again extracted from .txt files using VBA code, which extracted the torque value depending on angle and velocity conditions.

3.16 Ground Reaction Forces

GRFs were measured using a Kistler multichannel force platform (Dimensions: 60cm by 90cm) (Type 9287B, Kistler Instruments, Switzerland) sampling at 500Hz and captured using Bioware

3.0 software (V5.3.0.7, Switzerland). The platform was embedded flush with the laboratory floor, with a 20m run way to allow a natural gait pattern. The target speed throughout was $6.5km \cdot h^{-1} \pm 5\%$ replicating the pace during final load carriage assessment of British Army infantry training (Rayson et al., 2000). Participants were instructed to "walk across the platform until instructed to stop", in order to stop the participant from modifying their gait to meet the data collection parameters. A trial was deemed successful if the speed was attained, the participant's foot struck cleanly on the force plate and if a natural gait pattern was maintained.

Observed variables were calculated and extracted using custom written VBA code, from the unfiltered data. The scores from each of the five trials were averaged to provide the final output variable.

The calculated variables are presented in table 3.3, all variables were normalised to body weight (BW). For chapters 5 and 6 the day 1 pre-test body weight measurement was used. Analysis of the complete data in chapter 5 demonstrated that normalisation to each measurement or from the first measurement point did not change the significance of the findings. Rates were calculated from 0.035seconds either side of the single highest point to point increment on the curve. This method was chosen as it most closely reflects the true maximal rate of the curve.

Table 3.3 The GRF variables calculated

Variable	Description
Loading Peak	Highest value recorded during the loading phase
Force Minimum	Lowest value recorded between force minimum and thrust maximum
Thrust Maximum	Highest value recorded during the push off phase
First Positive Rate	Highest rate to loading peak
Second Positive Rate	Highest rate between force minimum and thrust maximum
First Negative Rate	Lowest rate between loading peak and force minimum
Second Negative Rate	Lowest rate after thrust maximum
Total Vertical Impulse	Total area under the vertical curve
Maximum Braking Force	Lowest recorded AP value
Maximum Propulsive Force	Highest recorded AP value
Braking Impulse	Total area under braking curve
Propulsive Impulse	Total area under propulsive curve
Mediolateral Maximum	Highest ML value
Mediolateral Minimum	Lowest ML value
Mediolateral Amplitude	The difference between mediolateral maximum and mediolateral minimum

3.17 Respiratory Gas

In order to observe any change to metabolic steady state expired respiratory gases were measured via continuous breath-by-breath analysis using an automated online metabolic cart (Oxycon Pro, CareFusion: USA), the cart has previously been demonstrated to be a valid and reliable instrument for measuring such parameters during exercise at Canterbury Christ Church University (Saunders et al., 2013).

The gas analyser and turbine were serviced annually. Calibration of the gas analyser and turbine was conducted before each testing bout. The gas analyser was calibrated using certified standardised gases of a known composition and the turbine was calibrated using a 3L syringe.

All data from the cart ($\dot{V}O_2$, $\dot{V}CO_2$, HR) were interpolated and averaged over 10second intervals. Data was screened for anomalies, by removing any value that was 3 Standard Deviations away from the mean.

Data is presented as $\dot{V}O_2$ normalised to the first BW measurement which was collected, again, the data in chapter 5 was compared via a number of methods of normalization and no change in significance was observed as a result of different time points. When appropriate the data is presented as estimated energy expenditure, to attempt to correct for substrate use using the following formula.

$$EE = \left(\left(\frac{\dot{V}O_2}{BW}\right) \times BW\right) \div 1000 \times kcal \tag{3}$$

Equation 3.3 Equation used to calculate estimated energy expenditure, adapted from (Kenney et al., 2015)

Chapter 4: Biomechanical and Physiological Changes During Acute Military Load Carriage

4.1 Introduction

There have been a few studies within published literature in which both physiological and biomechanical changes have been presented simultaneously (Coombes and Kingswell, 2005, Harman et al., 2008, Bennett et al., 2013). However, few have attempted to explore relationships between biomechanical and physiological measures such as movement economy (Lloyd and Cooke, 2011, Schiffman et al., 2009) and $\dot{V}O_{2max}$ (Bennett et al., 2013) and none using military load carriage systems. These association studies provide a mechanistic insight into changes which occur during load carriage, as Quesada et al. (2000) highlighted excessive knee extensor fatigue may occur during load carriage, even when the task was conducted at metabolic levels which were unlikely to induce fatigue, suggesting peripheral fatiguing factors were instigating the reduction in performance. While Bennett et al. (2013) observed that as $\dot{V}O_2$ increased so did GRF first positive rate, suggesting a positive relationship between $\dot{V}O_2$ and force loading during walking suggesting that as the energy demand of the task increase the participants ability to mitigate impact forces is also reduced.

Previous studies have explored the acute biomechanical effects of military load carriage, observing changes in the mediolateral impulse which are contrary to those observed during civilian load carriage (Birrell and Haslam, 2010). It has been suggested that the magnitude and distribution of the mass within the bergen results in the CoM of the pack being positioned further away from the participants body when compared to civilian equivalents, increasing the moments experienced and requiring changes in gait to occur to maintain stability (Birrell and Haslam, 2010). This is supported by Simpson et al. (2012) who observed changes in muscle activation as load position was changed. Furthermore, the orientation of a military load, carried across multiple items such as rifle, bergen and webbing, may be an influencing variable as it is indicated that rifle carriage affects gait and GRF, specifically increasing the mediolateral movement (Birrell et al., 2007). These alterations from basal gait may influence movement economy, as it is long established that the body naturally assumes the most economical gait pattern (Lloyd and Cooke, 2000b). The actual implications of these changes are relatively unknown and it is unclear what mechanisms instigate these changes.

Ground reaction forces have previously been shown to be related to running economy. Specifically, it has been observed that a reduction in AP braking forces can facilitate the forward advancement of the body during running (Ciacci et al., 2010), while reductions in force minimum suggest increased knee flexion, which in turn has been shown to relate to reduced running economy (Mizrahi et al., 2000). Saunders et al. (2004) discuss that increased vertical impulse be correlated to increased running economy. It is likely that these finding will transfer to a load carriage setting given that load carriage has previously been shown to elicit similar responses to prolonged running (Rice et al., 2016).

Previous studies have shown that strength, particularly lower limb strength can be used as a predictor of load carriage performance (Dziados et al., 1987, Mello et al., 1988), it is likely that this correlation is due to stronger participants being able to mitigate the effect of the load and therefore maintaining a normal gait pattern. This chapter will explore this link further by exploring relationships between participant strength and gait markers in the form of GRFs.

This will be the first study to explore the acute relationship between GRFs and movement economy using an occupationally relevant load carriage system. Therefore, the aim of this chapter is to explore the associations between the biomechanical and physiological changes associated with acute military load carriage of weapon, webbing and bergen, compared to unloaded walking for identification in follow up research.

The study will aim to achieve the following objectives:

1) Explore whether load carriage instigate changes in VGRF and APGRFs
2) Investigate whether load carriage instigate changes to the mediolateral ground reaction forces (MLGRFs)
3) Observe associations between movement economy and VGRFs
4) Explore lower limb strength correlation to movement economy during military load carriage.

Hypothesis

The study will examine the primary hypothesis that load carriage will instigate a statistically significant increase in VGRFs at loading peak, thrust maximum and force minimum. Secondary hypotheses which will be addressed are (1) movement economy will be significantly associated to VGRFs and (2) lower limb strength will be significantly correlated to movement economy.

4.2 Methods

Trial Design

This chapter employs an experimental, parallel groups design with a control group.

Participants

A total of 33 healthy participants (25 male, 8 female) provided their informed consent to take part in the study. All participants had previous experience of walking with backpack loads. Participants were matched on the basis of gender, stature, mass, NMF strength and age. No differences between groups were observed when assessed by T-test.

Table 4.1 Table presenting participant descriptive data.

Group	Body Mass (kg)	Stature (cm)	Age (yrs)	Males	Females
Loaded	77.63 (33.26)	179.76 (17.54)	25.(7)	12	4
Unloaded	75.21 (26.84)	165.42 (17.31)	27 (8)	13	4

Means presented in table with range presented in brackets.

Experimental Protocol

Participants were given the opportunity to familiarise themselves to the treadmill, force platform, dynamometer and load carriage systems prior to the testing session. The study involved participants being tested during the second visit to the lab. The participants were allocated to the loaded or unloaded group randomly by drawn lots. Testing was completed in the following order; preliminary tests, dynamometry, gait analysis and a 15min treadmill walk during which expired gasses are collected in the last 2 minutes.

The protocol used to undertake the preliminary tests, dynamometry, gas analysis, HR, gait analysis and treadmill walk are explained in chapter 3.

Interim Analysis

No interim analysis was conducted due to the acute nature of the study.

Environmental Conditions

Environmental temperature and humidity were monitored. No differences in environmental temperature were observed during testing (18.65˚C:2.64 ˚C) and 50.32%:9:32%).

Statistical Analysis

SPSS for windows version 23 (SPSS, Chicago: USA) and Excel (Microsoft: USA) was used for statistical analyses. Distribution of the data was assessed using Shapiro Wilk test for normality, no violations of normality were observed. Subsequently, differences between groups were assessed using independent group T-tests with an alpha level set at 0.05. Classical probability testing was supported by confidence intervals set to 90% in line with progressive best practice principals (Nakagawa and Cuthill, 2007, Hopkins et al., 2009, Schulz et al., 2010, Batterham and Hopkins, 2006).

Cohen's d (d_{cohen}) and Glass' d (dGlass) were used to examine the effect size of any significant difference between means. Two effect size measurements were used as Glass' d uses standard deviation drawn from the control condition while Cohen's d uses a pooled standard deviation, as such any difference between outcomes can be a guide to individual differences in response. However such differences should only be used an estimate of individual difference.

Relationships between any variables were examined using Pearson correlations. With qualitative descriptors defined by Cohen (1988).

Before change scores were compared and GRF were normalised to BW the data were log transformed and plotted to ensure that it did not violate the previously proposed scaling guidelines (Nevill et al., 1992, Davies and Dalsky, 1997, Atkinson and Batterham, 2012).

4.3 Results

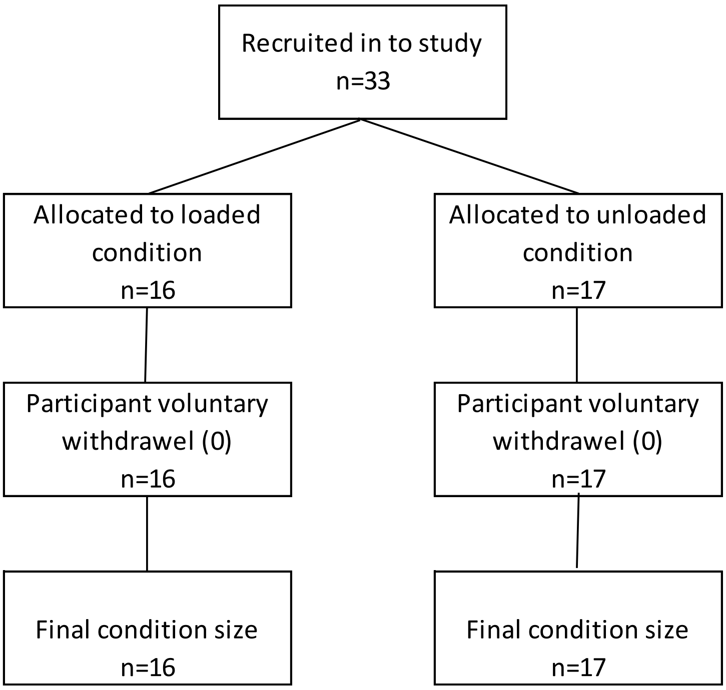
Adverse Events

No participants were harmed or injured while partaking in this study. No risk to the participants or researchers was experienced throughout the study.

Sample Size Profile

Recruitment was stopped when sample sizes were met, no participants dropped out at any stage of testing. Suspected failure of the Oxycon Pro means metabolic analysis was completed on n=32, while the inability to record the first positive rate on four participants meant that analysis was completed on n=29. All other analysis was completed on n=33. Correlations were completed on n=12 for first positive rate and n=16 for all other parameters, as they only considered the loaded participants in the first instance. Sample size calculations are presented in chapter 3.

Figure 4.1 Flow diagram displaying participant drop out



Vertical Ground Reaction Forces

Table 4.2 Mean vertical GRF parameters presented with effect sizes, confidence intervals and SD

Variable	Group	n	Lower CI	Mean(SD)	Upper CI	d_{Cohens}	d_{Glass}	p-Value
Loading Peak	**Unloaded**	**17**	**1.32**	**1.37 (0.11)**	**1.41**	**1.66**	**4.49**	**<0.0001**
	Loaded	**16**	**1.79**	**1.87 (0.21)**	**1.96**			
Force Minimum	**Unloaded**	**17**	**0.45**	**0.48 (0.10)**	**0.52**	**1.14**	**1.80**	**<0.0001**
	Loaded	**16**	**0.59**	**0.66 (0.15)**	**0.72**			
Thrust Maximum	**Unloaded**	**17**	**1.13**	**1.17 (0.10)**	**1.21**	**1.62**	**3.94**	**<0.0001**
	Loaded	**16**	**1.50**	**1.58 (0.18)**	**1.65**			
First Positive Rate	**Unloaded**	**17**	**6.12**	**8.56 (4.91)**	**11.00**	**1.11**	**1.69**	**0.023**
	Loaded	**12**	**10.91**	**16.9 (8.85)**	**22.83**			
Second Positive Rate	**Unloaded**	**17**	**4.84**	**6.03 (2.98)**	**7.23**	**0.94**	**1.04**	**0.005**
	Loaded	**16**	**7.92**	**9.13 (2.93)**	**10.34**			
First Negative Rate	Unloaded	17	-8.79	-7.5 (3.14)	-6.20			0.161
	Loaded	16	-10.35	-9.08 (3.09)	-7.80			
Second Negative Rate	**Unloaded**	**17**	**-14.85**	**-13.15 (4.24)**	**-11.45**	**1.35**	**1.53**	**<0.0001**
	Loaded	**16**	**-20.76**	**-19.66 (2.66)**	**-18.56**			

Magnitude variables are expressed as BW, while rates are explained as BW·S^{-1} and impulses are presented as BW·S. Bold text represents significance between groups to $p<0.05$.

Substantial significant changes were observed, the reader is directed to the large differences between effect sizes of the force variables in table 4.2, while the lack of change of the first negative rate will be discussed further in this chapter.

Anteroposterior Ground Reaction Forces

Table 4.3 Mean anteroposterior GRF parameters presented with effect sizes, confidence intervals and SD

Variable	Group	n	Lower CI	Mean(SD)	Upper CI	d_{Cohens}	d_{Glass}	p- Value
Max Braking Force	**Unloaded**	**17**	**-0.35**	**-0.33 (0.05)**	**-0.31**	**1.08**	**1.82**	**p<0.0001**
	Loaded	**16**	**-0.47**	**-0.43 (0.10)**	**-0.39**			
Max Propulsive Force	**Unloaded**	**17**	**0.27**	**0.29 (0.05)**	**0.31**	**1.57**	**2.59**	**p<0.0001**
	Loaded	**16**	**0.39**	**0.41 (0.05)**	**0.43**			
Braking Impulse	Unloaded	17	-0.07	-0.06 (0.02)	-0.05			0.487
	Loaded	16	-0.06	-0.06 (0.01)	-0.06			
Propulsive Impulse	**Unloaded**	**17**	**0.04**	**0.05 (0.02)**	**0.05**	**0.70**	**0.58**	**0.043**
	Loaded	**16**	**0.05**	**0.06 (0.01)**	**0.06**			

Magnitude variables are expressed as BW and impulses are presented as BW·S. Bold text represents significance between groups to $p<0.05$.

Mediolateral Ground Reaction Forces

Table 4.4 Mean mediolateral GRF parameters presented with effect sizes, confidence intervals and SD

Variable	Group	n	Lower CI	Mean(SD)	Upper CI	d_{Cohens}	d_{Glass}	p-Value
Medial Maximum	Unloaded	17	-0.09	-0.07 (0.03)	-0.06			0.282
	Loaded	16	-0.07	-0.06 (0.02)	-0.06			
Lateral Maximum	Unloaded	17	0.07	0.08 (0.02)	0.08			0.597
	Loaded	16	0.07	0.08 (0.03)	0.09			
Medial Impulse	Unloaded	17	-0.01	-0.01 (0.00)	0.00			0.338
	Loaded	16	-0.01	0.01 (0.01)	0.00			
Lateral Impulse	**Unloaded**	**17**	**0.04**	**0.05 (0.02)**	**0.06**	**0.71**	**0.59**	**0.038**
	Loaded	**16**	**0.06**	**0.06 (0.01)**	**0.06**			
ML Impulse	Unloaded	17	-0.01	-0.06 (0.01)	0.00			0.177
	Loaded	16	-0.01	-0.07 (0.01)	0.00			
ML Ratio	Unloaded	17	0.13	0.15 (0.04)	0.17			0.682
	Loaded	16	0.13	0.15 (0.03)	0.16			

Magnitude variables are expressed as BW and impulses are presented as BW·S. Bold text represents significance between groups to *p*<0.05.

Temporal Ground Reaction Forces

A significantly longer stance time was observed in the load carriage group (0.578±0.040s to 0.621±0.040s); this was accompanied by increases in absolute time for time to loading peak 11% (*p*=0.08), force minimum (8%, *p*<0.01), thrust maximum (7%, *p*<0.01), maximum braking force (16%, *p*<0.05) and maximum propulsive force (7%, *P*<0.01). However, when the times are normalised to stance time there are no differences between groups. The only exception was the time between medial and lateral peak, which increases from 22.66% to 30.09% (*p*<0.05) signified by no change in time to medial peak but an increase in time to lateral peak from 30.66% to 46.34% (*p*<0.05) for the loaded group.

Neuromuscular Function

MVC and dynamic scores are presented in the table below, while there is a trend suggesting higher scores in the loaded group, no significant difference was observed between the groups for any variable.

Table 4.5 Mean and maximum strength values presented with SD

	Contraction	Max Score		Mean Score	
Joint action	($°s^{-1}$)	Loaded	Unloaded	Loaded	Unloaded
Knee extension	180	144.8 (65.4)	135.8 (65.2)	139.2 (34.5)	128.8 (33.3)
	60	204.8 (87.8)	173.3 (42.8)	191.6 (71.3)	167.9 (41.5)
	0	244.2 (78.4)	233.3 (67.1)		
Knee Flexion	180	87.2 (33.3)	76 (28.6)	76.8 (30.3)	66.5 (26.1)
	60	102.2 (31.6)	92.1 (31.9)	85.4 (29.9)	77.3 (26.8)
	0	95.7 (31.3)	95.9 (30.3)		
Ankle Plantarflexion	120	46.1 (17.6)	50.8 (22.6)	41.6 (16.3)	46.8 (22.7)
	60	71 (16.8)	72.8 (19.8)	65.9 (16.2)	66.9 (19.6)
	0	98.7 (37)	84.7 (22.8)		
Ankle Dorsiflexion	120	14.9 (4.7)	12.6 (6.1)	12.4 (4.3)	9.8 (5.7)
	60	22.9 (5.9)	18.8 (6.0)	19.2 (5.5)	15.5 (6.3)
	0	24.3 (12.1)	18.9 (11.3)		

All measurements are in N·M, with standard deviations in brackets

No significant differences were observed between the strength scores in any of the measures displayed in table 4.5. However loaded participants showed a trend to being stronger than unloaded participants.

Respiratory Gas and HR

Table 4.6 Mean metabolic parameters presented with effect sizes, confidence intervals and SD

Variable	Group	n	Lower CI	Mean(SD)	Upper CI	d_{Cohens}	d_{Glass}	p-Value
HR	**Unloaded**	**16**	**92**	**100 (15)**	**107**	**1.37**	**1.82**	**p<0.001**
	Loaded	**16**	**118**	**127 (15)**	**135**			
EE	**Unloaded**	**16**	**5.53**	**6.00 (1.10)**	**6.40**	**1.40**	**1.64**	**p<0.001**
	Loaded	**16**	**8.00**	**9.20 (1.70)**	**9.47**			
$\dot{V}O_2$	**Unloaded**	**16**	**15.63**	**16.32 (1.70)**	**17.02**	**2.58**	**4.20**	**p<0.001**
	Loaded	**16**	**22.27**	**23.61 (3.10)**	**24.95**			

Bold text signifies significance to $p<0.05$.HR is presented as Beats·min^{-1}, EE is presented as cal·kg·min^{-1} and $\dot{V}O_2$ is presented as ml ·kg·min^{-1}.

Significant changes were observed for all three measurements, with large effect sizes for all variables displayed in table 4.6. Effect sizes were larger when control standard deviations were examined, suggesting larger variation within the data.

Associations

Lower Limb Strength, GRF and Estimated Energy Expenditure (EE)

Statistically significant relationships were observed between EE and ankle plantarflexion at 60°s^{-1} max (r= -0.47, VE=18%, $p<0.05$) and mean (r= -0.53, VE=28%, $p<0.05$) and near significance for 120°s^{-1}max (r= -0.42 VE=21%, $p=0.13$), while no significant correlation was observed in the ankle dorsiflexors or knee flexors. Statistically significant relationships were also observed between the knee extensors at isometric maximum (r= -0.46, VE=21%, $p<0.05$) and near significance for 60°s^{-1} maximum (r= -0.40, VE=16%, $p=0.11$) and mean (r= -0.43, VE=18%, $p=0.13$) and at 180°s^{-1} mean (r= -0.42, VE=17%, $p=0.11$) in relation to EE. First positive rate was shown to be significantly related to EE (r=0.75, VE=27%, $p<0.01$).

Associations Between Strength and GRF Variables.

Relationships were observed between knee extensors and braking impulse (180°s^{-1}, r=0.44, VE=19%, p<0.05; 60°s^{-1}, r=0.43, VE=19%, p<0.05). Correlations were also observed between ankle dorsiflexors and braking impulse (0°s^{-1}, r= -0.66, VE=44%, p<0.01 , 120°s^{-1}, r= -0.71, VE=51%, p<0.001 and 60°s^{-1}, r= -0.50,VE=26%, p<0.05) and between braking maximum and ankle dorsiflexors (0°s^{-1}, r=-0.53,VE=28%, p<0.05, 120°s^{-1}, r= -0.54,VE=29%, p<0.05 and 60°s^{-1}, r=-0.57, VE=32%,p<0.01).

Secondary Analysis

Secondary analysis was considered once it became clear that there was no progressive effect of the load for VGRF values.

Table 4.7 Mean estimated vertical GRF parameters when corrected for the static effect of load

Variable	n	Unloaded (SD) (N·BW)	Loaded (SD) (N·BW)	d_{Cohens}	d_{Glass}	P-Value
Loading Peak	33	1.37(0.11)	1.45 (0.21)			0.587
Force Minimum	**33**	**0.48(0.10)**	**0.23 (0.15)**	**1.44**	**2.64**	**p<0.0001**
Thrust Maximum	33	1.17(0.10)	1.15 (0.15)			0.639

Table 4.7 displays estimates of VGRF when the mass of the bergen was removed before the data was normalised to BW, providing an estimate of the impact forces based on the assumption of a proportional relationship between impact force and external load. Consequently, no difference was observed between groups for estimated loading peak and estimated thrust maximum while a large difference in SD remained between groups. Lower estimated VGRF at force minimum in the loaded group was observed significant to p<0.001, again a large SD change was observed in the loaded group, however, the change is supported by large effect sizes.

4.4 Discussion

The current study observed increases in the VGRF of loading peak, force minimum and thrust maximum, in agreement with the first hypothesis, however this section will discuss that these increases are not proportional to the magnitude of the external load. Furthermore this study observes correlations between VGRFs and movement economy and lower limb strength and movement economy in agreement with the secondary hypotheses. Finally, the study observes correlations between VGRF and lower limb strength providing support for the main thesis hypothesis that there is a mechanistic gait involvement to energy cost during load carriage.

The current study observed increases in VGRF parameters in agreement with previous research, specifically, loading peak, force minimum and thrust maximum (Birrell et al., 2007, Kinoshita, 1985, Bennett et al., 2013). It is widely accepted that repeated impacts over prolonged periods expose participants to overuse injuries (Knapik, 2001) and that increases in VGRF parameters are commonly accepted as markers of overuse injury risk (Christina et al., 2001, Ferber et al., 2002, Zadpoor and Nikooyan, 2011).

Previous work has shown that increases in VGRF parameters and APGRF parameters are proportional to the external load carried up to at least 40%BM (Birrell et al., 2007, Lloyd and Cooke, 2000a). When the mass of the load was removed before normalisation to BW, loading and thrust maximum peaks corroborated these findings. However, a previously unidentified significant reduction was observed in the force minimum. This is a novel finding as it had previously been assumed that the increase in VGRF was principally a result of the static mass of the load, as opposed to accelerative forces on the system (Birrell et al., 2007). These findings provide further support for the growing amount of literature suggesting that increased knee flexion is occurring during the stance phase, supporting the findings of Rice et al. (2016) and earlier research groups

(Kinoshita, 1985, Polcyn et al., 2002, Silder et al., 2013).

Increased knee flexion may be explained by the accelerative force of the bergen, the result of protective changes attempting to mitigate the effect of the load by lowering the bodies CoM to increase stability (Rice et al., 2016), or as a protective mechanism by reducing the impact of the load by increasing the time to decelerate the load (Polcyn et al., 2002). EMG studies have explained that the knee extensors act eccentrically to resist the effects of the load early in the stance phase to control knee flexion before the ankle plantar flexors act concentrically towards the end of the stance phase contributing to push off (Winter and Yack, 1987). These findings so far are in agreement with Rice (2016) who states that walking whilst carrying an external load is more physically demanding than unloaded walking, requiring greater demands of the knee and ankle musculature. As such prolonged load carriage is likely to instigate fatigue within these muscle groups. Gefen (2002) presented that changes in knee extensor moments provide evidence of a reduced ability of the quadriceps muscles to dissipate energy. Meaning a longer duration of time is required to decelerate the load and therefore increasing knee flexion. The secondary effect is that this increased flexion and fatigue may result in increased demand on other parts of the kinetic chain, as such this may increase the magnitude or rate of fatigue development in the plantarflexor muscles as they may have to assume a greater burden of the load carriage (Harman et al., 2000, Rice et al., 2016).

When APGRFs are considered, this study is not in agreement with previous work (Kinoshita, 1985, Lloyd and Cooke, 2000a) which suggest that the increase in AP variables are proportional to the static effect of the bergen, however it must be acknowledged that analysis of the presented literature it is not clear how the authors came to their conclusion. As once the static effect of the load is corrected for, a non-significant increase in braking force and a statistically significant reduction in propulsive force was observed, suggesting that the lower limb structure is exposed to more force than just the static vertical load. Furthermore it is commonly accepted that forward lean of the trunk occurs as a result of load carriage (Lloyd and Cooke, 2000a), this forward lean increases torque around the hips, due to gravity acting to a greater extent on the forward leaning trunk, this would suggest that less propulsive force is required to propel the system forward. Once again Rice et al. (2016) observed greater dorsiflexion moments and range of motion, suggesting increased demand on the plantarflexors and would suggest that push off force is mediated by the effect of the load.

These findings mean that in response to the first research objective, load carriage does instigate changes to VGRF and APGRFs. This study has been able to further suggest that such increases in load through the system instigate stress on muscle groups such as the knee extensors and ankle dorsiflexors. This change may instigate an increased workload on the knee extensors during prolonged exercise.

This study observed a significant increase in stance time in agreement with Rice et al. (2016) who observed significantly increased stance time as a result of load carriage and partial agreement with previous work (Lloyd and Cooke, 2000a, Kinoshita, 1985) which observed non-statistically significant increases in stride length and as such it is likely that this increase in stance time occurs in order to mitigate the effect of the vertical mass of the load by increasing the time over which the load is decelerated, signified by the lack of change in first negative rate, while all other rates significantly change and the significant increase in time to force minimum.

Differences between groups were observed in the lateral impulse, this may be due to the military nature of the load and rifle carriage, as carrying a rifle inhibits the participant's normal arm swing, while placing an additional load on the anterior of the body. It is likely that the lateral impulse elevation suggests that there is a consistent change in gait, as opposed to an acute change in stability. These findings are supported by Birrell and Haslam (2009) who observed a similar effect when comparing unloaded walking with and without a rifle.

No significant change in lateral maximum or time to lateral maximum was observed, suggesting that while gait has changed as a result of load carriage it may only have a marginal effect on the participant's stability when considered acutely, this is accompanied by a small effect size. These findings are broadly in agreement with previous studies as most studies report no meaningful change, or do not report ML variables (Lloyd and Cooke, 2000a, Kinoshita, 1985, Kinoshita and Bates, 1981).

In response to the second research objective, this study has observed a small change in lateral impulse, possibly as a result of rifle carriage. Given that prolonged load carriage typically involves repetitive movements, it is possible that this may have a cumulative effect over the duration of the prolonged activity. However, a large number of ML variables observed no change, so it is not possible to discuss these findings with any certainty, further research should be conducted to see if prolonged load carriage may alter these changes.

Large inter-participant variation is likely in this study, signified by greater effect sizes among many parameters in the loaded group than in the control group. Suggesting that the response represented in the sample mean data may not be representative of the response by individual participants. While this variation around the mean can make interpretation of mean trends difficult, it suggests that there may be a difference in response to load carriage from different participants. This is pertinent when markers such as loading peak (d_{Glass}=4.49) and first positive rate (d_{Glass}=1.69) are both shown as markers of injury risk of lower limb stress fracture (Polcyn et al., 2002, Cavanagh and Lafortune, 1980, Birrell et al., 2007, Knapik, 2001) and display significantly different effect sizes, when pooled and control based effect sizes are considered. These findings suggest that some members of the sample are placed at significantly higher risk of injury.

The same effect is observed in metabolic measures, where large differences are observed by the use of d_{Cohen} which uses a pooled SD while extremely large effect sizes were observed by the use of a controlled SD (d_{Glass}=4.20) suggesting that some participants are exposed to greatly different challenges. In an applied setting, this could mean some soldiers or hikers, require substantially different energy intakes or pacing strategies than their peers, which is not accounted for and could place the participants at greater injury risk. At this time it is unclear what may account for this difference in response; however correlations between knee flexor and ankle dorsiflexor strength scores and braking maximum and braking impulse suggest that differences in strength may have an effect on gait economy during loaded walking; these differences in participant strength may have an effect on the SDs of the values. While this chapter focuses on acute responses to load carriage, it has previously been demonstrated that load carriage instigates a reduction in NMF (Clarke et al., 1955) as such it is reasonable to hypothesize that such changes may instigate a negative change in APGRF parameters, meaning over a prolonged load carriage task soldiers may be placed under increaseing GRF stress.

In response to the third research objective, there were no significant correlations observed between any VGRF value and EE. As discussed in chapter 2, research exploring GRF and running economy has produced varied responses. It is likely that the acute nature of this study was not able to elicit stress high enough to instigate a change in GRF forces, which could be related to EE. As such future research should try and modify GRF in order to see if it has any effect on EE over a load carriage task.

Small relationships were observed between GRF parameters, energy expenditure and movement economy. Larger inverse relationships existed between ankle plantarflexors and knee extensors and energy expenditure, this is unsurprising given the role of the plantarflexors during the propulsive phase and the role of the knee extensors in mitigating knee flexion during mid-stance. In conclusion to the fourth research objective, this study suggests that strength is correlated to movement cost. These findings suggest that stronger participants are likely to be protected from fatigue under load carriage conditions; however it is not possible to draw further conclusions from these findings given the acute nature of this study.

4.5 Conclusions

This study has demonstrated a number of novel and significant findings; it is the first study to suggest that externally carried load has a greater effect on the lower limb system than the effect of the static mass alone. It has also demonstrated that there is a link between GRF parameters associated with injury risk and neuromuscular function. This is worthy of further study when it is considered that previous research suggests participants experience reductions in NMF as a result of load carriage.

This study demonstrated that load carriage instigates small changes to lateral impulse, possibly due to the effect of a carried rifle. It is possible that reduction of NMF may also increase ML changes, and instigate instability in the lower limb system, given the demonstrable relationship between metabolic and GRF parameters. Due to the capacity of prolonged load carriage to manipulate NMF, it is likely that a study designed with a high likelihood of manipulating NMF will instigate a change in GRF parameters.

Finally, this study observed large inter-participant variation, suggesting that the effect of the load may affect participants differently, possibly due to the absolute mass the participants are required to carry. This is significant as it means participants may be exposed to different levels of work during prolonged load carriage tasks.

This chapter has highlighted that increased energy cost occurs as a result of acute load carriage, it has also highlighted that a number of GRF variables and participant strength may account for this change. However due to the short duration of the trials, it has not been possible to manipulate these variables to assess whether they do have an impact on energy cost. As such the next chapter will use prolonged load carriage to manipulate variables with the aim of highlighting GRF predictors of energy cost.

Chapter 5: Biomechanical and Physiological Changes as a Result of Two Hours Treadmill Load Carriage

5.1 Introduction

The previous chapter demonstrated that externally carried loads cause a number of acute changes in gait, which are commonly cited as markers for injury risk (Saunders et al., 2004, KyrÖlÄinen et al., 2001). Furthermore, the neuromuscular strength of the ankle plantarflexors correlated to braking impulse and braking maximum and strength of the knee extensors correlated to relative $\dot{V}O_2$. As such it appears logical that if NMF were to be reduced, as a result of load carriage, then the GRFs which the participant experiences may change. Change of NMF via prolonged load carriage may highlight further mechanistic changes to GRF gait pattern. Given these changes occur acutely in response to the application of load, and the evidence that these loads are frequently carried over prolonged periods (Orr, 2010), investigation of the impact of prolonged load carriage is merited.

Reduced NMF has been observed in the knee extensors up to 72 hours after 2 hours treadmill load carriage (Blacker et al., 2013), while Clarke et al. (1955) observed reduced plantar flexor output as a result of a similar load carriage task. As discussed in the previous chapter, it is possible that external load carriage instigates a distal move of muscular contribution to load carriage. Whereby the increased effort required during force attenuation and unloading to mid-stance does not completely halt the load during mid-stance, resulting in increased work from the ankle plantarflexors which instigates reduced NMF output of the muscles (Rice et al., 2016).

The previous chapter observed that for a number of critical markers such as $\dot{V}O_2$, loading peak and thrust maximum, there were substantially greater standard deviations for the load carriage group compared to the unloaded group, suggesting that there was individual variation within the data. It therefore could be proposed that participant’s injury risk should be seen as individualised when carrying loads for a prolonged period of time. This has implications in an applied setting, as participants are exposed to differing injury risk and energy cost, requiring substantially different physical training programmes and associated dietary requirements, despite the assumption of the cohort being homogeneous.

To date, all research which has explored load carriage has considered analysis via differences in means, which has served to demonstrate the physiological demands involved within load carriage. However, this approach fails to acknowledge that while soldiers are frequently required to complete similar tasks, such as load carriage as a group, at the same speed and load as their peers, they do not have the same physiological characteristics and as such may respond differently. Physiological differences between participants have been shown to predict load carriage performance in regression models (Simpson et al., 2006, Rayson et al., 2000), when researchers have attempted to develop physical selection criteria for military training. Despite this no current research as explored any role of biomechanical changes within predictive models of $\dot{V}O_2$ change.

During submaximal steady state exercise such as treadmill based load carriage increases in metabolic measures such as HR or $\dot{V}O_{2,}$ have been observed. The possible mechanisms behind this have previously been discussed in chapter 2. Load carriage has previously been demonstrated to instigate $\dot{V}O_{2drift}$ over 120 minutes of treadmill walking (Blacker, 2009, Mullins et al., 2015). However, while Mullins et al. (2015) observed no change in standard deviations, analysis of the data presented by Blacker (2009) suggests notable increase in standard deviation of the $\dot{V}O_2$ SD between groups and as a result of time, suggesting large individual variance within the data. As such this study will in the first instance be a repeatability study exploring whether standard deviation does increase with prolonged load carriage, while in the second instance attempting to explore mechanisms for this change.

This chapter will be the first study to assess alteration in GRF as a result of prolonged load carriage. It will examine individual differences as a result of load carriage and will attempt to further explore links between physiological and biomechanical determinants of load carriage. Furthermore it will investigate whether the previously observed reductions in NMF of the knee extensors and ankle plantarflexors are related, the study will aim to further explain the effect this has on injury risk to the performer by studying the changes in relation to GRF variables and studying the effect it has on energy cost variables by explaining its relationship to $\dot{V}O_2$.

This will be the first study to examine knee extensor and flexor NMF at multiple joint angles, this will provide an extra insight into the muscle function. It has previously been shown that during some fatiguing exercise the angle of peak torque can change, this would not be observed during normal peak value testing. Moreover it enables conclusions to be drawn about the joint position which experiences greater NMF loss. While there is no research exploring the measure it is logical that muscle groups will experience NMF loss at joint positions which most commonly reflect the angles used during locomotion.

Research Objective

1) Explore whether prolonged load carriage instigates a reduction in ankle plantarflexor NMF via reduction of knee extensor NMF
2) Examine whether prolonged load carriage instigates change in GRF variables which are considered markers for injury
3) Consider whether individual differences in neuromuscular variables mean participants are exposed to variations in energy costs
4) Explore whether participants experience different neuromuscular and energy cost during apparently identical load carriage tasks

Hypotheses

This chapter will explore the primary hypothesis that there is a statistically significant reduction in ankle plantarflexor NMF output as a result of two hours treadmill load carriage. Secondary hypotheses are that (1) reductions in NMF output of the ankle and knee extensors and flexors can be significantly correlated with changes in VGRF variables, (2) reductions in NMF can be significantly correlated with increases in $\dot{V}O_2$ and (3) changes in GRF can be significantly correlated with increases in $\dot{V}O_2$.

5.2 Methods

Trial Design

This chapter employs an experimental, parallel independent groups design with a control group, measurements were taken before and after a load carriage task.

Participants

Voluntary, informed consent was collected from 32 healthy participants. All participants had recreational experience of carrying backpacks and were recruited from Canterbury Christ Church University.

Table 5.1 Table presenting participant descriptive data.

Condition	Body Mass (kg)	Stature (cm)	Age (yrs)	Males (n)	Females (n)
Loaded	76.45 (27.12)	178.56 (17.63)	23(6)	13	3
Unloaded	73.69 (24.19)	178.89 (18.49)	22(5)	14	4

Mean values presented with range presented in brackets

Participants consumed water with no restrictions during the treadmill protocol, which reflected the occupational military setting. The bottle from which the water was drunk was not carried within the load carriage system and was weighed in order to estimate water intake and sweat loss.

While every effort was made to recruit participants in an even fashion, explanation of the study involved that the load is substantial, as such it is possible that the finally recruited participants may be stronger than a true reflection of the population as discussed in chapter 3.

A number of participants voluntarily withdrew of the loaded group due to the physical discomfort of the task, while no participants withdrew from the unloaded group. It is possible that this may also have resulted in physically more robust participants completing the loaded protocol than the unloaded. Despite this, while there was a trend towards the loaded group being stronger, there were no statistically significant differences between the loaded and unloaded groups.

Experimental Design

All aspects of this research were conducted by the author in the sport and exercise laboratories at Canterbury Christ Church University. Participants walked on a level motorised treadmill (Woodway ELG, Birmingham, UK) for 120minutes, at 6.5km$\cdot$h^{-1}(0% gradient).

The loaded group consisted of a 32kg external load spread across, webbing (10kg), bergen (15kg) and a dummy rifle (7kg), this load was chosen as it reflects the load carriage system which would be carried during occupational military tasks. During the task, participants wore their own walking boots, shirt, and shorts. Participants were advised to wear a polo neck shirt to avoid the rifle sling rubbing the neck causing skin sores.

Before and after the treadmill protocol participants underwent preliminary measurement, dynamometry, and gait analysis, the protocols followed those described in chapter 3. Metabolic measurements were taken every 30 minutes during the load carriage task following the guidelines laid out in chapter 3.

During the load carriage activity, the participant's HR was monitored at 30 minute intervals. Participants were withdrawn if they voluntarily declared themselves unable to complete the task or if they became unable to maintain the walking speed required.

Neuromuscular Function

Participants completed the muscle testing protocol presented in chapter 3 before commencing treadmill walking (baseline) and post treadmill walking. The test order was the same on each occasion and conducted at approximately the same time of day (early morning) to control for diurnal variation in the force producing capabilities of the muscles (Sedliak et al., 2008).

This chapter used an additional measure of NMF. Raw exported data was processed via Excel VBA to allow interpretation of torques at individual joint angles during the isokinetic testing. Analysis was only conducted on maximum values due to the increased range of motion this allowed. Additionally, the analysis only concerned torque values which were collected at the target velocity to maintain the reliability of the data. The range of measurement was not large enough to examine ankle data, so only knee extension and flexion data are analysed.

Knee joint angle was defined as the internal measurement of the knee angle. For example, if the leg is fully extended the angle would be 0°, while a seated position would present a joint angle of roughly 90° (appendix 3).

Environmental Conditions

Environmental temperature and humidity were monitored during all the testing period. No differences in environmental temperature were observed during testing (Mean: Range), with a temperature of 18.73:2.76°C and humidity 50.05:9.35%.

Statistical Analysis

SPSS for windows version 23 (SPSS, Chicago, USA) and Excel (Microsoft: USA) were used for statistical analyses. Distribution of the data was assessed using the Shapiro-Wilk test for normality, if any time points were found to be violation of normality, then a non-parametric test was also run. In all circumstances T-tests were shown to be robust enough to withstand any violation of normality. Subsequently differences between groups were assessed using independent group T-tests with an alpha level set at 0.05. Classical probability testing was supported by confidence intervals set to 90% in line with progressive best practice principals (Nakagawa and Cuthill, 2007, Hopkins et al., 2009, Schulz et al., 2010, Batterham and Hopkins, 2006). Correlation coefficients were calculated using the repeated measures correlation within subjects method defined by Bland and Altman (1995).

Analysis of the NMF at joint angles was examined by three-way ANOVA of the change scores once normality was confirmed. Post hoc pairwise analysis was conducted to confirm the significant differences at individual joint angles.

Before change scores were compared and GRF were normalized to BW the data was log transformed and plotted to ensure that it did not violate the scaling guidelines proposed by (Nevill et al., 1992, Davies and Dalsky, 1997, Atkinson and Batterham, 2012).

Effects sizes were presented as both d_{Cohen} and d_{Glass}. Due to the use of pooled standard deviations and the unloaded groups standard deviation used in $d_{Glass.}$ Presenting them in this way allows for an estimation of whether there are any individual differences in the responses. The primary measure of individual differences was conducted using standardised standard deviations from as adapted from Hopkins (2015). Qualitative thresholds were taken from Smith and Hopkins (2011).

5.3 Results

Adverse Events

No participants experienced long term injury as a result of this study. However, six participants experienced blisters on their feet as a result of the load carriage protocol. While three participants noted hotspots due to rubbing on their shoulders and hips due to the load carriage equipment. Fifteen participants stated they experienced muscle soreness, however, all said it was less than they would experience as a result of other forms of frequent physical activity.

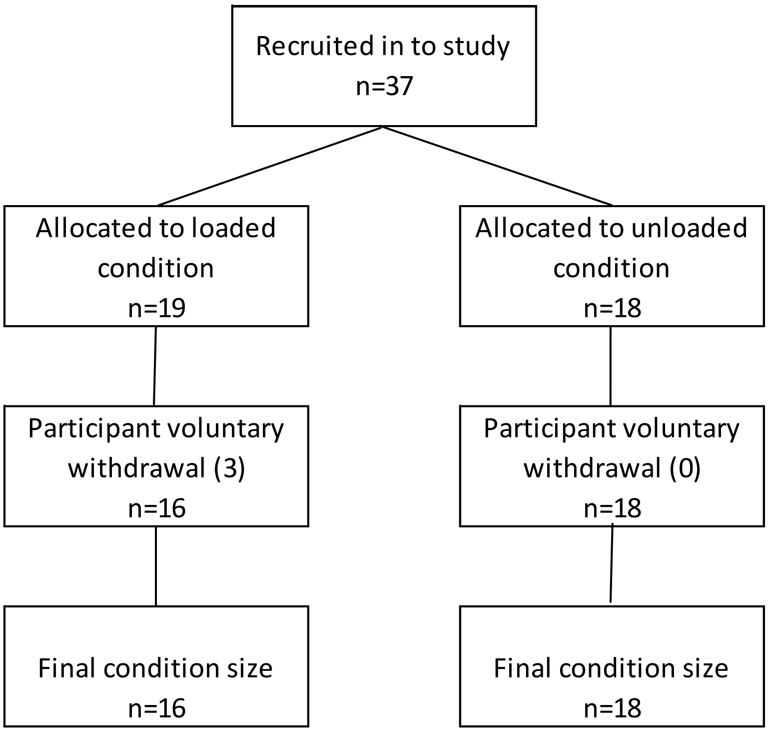
Grannuflex and zink-oxide tape were provided to the participants during and after the study, and the participants were advised to wear polo neck shirts. Participants reported that these were very useful in mitigating the skin sores.

Sample Size Profile

Three participants failed to complete the load carriage task, these consisted of two females and one male. All three participants stated the reason for withdrawal was excessive pain across their shoulders as a result of the load.

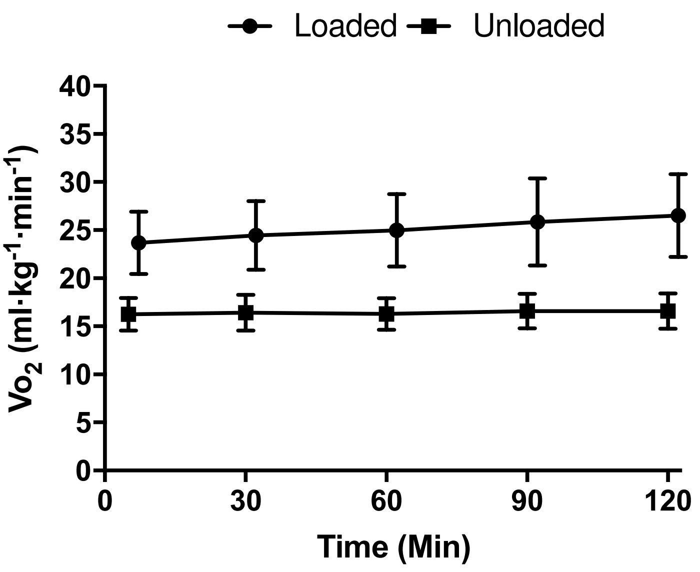
Inability to record the first positive rate on four participants meant that analysis was completed on n=29. All other analysis was completed on n=33. Correlations were completed on n=12 for first positive rate and n=16 for all other parameters.

Figure 5.1 Flow diagram displaying participant voluntary withdrawal



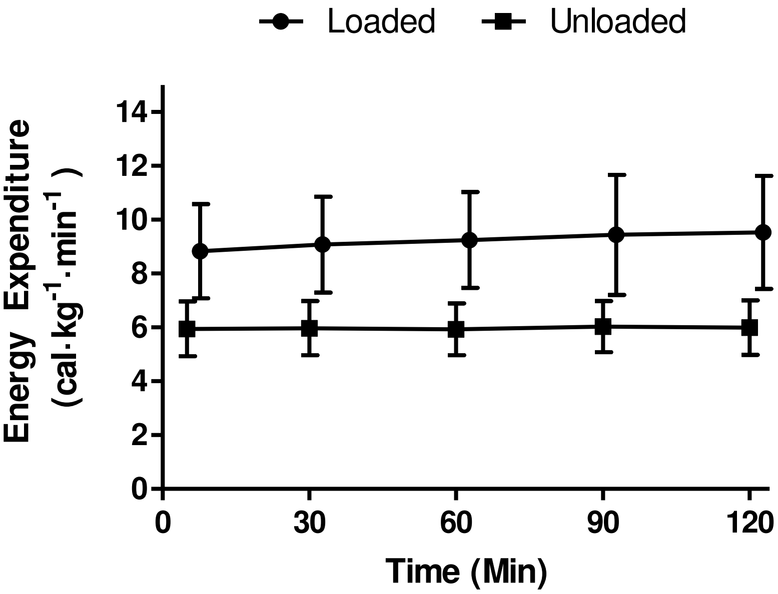
Expired Gas Analysis

Figure 5.2 $\dot{V}O_2$ values for all time points measured



$\dot{V}O_2$ was significantly ($p < 0.001$) higher for the loaded group at all measurements from baseline ([10min] 23.67±3.26ml·kg·min^{-1} (25.12, 22.25) to completion ([120min] 26.5±4.32ml·kg·min^{-1} (28.48, 24.53)) compared to the unloaded scores from 10min (16.26±1.7ml·kg·min^{-1}, CI (16.93, 15.6)) to 120min (16.57±1.85ml·kg·min^{-1} (17.28, 15.85)). This was supported by significantly greater drift ($p < 0.001$) in scores from the first to last measurement for the loaded group (10.41±7.53ml·kg·min^{-1} CI (13.87, 6.97)) compared to the unloaded group (1.86±3.54ml·kg·min^{-1} CI (3.23, 0.49)) explained by effect sizes of d_{Cohen}=1.2 and d_{Glass}=2.4 classifying the effect as 'large', as there is a difference between the two equations, individual differences will be assessed.

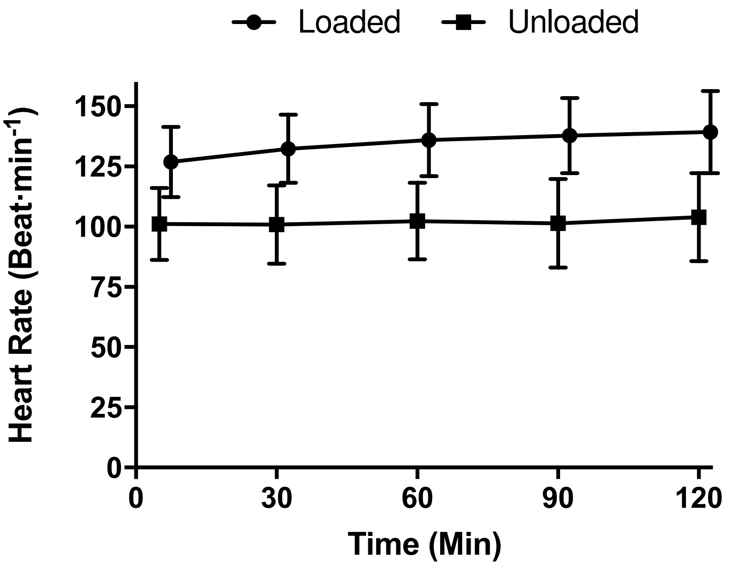
Figure 5.3 EE values at all time points measured



Means are presented alongside standard error bars.

EE in figure 5.3 follows a similar trend to $\dot{V}O_2$ with a significant univariate effect with the unloaded group experiencing lower EE ($p<0.001$), with a baseline (10min) of 5.95±1.02cal·kg·min^{-1}, CI (6.34, 5.55) to completion (120min) at 5.99±1.01cal·kg·min^{-1}, CI (6.38, 5.60). The loaded group experienced statistically significant drift as a result of the task ($p<0.001$) from baseline (8.83±1.75cal·kg·min^{-1}, CI (9.60, 8.06)) to completion at 120min (9.54±2.10cal·kg·min^{-1}, CI (10.50, 8.58), the change was explained by effect sizes of 1.78d_{Cohens} and 3.51d_{glass}.

Figure 5.4 HR values for all time points measured



Means are presented alongside standard error bars

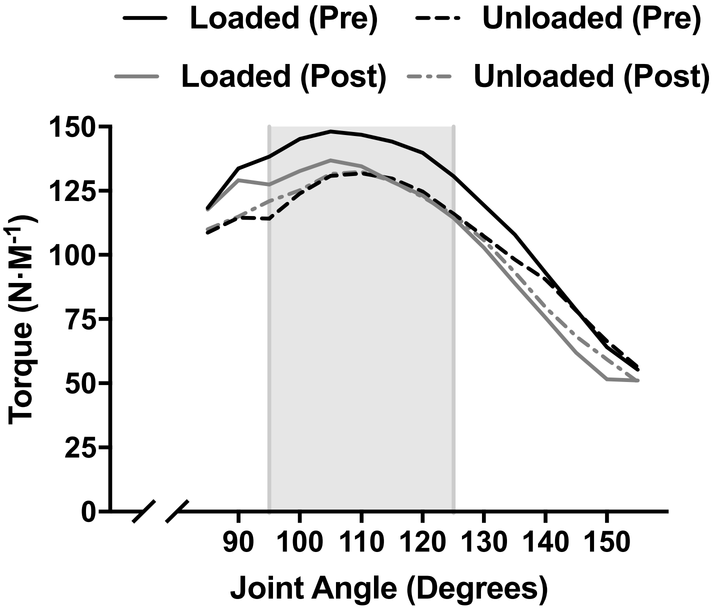
Similar elevated response was observed for the loaded group compared to unloaded in HR from baseline (101±15beats·min^{-1} CI (108, 93) and 127±15beats·min^{-1} CI (135, 118) to completion (103±17beats·min^{-1} CI (113, 94) and 139±18beats·min^{-1} CI (149, 129)), which resulted in a statistically greater ($p<0.05$) drift for loaded participants (9±7beats·min^{-1} CI (13, 6) compared to 2±1beats·min^{-1} CI (6, -1) supported by large effect sizes (d_{Cohen}=0.93 and d_{Glass}=0.96).

At baseline $\dot{V}Co_2$ was observed to be significantly ($p<0.05$) elevated for loaded participants (unloaded: 13.94±1.20ml·kg·min^{-1} CI (14.57, 13.32), loaded: 20.98±1.6ml·kg·min^{-1} CI (22.37, 19.6)) however no drift was observed temporally. This characterises a change in RER while no significant difference was observed in RER at baseline (loaded: 0.88±0.04, to unloaded 0.85±0.04) change scores show that RER was significantly reduced to 0.86±0.03CI (0.87, 0.83) and 0.81±0.05CI (0.83, 0.79) for the loaded group over unloaded.

Individual differences were assessed for $\dot{V}O_2$ (Upper SDCI, SD_{ir}, Lower SDCI) (8.60, 6.47, 3.20) and $\dot{V}Co_2$ (8.80, 6.70, 3.20) which allow the calculation of standardised standard deviations of 23.97 for $\dot{V}O_2$ and 13.6 classifying individual variability of the sample as ‘extremely large’ (>2) for both values.

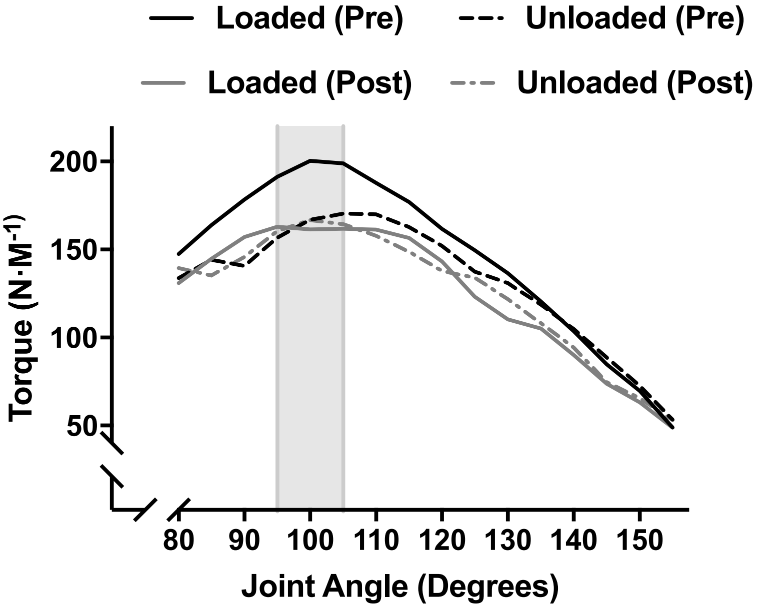
Neuromuscular Function

Figure 5.5 The torque curve during knee extension at 180°s^{-1}



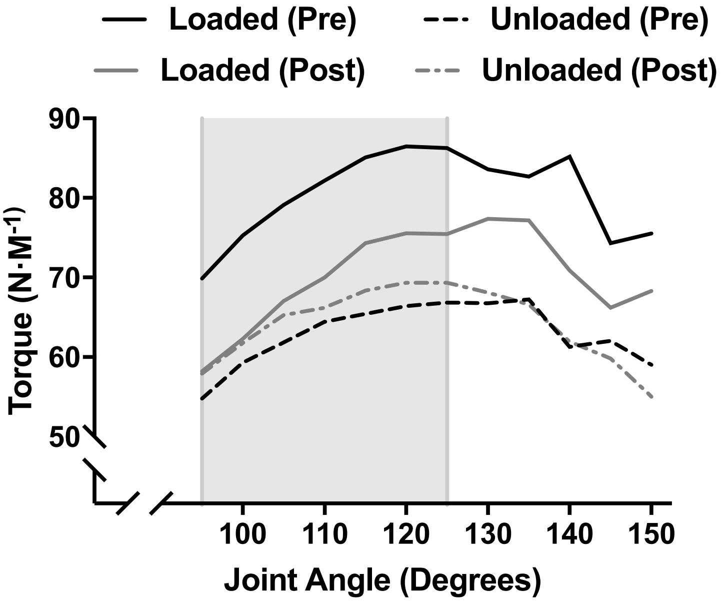
Grey area represents joint angles (95°-125°) shown to display an interaction effect and pairwise difference to at least $p<0.05$. Standard error bars are not presented to aid clarity, the supporting data can be observed in appendix 4.

Figure 5.6 The torque curve during knee extension at 60°s^{-1}



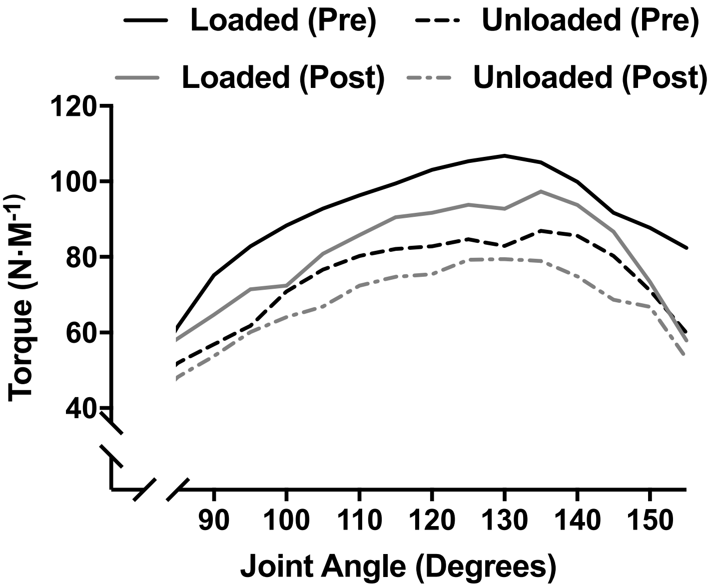
Grey area represents joint angles (95°-105°) shown to display an interaction effect and pairwise difference to at least $p<0.05$. Standard error bars are not presented to aid clarity, the supporting data can be observed in appendix 5.

Figure 5.7 The torque curve during knee flexion at 180°s^{-1}



In figure 5.7 the grey area represents joint angles (95°-125°) shown to display an interaction effect and pairwise difference to at least $p<0.05$. Standard error bars are not presented to aid clarity, the supporting data can be observed in appendix 6.

Figure 5.8 The torque curve during knee flexion at 60°s^{-1}



There is no significant interaction observed. Standard error bars are not presented to aid clarity, the supporting data can be observed in appendix 7.

In table 5.2 17 participants completed the unloaded protocol and 16 completed the loaded protocol, however some participants were not able to achieve the target velocity so were excluded from the analysis. Large effect sizes were observed for all significant variables displayed in table 5.2, with each measure displaying larger sizes for d_{Glass} than d_{Cohens}.

Table 5.2 Means, change scores and CI's for knee NMF values supported by their significance and effect sizes

Variable		Group	n	Lower CI	Baseline (SD) (N·M)	Upper CI	Lower CI	Change(SD) (%)	Upper CI	p-Value	d_{Cohens}	d_{Glass}
Knee Flexion 180°s^{-1}	**Max**	**Unloaded**	**17**	**63.59**	**74.65 (28.44)**	**85.71**	**-1.63**	**4.64 (16.10)**	**10.90**	**0.008**	**1.00**	**1.11**
		Loaded	**16**	**78.89**	**98.12 (41.77)**	**117.35**	**-16.26**	**-9.81 (14.62)**	**-3.36**			
	Average	**Unloaded**	**17**	**61.26**	**71.96 (27.52)**	**82.67**	**-2.18**	**4.52 (17.24)**	**11.22**	**0.008**	**1.00**	**1.10**
		Loaded	**16**	**73.91**	**92.02 (39.34)**	**110.13**	**-17.79**	**-10.91 (15.6)**	**-4.03**			
Knee Flexion 60°s^{-1}	Max	Unloaded	17	79.39	91.93 (33.29)	104.46	-11.14	-5.9 (13.49)	-0.65	0.350		
		Loaded	16	94.07	112.09 (39.15)	130.12	-15.69	-10.34 (12.14)	-4.99			
	Average	Unloaded	17	75.34	86.66 (30.06)	97.98	-10.30	-4.89 (13.91)	0.52	0.154		
		Loaded	16	88.20	105.76 (38.19)	123.32	-17.99	-12.22 (13.07)	-6.45			
Knee Flexion 0°s^{-1}	Max	Unloaded	16	41.33	90.06 (29.53)	138.79	-23.86	0.27 (10.19)	23.59	0.248		
		Loaded	16	86.92	101.34 (32.68)	115.75	-12.01	-5.78 (13.74)	0.45			
Knee Extension 180°s^{-1}	**Max**	**Unloaded**	**17**	**124.77**	**138.01 (34.04)**	**151.25**	**-1.97**	**0.87 (7.31)**	**3.71**	**p<0.0001**	**1.19**	**1.57**
		Loaded	**16**	**133.26**	**153.80 (45.82)**	**174.34**	**-14.91**	**-10.62 (9.72)**	**-6.34**			
	Average	**Unloaded**	**17**	**117.29**	**130.16 (33.09)**	**143.03**	**-2.00**	**2.12 (10.61)**	**6.25**	**0.009**	**0.97**	**1.06**
		Loaded	**16**	**127.73**	**146.52 (41.80)**	**165.31**	**-14.22**	**-9.12 (11.57)**	**-4.01**			
Knee Extension 60°s^{-1}	**Max**	**Unloaded**	**17**	**166.65**	**180.78 (36.33)**	**194.91**	**-6.65**	**-2.17 (11.53)**	**2.32**	**0.010**	**0.81**	**1.12**
		Loaded	**16**	**172.15**	**214.29 (91.96)**	**256.43**	**-21.25**	**-15.07 (14.00)**	**-8.90**			
	Average	**Unloaded**	**17**	**156.64**	**172.83 (39.98)**	**187.74**	**-5.92**	**-2.24 (9.46)**	**1.44**	**0.022**	**0.74**	**1.04**
		Loaded	**16**	**157.33**	**195.00 (75.74)**	**226.29**	**-17.73**	**-12.08 (12.81)**	**-6.43**			
Knee Extension 0°s^{-1}	**Max**	**Unloaded**	**17**	**108.44**	**225.22 (70.91)**	**342.22**	**-15.97**	**0.84 (14.62)**	**16.81**	**0.005**	**0.96**	**1.25**
		Loaded	**16**	**221.08**	**269.9 (110.71)**	**318.72**	**-17.94**	**-11.88 (14.13)**	**-5.83**			

Bold text represents significant interactions at $p<0.05$.

Table 5.3 Means, change scores and CI's for ankle NMF values supported by their significance and effect sizes

Variable		Group	n	Lower CI	Baseline (SD) (N·M)	Upper CI	Lower CI	Change (SD) (%)	Upper CI	p-Value	d_{Cohens}	d_{Glass}
Ankle Dorsiflexion 120°s^{-1}	Max	Unloaded	16	9.52	11.93 (22.87)	14.33	-9.93	-1.04 (22.85)	7.85	0.409		
		Loaded	16	13.23	15.9 (5.82)	18.57	-18.78	-6.42 (28.01)	5.93			
	Average	Unloaded	16	8.53	10.75 (24.10)	12.98	-14.69	-2.85 (30.46)	9.00	0.224		
		Loaded	16	12.22	14.7 (5.44)	17.17	-27.11	-12.19 (33.83)	2.73			
Ankle Dorsiflexion 60°s^{-1}	Max	Unloaded	16	16.88	18.83 (6.32)	20.79	-2.20	7.26 (24.32)	16.72	0.647		
		Loaded	16	21.58	23.98 (5.35)	26.39	-9.23	0.08 (21.11)	9.39			
	Average	Unloaded	16	15.88	17.76 (5.80)	19.64	-2.43	7.15 (24.61)	16.72	0.617		
		Loaded	16	19.69	21.92 (5.02)	24.15	-6.45	2.19 (19.6)	10.84			
Ankle Plantarflexion 120°s^{-1}	Max	Unloaded	16	42.05	50.94 (20.22)	59.84	-2.69	6.11 (22.62)	14.90	0.076		
		Loaded	16	41.97	50.51 (18.64)	59.04	-19.61	-13.60 (13.62)	-7.60			
	Average	Unloaded	16	38.26	46.76 (20.94)	57.00	-5.12	-1.58 (9.10)	1.96	0.052		
		Loaded	16	37.83	45.53 (17.29)	53.73	-16.86	-10.97 (13.36)	-5.08			
Ankle Plantarflexion 60°s^{-1}	**Max**	**Unloaded**	**16**	**64.52**	**72.38 (4.73)**	**80.25**	**-10.55**	**-2.54 (20.60)**	**5.48**	**0.042**	**1.09**	**0.63**
		Loaded	**16**	**69.19**	**77.12 (18.64)**	**85.05**	**-21.77**	**-15.16 (15.01)**	**-8.54**			
	Average	**Unloaded**	**16**	**59.17**	**67.21 (4.66)**	**75.45**	**-4.55**	**2.80 (18.91)**	**10.16**	**0.045**	**0.92**	**0.62**
		Loaded	**16**	**65.24**	**70.61 (16.85)**	**79.57**	**-21.14**	**-14.58 (14.86)**	**-8.03**			
Ankle Plantarflexion 0°s^{-1}	**Max**	**Unloaded**	**14**	**30.77**	**77.57 (28.36)**	**124.37**	**-36.62**	**7.04 (26.46)**	**50.70**	**0.004**	**0.99**	**0.89**
		Loaded	**16**	**96.95**	**113.4 (37.29)**	**129.85**	**-26.63**	**-19.91 (6.61)**	**-13.18**			

Bold text represents significant interaction effects at $p < 0.05$. 17 participants completed the unloaded protocol and 16 completed the loaded protocol, however some participants were not able to achieve the target velocity and one failed to complete the protocol so were excluded from the analysis.

Table 5.4 Individual differences, SD confidence intervals and standardised standard deviations

Variable	S_{dir}	SD Upper CI	SD Lower CI	Standardised SD	Qualitative Description
Knee Flexion 180°s^{-1} Max	9.66	18.94	-13.11	2.24	Extremely Large
Knee Flexion 180°s^{-1} Average	9.23	10.28	-4.83	2.17	Extremely Large
Knee Extension 180°s^{-1} Max	6.41	0.77	-6.43	0.69	Large
Knee Extension 180°s^{-1} Average	4.62	0.51	-9.26	0.51	Large
Knee Extension 60°s^{-1} Max	7.94	14.43	-9.07	0.90	Large
Knee Extension 60°s^{-1} Average	8.64	13.70	-6.21	0.98	Large

Extremely large standardised SD were observed for both measures of knee flexion displayed in table 5.4, while all other measures showed large standardised SDs. No individual differences were observed for any ankle measurement.

Hydration Estimate

Loaded participants drank significantly more water than unloaded participants (0.24±0.213L CI (0.59, 0.15) to 0.653±0.260L CI (0.790, 0.510), $P<0.001$) during load carriage supported by effect sizes of $d_{Cohens}=1.34$ and $d_{Glass}=1.94$. This accompanies increased sweat loss experienced by the loaded participants (0.396±0.304kg CI (0.89, 0.27) and 1.289±0.552kg CI (1.58, 1.00), $P<0.01$) supported by large effect sizes of $d_{Glass}=1.478$ and $d_{Cohens}=2.934$, BM remained not significantly different during the testing.

Ground Reaction Forces

Table 5.5.1 Significance, means changes scores and confidence intervals for VGRF and APGRF variables

Variable	Group	n	Lower CI	Baseline (SD)	Upper CI	Lower CI	Change (SD) (%)	Upper CI	*p*-Value	d_{Cohens}	d_{Glass}
Loading Peak	Unloaded	16	1.32	1.37 (0.11)	1.41	1.17	4.98 (9.25)	8.79	0.387		
	Loaded	14	1.79	1.87 (0.21)	1.96	-2.31	1.83 (10.40)	7.30			
Force Minimum	**Unloaded**	**16**	**0.45**	**0.48 (0.10)**	**0.52**	**-5.22**	**-0.68 (11.01)**	**3.86**	**0.038**	**0.75**	**0.87**
	Loaded	**14**	**0.59**	**0.66 (0.15)**	**0.72**	**-15.03**	**-8.9 (13.18)**	**-2.48**			
Thrust Maximum	Unloaded	16	1.13	1.17 (0.10)	1.21	-0.40	2.61 (7.30)	5.61	0.764		
	Loaded	14	1.50	1.58 (0.18)	1.65	-1.13	3.65 (11.36)	9.52			
Average Vertical Impulse	Unloaded	16	0.53	0.63 (0.25)	0.73	-2.50	3.89 (15.51)	10.29	0.993		
	Loaded	14	0.67	0.70 (0.07)	0.72	-0.90	3.85 (11.01)	9.48			
Total vertical impulse	Unloaded	16	146.71	174.83 (70.27)	202.94	-9.94	-2.12 (18.95)	5.69	0.549		
	Loaded	14	152.03	163.83 (26.36)	175.64	-3.80	1.45 (11.88)	7.43			
First Positive Rate	Unloaded	12	6.59	8.56 (4.91)	10.52	-206.45	-135.75 (171.39)	-65.06	0.742		
	Loaded	11	13.22	16.87 (8.85)	20.52	-219.74	-95.21 (182.60)	-23.95			
Second Positive Rate	Unloaded	16	4.84	6.03 (2.98)	7.23	-13.58	4.78 (44.52)	23.14	0.673		
	Loaded	14	7.92	9.13 (2.93)	10.34	-11.21	-0.97 (25.12)	12.16			
First Negative Rate	Unloaded	16	-8.75	-7.50 (3.14)	-6.24	-52.14	-19.63 (20.21)	12.87	0.849		
	Loaded	14	-10.35	-9.08 (3.09)	-7.80	-50.25	-26.67 (49.05)	-3.53			
Second Negative Rate	Unloaded	16	-14.85	-13.15 (4.24)	-11.45	-10.31	-1.05 (22.45)	8.21	0.344		
	Loaded	14	-20.76	-19.66 (2.66)	-18.56	0.28	5.33 (11.22)	10.92			
Maximum braking Force	Unloaded	16	-0.35	-0.33 (0.05)	-0.31	2.04	8.36 (15.32)	14.68	0.127		
	Loaded	14	-0.47	-0.43 (0.10)	-0.39	-5.67	-0.31 (14.80)	7.64			
Maximum Propulsive Force	Unloaded	16	0.27	0.29 (0.05)	0.31	-1.96	4.76 (16.28)	11.48	0.973		
	Loaded	14	0.39	0.41 (0.05)	0.43	0.02	4.58 (10.71)	10.08			
Braking Impulse	Unloaded	16	-0.07	-0.06 (0.02)	-0.05	-0.55	7.84 (20.35)	16.24	0.394		
	Loaded	14	-0.06	-0.06 (0.01)	-0.06	-4.18	2.02 (15.74)	10.34			
Propulsive Impulse	Unloaded	16	0.04	0.05 (0.02)	0.05	-2.13	3.46 (13.57)	9.06	0.815		
	Loaded	14	0.05	0.06 (0.01)	0.06	-2.59	2.35 (12.13)	8.69			

Magnitude variables are expressed as BW, while rates are explained as $BW \cdot S^{-1}$ and impulses are presented as $BW \cdot S$. Bold text represents significance between groups to $p<0.05$.

One force parameter was observed to be changed as a result of load carriage, force minimum, 0.480±0.023BW CI (0.64, 0.44) to 0.47±0.10BW CI (0.64, 0.44) for unloaded and 0.66±0.15BW CI (0.91, 0.41) to 0.62±0.15BW CI (0.86, 0.37) $p<0.05$, $d_{Cohen}=0.75$ and $d_{Glass}=0.87$, SSD=22.67) for the loaded group. A significant change was observed in time to loading peak with the unloaded group experiencing a significant reduction in time (-14.74%) and with the loaded group staying comparatively stable with an increase of 3.88%.

Table 5.5.2 Significance, means changes scores and confidence intervals for MLGRF variables

Variable	Group	n	Lower CI	Baseline(SD)	Upper CI	Lower CI	Change (SD) (%)	Upper CI	*P*-Value
Mediolateral Minimum	Unloaded	16	-0.09	-0.07 (0.03)	-0.06	-10.16	0.39 (25.60)	10.95	0.388
	Loaded	14	-0.07	-0.06 (0.02)	-0.06	-29.69	-10.01 (38.86)	7.04	
Mediolateral Maximum	Unloaded	16	0.07	0.08 (0.02)	0.08	-6.09	7.04 (31.82)	20.17	0.434
	Loaded	14	0.07	0.08 (0.03)	0.09	-17.49	-2.15 (31.38)	12.37	
Medial Impulse	Unloaded	16	-0.01	-0.01 (0.00)	0.00	-22.34	-4.79 (42.55)	12.76	0.907
	Loaded	14	-0.01	-0.01 (0.01)	0.00	-25.97	-2.88 (45.98)	17.58	
Lateral Impulse	Unloaded	16	0.04	0.05 (0.02)	0.06	-2.07	3.49 (13.48)	9.05	0.816
	Loaded	14	0.06	0.06 (0.01)	0.06	-2.53	2.38 (12.08)	8.70	
Mediolateral Impulse	Unloaded	16	-0.01	-0.01 (0.01)	0.00	35.23	215.11 (436.08)	394.99	0.388
	Loaded	14	-0.01	0.00 (0.01)	0.00	-129.44	82.22 (387.56)	190.44	
Medial Lateral Ratio	Unloaded	16	0.13	0.15 (0.04)	0.17	-3.37	4.60 (19.31)	12.56	0.214
	Loaded	14	0.13	0.15 (0.03)	0.16	-13.89	-4.29 (18.82)	3.84	

Magnitude variables are expressed as BW and impulses are expressed as BW·S.

Table 5.5.3 Significance, means changes scores and confidence intervals for absolute temporal GRF variables

Variable	Group	n	Lower CI	Baseline (SD) (Sec)	Upper CI	Lower CI	Change (%)	Upper CI	*p*-Value	d_{Cohens}	d_{Glass}
Time to Loading Peak	**Unloaded**	**16**	**0.09**	**0.1 (0.02)**	**0.11**	**-29.23**	**-14.73 (35.13)**	**-0.24**	**0.043**	**0.68**	**0.53**
	Loaded	**14**	**0.11**	**0.12 (0.02)**	**0.12**	**0.15**	**3.88 (8.00)**	**7.76**			
Time to Force Minimum	Unloaded	16	0.28	0.29 (6.54)	0.29	-4.31	-1.61(6.54)	1.08	0.793		
	Loaded	14	0.30	0.31 (6.84)	0.32	-4.24	-0.96 (6.84)	2.28			
Time to Thrust Maximum	Unloaded	16	0.44	0.45 (8.49)	0.46	-4.44	-0.94 (8.49)	2.56	0.635		
	Loaded	14	0.47	0.48 (5.02)	0.50	-1.94	0.31 (5.02)	2.82			
Stance Time	Unloaded	16	0.56	0.58 (7.83)	0.59	-6.12	-2.89 (7.83)	0.34	0.231		
	Loaded	14	0.61	0.62 (5.09)	0.64	-2.18	0.11 (5.09)	2.65			
Time to Maximum Braking Force	Unloaded	16	0.07	0.08 (15.33)	0.08	-11.86	-5.53 (15.33)	0.79	0.324		
	Loaded	14	0.08	0.09 (12.22)	0.10	-6.64	-0.40 (12.22)	4.86			
Time to Maximum Propulsive Force	Unloaded	16	0.49	0.50 (7.64)	0.51	-5.71	-2.55 (7.64)	0.60	0.250		
	Loaded	14	0.52	0.54 (5.70)	0.56	-2.19	0.37 (5.70)	3.21			
Time to ML Maximum	Unloaded	16	0.13	0.18 (84.70)	0.22	-45.14	-10.2 (84.70)	24.73	0.959		
	Loaded	14	0.22	0.28 (40.33)	0.34	-33.52	-11.5 (40.33)	-0.05			
Time to ML Minimum	Unloaded	16	0.03	0.05 (37.56)	0.06	-27.90	-12.41(37.56)	3.08	0.339		
	Loaded	14	0.03	0.05 (161.24)	0.06	-133.76	-52.75 (161.24)	18.94			
Time from Medial to Lateral Peak	Unloaded	16	0.09	0.13 (100.62)	0.17	-50.51	-9 (100.62)	32.50	0.975		
	Loaded	14	0.18	0.23 (48.32)	0.29	-34.38	-8.08 (48.32)	7.48			

Bold text represents significance between groups to $p<0.05$.

Table 5.5.4 Significance, mean change scores and confidence intervals for relative temporal variables

Variable	Group	n	Lower CI	Baseline	Upper CI	Lower CI	Change (%)	Upper CI	*p*-Value	d_{Cohens}	d_{Glass}
Time to loading Peak	Unloaded	16	16.25	17.63 (21.50)	19.01	-14.40	-5.53 (21.50)	3.34	0.141		
	Loaded	14	17.71	18.47 (5.72)	19.23	1.17	3.81 (5.72)	6.40			
Time to Force Minimum	Unloaded	16	48.39	49.42 (4.60)	50.44	-0.82	1.08 (4.60)	2.97	0.334		
	Loaded	14	48.52	49.55 (9.26)	50.58	-5.76	-1.37 (9.26)	2.72			
Time to Thrust Maximum	Unloaded	16	77.16	77.78 (1.60)	78.40	-0.11	0.55 (1.60)	1.21	0.469		
	Loaded	14	77.20	77.67 (0.75)	78.14	-0.15	0.18 (0.75)	0.54			
Time to Maximum Braking Force	Unloaded	16	12.07	13.29 (13.98)	14.51	-8.56	-2.80 (13.98)	2.97	0.754		
	Loaded	14	13.75	14.5 (11.92)	15.25	-6.70	-0.63 (11.92)	4.21			
Time to Maximum Propulsive Force	Unloaded	16	86.10	86.63 (1.53)	87.15	-0.35	0.28 (1.53)	0.91	0.964		
	Loaded	14	86.28	86.59 (0.83)	86.90	-0.08	0.29 (0.83)	0.68			
Time to ML Maximum	Unloaded	16	22.18	30.66 (87.63)	39.14	-50.57	-14.43 (87.63)	21.72	0.634		
	Loaded	14	35.27	44.78 (49.59)	54.29	-50.27	-22.98 (49.59)	-4.88			
Time to ML Minimum	Unloaded	16	5.67	8.00 (55.17)	10.32	-42.13	-19.37 (55.17)	3.39	0.422		
	Loaded	14	4.67	7.43 (6.12)	10.19	-132.28	-72.99 (167.54)	21.06			

All variables are presented as % of total stance time

Associations

Repeated measure correlations were studied providing analysis of the change scores for the specified variables.

Physiological Measurement and NMF

All NMF variables were assessed for association with $\dot{V}O_2$, correlations were observed for knee extension at 60°s^{-1}, for both average ($r=-0.74$, $p<0.01$, VE=54%) and maximum values (, $r=-0.69$, $p<0.01$, VE=48%) no significant correlations were observed for knee extension at 180°s^{-1} or isometric knee flexion. Correlations were observed for ankle plantarflexion max and average values at 60°s^{-1} ($r=-0.56$, $p<0.05$, VE=31%; $r=-0.7$, $p<0.01$, VE=0.49, respectively).

Physiological Measurement and GRF

A number of GRF parameters were assessed for association with $\dot{V}O_2$ based on the previous chapters, the only significant correlation was observed between $\dot{V}O_2$ and second positive rate ($r=0.58$, $p<0.05$, VE=33%).

NMF and GRF

Table 5.6 Correlations of the change scores between selected NMF and VGRF variables

Variable 1	Variable 2	r Value	VE	*P* Value
Total Vertical Impulse	Ankle 60°s^{-1} Plantarflexion(Ave)	0.53	28.00	$p<0.05$
	Ankle 60°s^{-1} Plantarflexion (Max)	0.56	31.46	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Ave)	0.61	36.92	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Max)	0.69	46.92	$p<0.001$

Table 5.7 Correlations of the change scores between selected NMF and VGRF variables during midstance

Variable 1	Variable 2	r Value	VE	*p* Value
Force Minimum	Knee 60°s^{-1} Extension (Max)	0.55	30.79	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	0.71	51.10	$p<0.001$
	Knee Isometric Extension	0.55	30.64	$p<0.05$
	Ankle 60°s^{-1} Plantarflexion (Ave)	0.55	30.14	$p<0.05$
Time to Force Minimum	Ankle 120°s^{-1} Plantarflexion (Max)	-0.59	34.69	$p<0.05$
	Ankle 120°s^{-1} Plantarflexion (Ave)	-0.57	32.72	$p<0.05$

Table 5.8 Correlations of the change scores between selected NMF and VGRF variables during push off

Variable 1	Variable 2	r Value	VE	*p* Value
Second Positive Rate	Ankle 60°s^{-1} Plantarflexion (Max)	0.37	13.66	$p<0.05$
	Ankle 60°s^{-1} Plantarflexion (Ave)	0.47	21.80	$p<0.05$
	Knee 60°s^{-1} Flexion (Max)	0.56	31.06	$p<0.05$
	Knee 60°s^{-1} Flexion (Ave)	0.44	19.48	$p<0.05$
Thrust Maximum	Knee Isometric	0.57	32.93	$p<0.05$
	Knee 60°s^{-1} Extension (Max)	0.40	16.29	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	0.57	32.70	$p<0.05$

A number of variables were studied examining the relationships at push off, significant findings are presented in the table above. No meaningfully significant findings were observed during the loading phase.

Table 5.9 Correlations of the change scores between selected NMF and APGRF variables

Variable 1	Variable 2	r Value	VE	*p* Value
Braking Impulse	Knee 60°s^{-1} Extension (Max)	-0.61	36.78	*p*<0.05
	Knee 60°s^{-1} Extension (Ave)	-0.72	52.16	P<0.001
	Ankle 60°s^{-1} Plantarflexion (Ave)	-0.51	26.51	*p*<0.05
Maximum Braking Force	Knee 60°s^{-1} Extension (Max)	-0.57	32.30	*p*<0.05
	Knee 60°s^{-1} Extension (Ave)	-0.67	44.71	*p*<0.01
Propulsive Impulse	Ankle 60°s^{-1} Dorsiflexion (Max)	0.56	31.26	*p*<0.05
	Ankle 60°s^{-1} Dorsiflexion (Ave)	0.53	28.53	*p*<0.05
	Knee Isometric Extension	0.66	43.05	*p*<0.01
	Ankle 60°s^{-1} Plantarflexion (Max)	0.53	28.53	*p*<0.05
	Ankle 60°s^{-1} Plantarflexion (Ave)	0.56	31.26	*p*<0.05

Table 5.10 Correlations of the change scores between selected NMF and MLGRF variables

Variable 1	Variable 2	r Value	VE	*p* Value
Medial Lateral Ratio	Ankle 120°s^{-1} Plantarflexion (Max)	0.60	36.11	$p<0.05$
	Ankle 120°s^{-1} Plantarflexion (Ave)	0.56	31.51	$p<0.05$
Time from M-Peak to L-Peak	Ankle Isometric Flexion	0.73	53.08	$p<0.001$
	knee 60°s^{-1} Flexion (Max)	0.65	41.78	$p<0.01$
	knee 60°s^{-1} Flexion (Ave)	0.63	39.27	$p<0.01$
	Knee 60°s^{-1} Extension (Max)	0.59	34.67	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	0.57	32.61	$p<0.05$
Medial Impulse	Ankle 60°s^{-1} Plantarflexion (Ave)	-0.51	26.01	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Max)	-0.61	37.21	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Ave)	-0.52	27.04	$p<0.05$
	Knee 60°s^{-1} Extension (Max)	-0.60	36.00	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	-0.72	51.84	$p<0.001$
Time to ML Max	Ankle 60°s^{-1} Dorsiflexion (Max)	0.51	25.53	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Ave)	0.54	29.00	$p<0.05$
	Knee 60°s^{-1} Extension (Max)	0.57	31.98	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	0.55	30.53	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Max)	0.67	44.67	$p<0.01$
	Ankle 60°s^{-1} Dorsiflexion (Ave)	0.66	44.01	$p<0.01$
	Ankle Isometric Flexion	0.71	50.92	$p<0.001$
Lateral Impulse	Knee 60°s^{-1} Extension (Max)	-0.55	30.25	$p<0.05$
	Knee 60°s^{-1} Extension (Ave)	-0.63	39.69	$p<0.01$
	Knee 60°s^{-1} Flexion (Max)	-0.61	37.21	$p<0.05$
	Knee 60°s^{-1} Flexion (Ave)	-0.67	44.89	$p<0.01$
	Ankle Dorsiflexion 120°s^{-1} (Ave)	-0.56	31.36	$p<0.05$
	Ankle 60°s^{-1} Dorsiflexion (Max)	-0.56	31.36	$p<0.05$
Time to ML Min	Knee 60°s^{-1} Flexion (Max)	0.61	37.58	$p<0.05$
	Knee 60°s^{-1} Flexion (Ave)	0.69	47.32	$p<0.01$
	Ankle 60°s^{-1} Dorsiflexion (Max)	0.53	28.11	$p<0.05$
	Ankle 60°s^{-1} Plantarflexion (Ave)	0.56	31.55	$p<0.05$

5.4 Discussion

This chapter observes reductions in NMF of the ankle plantarflexors and knee extensors affirming the primary hypothesis, these changes were observed in a broad range of variables and with large effect sizes providing confidence in the findings. This chapter also observes changes in force minimum which is significantly correlated to energy demands of the task affirming secondary hypothesis (1), these variables exhibit correlation with a number of other variables which will be discussed in this section.

Reductions of the ankle plantarflexors and knee extensors were negatively correlated to energy cost in agreement with secondary hypothesis (2). Moreover, the ankle plantarflexors are demonstrated to be correlated to a range of GRF variables associated with the propulsive phases of gait which affirms both secondary hypothesis (3) and the main thesis hypothesis of a three way GRF, NMF and movement economy relationship within load carriage.

Metabolic responses from baseline in the current study appear to be comparable to previous work (Mullins et al., 2015, Epstein et al., 1988, Grenier et al., 2012b, Patton et al., 1991) which observed $\dot{V}O_{2drift}$ between 10 and 18% change. Standardised standard deviations were examined, and extremely large inter-participant variance was observed making this the first study to highlight such changes. However, analysis of presented published research suggests that while most studies observe no individual differences it is likely that Blacker et al. (2009b) would have experienced large individual differences even once baseline variance is accounted for.

Reductions in NMF were observed for almost all measures of knee flexion and knee extension supported by large effect sizes, and even larger sizes when changes in SD were considered. Furthermore while reductions of NMF between 9% and 15.1% were observed for knee flexion in alignment with Blacker et al. (2010), notable increases from baseline were observed for the unloaded group suggesting that even greater changes than those observed are possibly occurring.

The examination of knee extension and flexion at multiple joint angles is novel to the field. It is clear that the faster joint movements displayed reduced NMF over a larger proportion of the joint angle. In all cases the peak torque value occurred within the significantly reduced part of the torque curve, suggesting that there was no shift in the position of peak torque as a result of load carriage. In all instances the peak torque values occurred during the optimal muscle length for force, displayed by a flattening of the curve around its peak of the loaded post-test measurements. It is notable that these are muscle lengths (95°-125°) which will not occur during load carriage. So when the muscle is at lengths which are reflective of locomotion (130°-180° (Kadaba et al., 1990)) then the appears to be no significant change between loaded and unloaded groups. These findings suggest that while changes in torque and peak torque can be observed by isokinetic dynamometry of the whole muscle function, this loss may not have a pronounced effect on the muscle's ability to produce force at muscle lengths relevant to walking with or without external load.

Significant reductions in ankle plantarflexor NMF were observed as a result of the load carriage across all parameters, these were supported by moderate to large effect sizes. These findings further support the previous chapter and the work of Clarke et al. (1955) which proposes that reduced knee extensor function requires greater work from the distal end of the kinetic chain. These findings suggest that the first research objective can be answered in the affirmative, by stating that it is likely that reduction in knee extensor NMF will reduce ankle plantarflexor force, possibly due to a distal shift in work load.

When GRF data was assessed an interaction effect was observed as a reduction in force minimum of the loaded group. Changes in force minimum have previously been used as a marker of change in knee flexion (Rice et al., 2015, Birrell et al., 2007). The role of force minimum within the gait cycle is further highlighted when it is noted that there is a significant correlation between reduction in knee extensor NMF and force minimum, suggesting that as the knee extensors become less able to exert force, the body is less able to mitigate the effect of the load. Correlations were also observed between force minimum and ankle plantarflexors, it is likely that this is a secondary effect in line with the distal shift of workload.

Furthermore the supporting standardised standard deviation presents that individual differences for mid-stance are extremely high, and are supported by large effect sizes, these findings suggest that different levels of NMF are creating large interindividual effects amongst the participants. Signifying that participants are experiencing different levels of knee flexion as a result of reducing the effect of the load over different distances, which would mean some participants are able to mitigate the vertical effect of the load more effectively than others.

No other temporal alterations were observed in GRF change scores, so in response to the second research objective it is possible to suggest that this study observed no change in GRF parameters, meaning that while changes are observed acutely, which may place the participants at injury risk via repeated ground impacts, load carriage over two hours may not pose any risk beyond the initial acute change. However as chapter 4 demonstrated that GRF parameters correlate to different NMF magnitudes, GRF changes may occur but on a much smaller magnitude than the NMF changes and as such are not noticeable during a relatively short duration load carriage task. It should be acknowledged that analysis of the baseline values suggests that participants experience increased GRF values in line with the first study. As such, it is possible to suggest reductions of up to 20% in NMF of the agonists and antagonists of sagittal plane motion around the ankles and knee do not instigate changes to gait associated with injury risk through impact peaks, beyond those observed from the acute application of load.

Correlation analysis shows that there are some moderate and strong associations between knee flexors and $\dot{V}O_2$ and ankle plantarflexors and $\dot{V}O_2$. These findings relating knee extension with $\dot{V}O_2$ concur with findings by Blacker (2009), while the ankle plantar flexion correlation is a novel finding. Ankle plantarflexion was also observed to be correlated to force minimum, second positive rate and propulsive impulse which are all parameters which share components relating to push off. Somewhat pleasingly, $\dot{V}O_2$ was shown to share moderate correlation with second positive rate, providing triangulation between the three measurements providing confidence in the reply to the third research objective that changes in NMF are associated to variations in energy costs of load carriage. It can be further stated that this occurs by the ankle plantarflexors being weakened by prolonged load carriage and consequently not able to exert as much force against the ground to propel the body forward. This less economical gait pattern may account for part of the variation observed in $\dot{V}O_2$. What is more, none of these correlations were observed within the unloaded group suggesting that load carriage increases the importance of the plantar flexors within the gait cycle.

A surprising finding was the high number of correlations observed between NMF of the knees and ankle action groups and ML GRF variables. Caution must be exerted as there appears to be little triangulatory trend within the variables possibly due to the NMF variables being collected in the sagittal plane while ML variables occur in the frontal plane. It is possible that muscles which predominantly contribute to the actions considered on the NMF tests have a secondary role acting as joint stabilisers, for example the PL (Gefen, 2002).

This study has highlighted a number of metabolic variables, which have been shown to be susceptible to very large inter individual variation, suggesting that participants experience vastly different physiological changes as a result of load carriage. This study has not been able to find any explanations for this range of individual difference, as BM was not statistically related to measures of energy cost, moreover, NMF did not display notable individual differences, so while it did correlate and is a likely predictor of energy cost it amounts to a small amount of the VE and as such is unlikely to account for the individual variation. It is frequently noted that occupational tasks such as load carriage occur over several consecutive days. In response to the fourth research objective is it clear that the energy cost of the task experiences large individual differences, which may partly be a consequence of relatively large participant differences in NMF change.

5.5 Conclusion

The most novel aspect of this chapter of the analysis of NMF of the knee extensors and flexors at multiple joint angles which highlighted that reductions in NMF occur at muscle lengths not typically used during locomotion. This suggests that it is acceptable for peak torque variables to be used in limited circumstances. This chapter also provided triangulated findings which suggested that increased knee flexion occurred as a result of prolonged load carriage, suggesting that increases to energy cost may be derived from changes in gait biomechanics.

The findings from this study are novel in that is it the first study to try and separate inter individual change from the variation of the measurements, this highlights that conclusions drawn from single day exercise may not be transferable to multiple day exercise. This study has examined possible mechanisms for this individual variation, however, has not been able to draw conclusive findings. Similar findings where observed in this study for the NMF variables which demonstrated significant reductions in line with previous work, but additionally demonstrated large individual differences in the performance, making this the first study to highlight this fact.

This provides the researcher with a number of interesting questions; can one-day activity be used as a predictor for subsequent day performances? If it is assumed that participants would start a second load carriage task with lower measurements of key variables, does multiple day activity exacerbate the inter individual differences between participants? The next chapter will attempt to consider these questions and will study the effect of two consecutive days of load carriage on various physiological and biomechanical parameters.

Biomechanical and Physiological Changes as a Result of Two Hours Treadmill Load Carriage on Two Consecutive Days.

Conference Presentations

Scales, J. F., Coleman, D. A. and Brown, M. B. (2016) Energetic and neuromuscular responses to consecutive day military load carriage. In: 21st Annual Congress of the European College of Sports Science, 6th-9th June 2016, Vienna, Austria. [Available at: http://wp1191596.server-he.de/DATA/CONGRESSES/VIENNA_2016/DOCUMENTS/VIENNA_BoA.pdf].

Scales, J. F., Coleman, D. A. and Brown, M. B. (2017) Factors effecting energy cost during consecutive day military load carriage. In: American College of Sports Medicine, 30th May- 3rd June 2017, Colorado, USA. [Available at: http://www.acsm.org/docs/default-source/meetings-documents/2017-abstracts-full-book.pdf?sfvrsn=4].

6.1 Introduction

Chapter 5 demonstrated that there are a number of interesting associations between physiological measures of energy cost and NMF during load carriage. A number of associations were observed between measures of NMF and GRF, notably in measures allied with an increased risk of injury such as total vertical impulse (Zadpoor et al., 2011) and ankle plantarflexion variables (Birrell et al., 2007). While these findings in themselves are novel it is important to remember that correlation does not necessarily mean causation. This chapter will further examine some of the associations which exhibit strong correlation and empirical support. However, the principal and novel aim of this chapter will be to examine load carriage during two bouts of exercise on two consecutive days and to examine any cumulative changes in performance.

Despite most military exercises and operations requiring multiple days of substantial physical stress (Knapik, 2001), no study has investigated the changes which may occur as a result of cumulative day load carriage. Most research which has considered military activity over repeated days has been classifying energetic demands of recruit training as part of wider programmes informing military policy, usually through single index measures such as HRR (Blacker et al., 2009a) and accelerometery (Horner et al., 2013). A number of studies have observed consecutive day tasks, notably, Welsh et al. (2008) who observed reduction vertical jump test measures as a result of eight days military activity, while Margolis et al. (2016) observed daily energy, and protein debt as a result of four days Arctic training.

When temporal measures were taken during a four-day military exercise, a progressive reduction in vertical jump scores was observed between days and between start to finish (Nindl et al., 2002), suggesting that participants are not able to recover between days. However, due to the nature of the study, it is not possible to separate the physical demands of load carriage, from the other physiological demands of military exercise.

The previous chapter saw significant drift in $\dot{V}O_2$ and EE in line with previous research (Quesada et al., 2000, Mullins et al., 2015), in addition to which large individual differences were observed in responses, something not identified in previous research. Such variability across participants for a single prolonged bout of load carriage, leads to the logical consideration that by the commencement of a second bout some participants may not have recovered to baseline. Furthermore, by undertaking a second physically demanding task, that has previously been shown to manipulate factors such as EE and $\dot{V}O_2$, will provide opportunity to temporally examine relationships between two activity interventions and two recovery phases providing greater evidence to support observed relationships between key variables which displayed change in previous studies.

The previous chapter highlighted significant reduction in NMF of ankle plantarflexors and knee extensors, as a result of load carriage, this work is in line with Clarke et al. (1955) who observed change in ankle plantarflexors and Blacker et al. (2010) who observed reduction in knee extensor force up to 72hours after exercise. This suggests that if participants were to undergo exercise 24hours after the secession of the initial bout, they would be starting performance at different levels of NMF. Furthermore, chapter 3 demonstrated that participants with different NMF strength scores for knee extensors and ankle plantarflexors experienced different EE as a result of load carriage, suggesting that load carriage on day two (d2) will elicit different responses than those on day one (d1). This has occupational relevance to a military field when it is considered that most military load carriage is completed over consecutive days, with field exercises lasting up to two weeks or more (Knapik et al., 2012).

This chapter is novel in two aspects, it is the first to examine load carriage over consecutive days and secondly, it is the first study to examine individual differences during load carriage over consecutive days. Therefore the aims of this chapter are to investigate changes in means and individual differences for energetic cost, NMF and GRF during two 120 minute bouts of treadmill loaded walking and to examine changes in the recovery profile following two 120 minute bouts of treadmill loaded walking.

Research Objectives

1. Explore whether consecutive day load carriage instigates greater energy expenditure (measured by difference in means) for d2 than d1
2. Examine whether consecutive day load carriage instigates increased variability (measured by changes in SD) in participants energy expenditure
3. Investigate whether greater reductions in NMF are observed in d2 than in d1

4. Evaluate whether consecutive day load carriage exacerbate changes previously identified in GRF following a single prolonged bout of load carriage
5. Explore whether energy demand can be correlated with changes in extension components of the lower kinetic chain during load carriage.

Hypothesis

This chapter will be examining load carriage over two consecutive days, in order to examine the hypothesis that two day load carriage will instigate statistically significant increases in energy cost on 2d compared to day one. Secondary hypothesis (1) is that energy cost will not return to baseline 24 hours post day one at the start of day two. The chapter will also examine the secondary hypothesis (3) that two day load carriage will instigate statistically significant reductions in NMF of the ankle plantarflexors and knee extensors greater than that of a single day of load carriage.

6.2 Methods

Trial Design

This chapter employs an experimental, repeated measures, parallel groups design with a control group, measurements were taken before and after a load carriage task on day one, day two and 24 hours later on day three.

Participants

Twenty-four healthy participants volunteered to participate in the study by giving their informed consent. All participants had recreational experience of carrying backpacks and were recruited from Canterbury Christ Church University.

Table 6.1 Table presenting participant descriptive data.

Condition	Body Mass (kg)	Stature (cm)	Age (yrs)	Males (n)	Females (n)
Loaded	78.27 (36.75)	179.2 (17.98)	22(6)	10	2
Unloaded	73.77 (34.75)	177.98 (17.45)	21(5)	11	3

Mean values presented with range presented in brackets

Participants consumed water with no restrictions during the treadmill protocol, which reflected the occupational military setting. The bottle from which the water was consumed was not carried within the load carriage system and was weighed in order to estimate water intake and sweat loss.

While every effort was made to recruit participants in an even fashion, explanation of the study involved clarification that the load is substantial. As such it is possible that the finally recruited participants may be stronger than a true reflection of the population. A number of participants voluntarily withdrew from the loaded group due to the physical discomfort of the task. While no participants dropped out of the unloaded group, it is possible that this may also have resulted in physically more robust participants completing the loaded protocol than the unloaded. Despite this, while there was a trend towards the loaded group being stronger, there were no statistically significant differences between the loaded and unloaded groups.

Experimental protocol

All aspects of this research were conducted by the author in the sport and exercise laboratories at

Canterbury Christ Church University. The study was conducted in a parallel group design with both groups running concurrently.

Participants walked on a level motorised treadmill (Woodway ELG, Birmingham, UK) (0% gradient) for 120minutes, at 6.5km·h^{-1} at the same time on two consecutive days, for which dynamometry, gait and respiratory gas parameters were collected pre and post following protocol specified in chapter 3. Upon visiting on a third day, 24hours post activity participants completed the dynamometry and GRF protocols as defined in chapter 3. Participants were given the opportunity to familiarise themselves to the treadmill, force platform and load carriage systems prior to the testing session.

The loaded group consisted of a 32kg external load spread across, webbing (10kg), bergen (15kg) and a dummy rifle (7kg).

Interim Analysis

During the load carriage activity, the participants' HR were continuously monitored. Participants were withdrawn if they voluntarily declared themselves unable to complete the task or if they became unable to safely maintain the walking speed required.

At the start of d2 participants were questioned and examined for injuries. If participants experienced injury which is likely to be prolonged by load carriage they were withdrawn from the testing (See figure 6.1).

Environmental Conditions

Environmental temperature and humidity were monitored during the testing period. No differences in environmental temperature were observed during testing (Mean: Range) (D1:18.66°C: 2.83°C, 51.05%:18.15%. D2: 18.17°C:1.83°C, 49.4%:15.00%).

Statistical Analysis

SPSS for windows version 23 (SPSS, Chicago, USA) and Excel (Microsoft: USA) were used for statistical analyses.

Differences in means were explored using mixed methods ANOVA, when sphericity was found to be violated Greenhouse Geisser correction was used. Data was also checked for normality, all data was found to be parametric so a mixed methods ANOVA was used. No covariates were used due to the investigation of individual differences. As such differences between participants can be viewed as relevant to the research question, moreover likely covariates based on previous research were correlated to the live data and were shown not to demonstrate any relationship.

Associations were examined and presented using repeated measure correlations procedures (Bland and Altman, 1995, Bland and Altman, 1994), while individual differences were presented in accordance with Hopkins (2015) and Smith and Hopkins (2011). Correlations were chosen depending subjective analysis of data from previous studies within the thesis and the literature.

Before change scores were compared and GRF were normalised to BW the data were log transformed and plotted to ensure that it did not violate any scaling guidelines (Nevill et al., 1992, Davies and Dalsky, 1997, Atkinson and Batterham, 2012).

6.3 Results

Adverse Events

No participants experienced long term injury as a result of this study. However nine participants experienced blisters on their feet as a result of the load carriage protocol. While eight participants noted skin sores due to rubbing on their shoulders and hips due to the load carriage equipment. 11 participants stated they experienced muscle soreness, however, all said it was less than they would experience as a result of other forms of daily physical activity.

10 Participants stated it required substantial mental determination to start d2, while all participants started the d2 with some acute sores, such as blisters, hotspot or musculoskeletal soreness.

Grannuflex and zink-oxide tape were provided to the participants during and after the study, and the participants were advised to wear polo neck shirts to prevent skin sores from the weapon sling. Participants reported that these were very useful in mitigating the skin wounds.

Sample Size Profile

Figure 6.1 Flow diagram of participant voluntary withdrawal

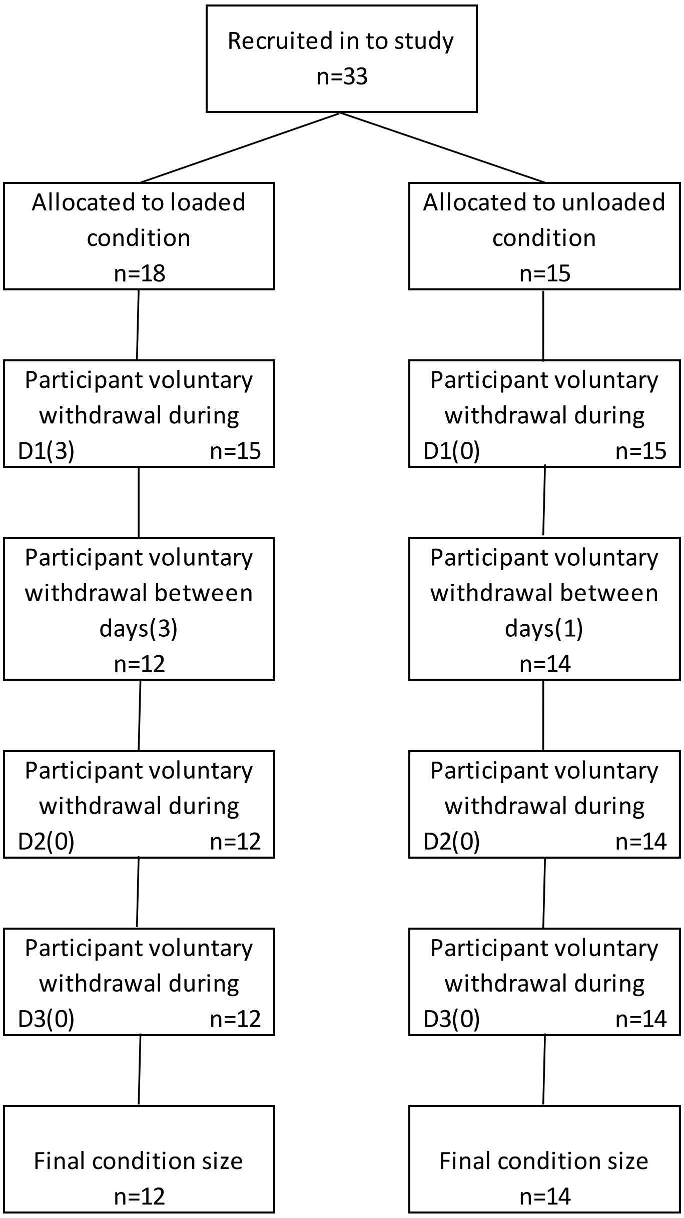


Table 6.2. Metabolic variables of estimated energy expenditure at baseline and change scores from baseline at subsequent time intervals

			Day 1		Day 2			
Variable	Group	n	Baseline (SD)	Post (SD) (%)	Pre (SD) (%)	Post (SD) (%)	*p*-Value	Eta Squared
EE (cal·kg·min^{-1})	**Unloaded**	**14**	**5.96 (1.14)**	**0.76 (3.59)**	**1.49 (5.34)**	**1.49 (6.4)**	**Time·Load**	**0.29**
	Loaded	**12**	**8.91 (1.96)**	**8.49 (7.23)***	**4.41 (4.57)*†**	**13.68 (7.32)*†§**		
VO$_2$ (ml·kg·min^{-1})	**Unloaded**	**14**	**16.28 (1.89)**	**2.12 (3.71)**	**1.88 (5.94)**	**3.16 (6.97)**	**Time·Load**	**0.24**
	Loaded	**12**	**23.26 (3.06)**	**9.56 (7.14)***	**4.15 (4.74)**	**15.5 (7.59)*†§**		
VCo$_2$ (ml·kg·min^{-1})	**Unloaded**	**14**	**13.98 (1.80)**	**-4.41 (6.13)**	**-1.43 (6.91)**	**-6.23 (7.88)*§**	**Time·Load**	**0.16**
	Loaded	**12**	**20.53 (3.20)**	**0.96 (5.25)**	**2.96 (5.91)**	**3.06 (6.26)**		
RER	Unloaded	14	0.86 (0.04)	-6.14 (5.44)	-2.87 (6.60)	-8.75 (6.63)‡	Time	0.22
	Loaded	12	0.88 (0.05)	-8.15 (4.25)	-0.65 (5.43)	-10.13 (6.3)‡		

Bold text highlights significant interaction effects to p<0.05, * denotes statistical significance (p< 0.05) from baseline while †denotes statistical significance from post d1, ǂ denotes a simple effect of time, and § represents statistical significance from d2 pre.

Table 6.3 Absolute RER values

	Day 1		Day 2	
	Baseline	Post	Pre	Post
Unloaded	0.85 (0.05)	0.80 (0.04)	0.83 (0.06)	0.78 (0.06)
Loaded	0.88 (0.05)	0.81 (0.04)	0.87 (0.04)	0.79 (0.05)

Findings are presented in table 6.3 as absolute RER values for clarity; analysis was only conducted on the change scores.

Figure6.2 Energy expenditure during 2d load carriage

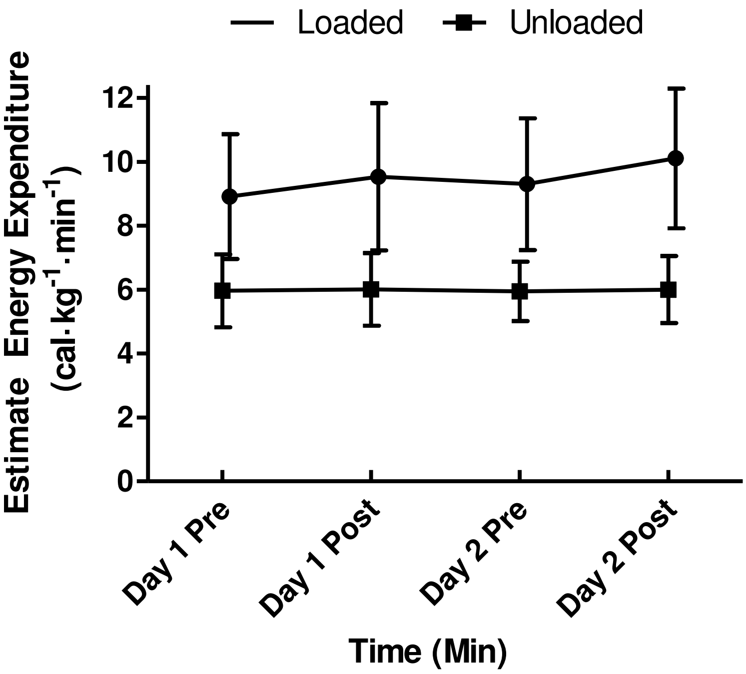


Figure displays means with standard error bars. Statistically significant differences from baseline for the loaded group were observed at all time points. Day two pre and post was observed to be significantly different from day one post and day two post was observed to be different from day two pre.

Figure 6.3 V̇O$_2$ during 2d load carriage

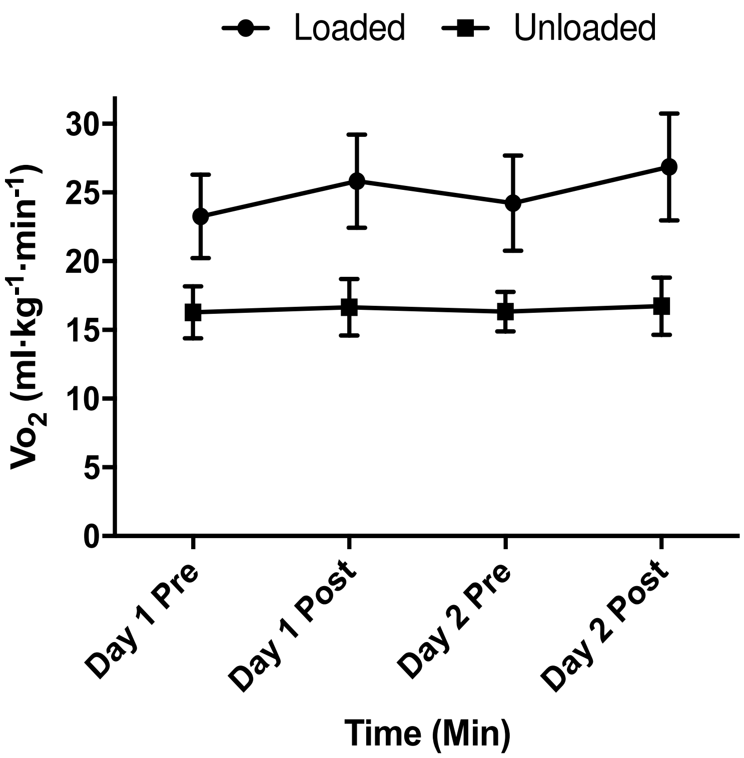


Figure displays means with standard error bars. V̇O$_2$ for the loaded group was shown to be statistically significantly different from baseline at day one post and day two post time points. Day two post was observed to be statistically different from day two pre and day one post.

Analysis shows that for EE (Table 6.2), V̇O$_2$ (Table 6.2) and V̇Co$_2$ there is a main effect for the effect of load in addition to the interaction effects reported in the table. Post hoc assessment identified that the loaded group had significantly higher EE in comparison to baseline at all time points and both d2 measures were significantly different to d1 post. Specifically, estimated EE for d2 pre was significantly lower than d1 post, while d2 post was significantly higher than d1 and d2 pre. V̇O$_2$ displayed significant difference from baseline at post d1 and post d2, although no significant change was observed from baseline at pre d2. Furthermore, V̇O$_2$ was significantly higher post d2 when compared to post d1. V̇Co$_2$ displayed no change at post d1 and pre d2 when compared to baseline; however post d2 was significantly reduced. RER shows no simple effect of load, but does show significant effects of time at both d2 post measurements suggesting that the changes in RER presented are significant but not significantly different from unloaded walking. Qualitative assessment of the effect sizes suggest that all differences were large.

Table 6.4 Individual differences selected from selected time points

	Day 1	Day 2	Recovery	Total task
EE	2.79	0.40	0.41	0.45
VO_2	3.43	0.71	0.68	0.75
VCO_2	2.83	0.75	0.95	0.44
RER	5.17	-	-	-

Extremely large individual differences were observed for EE, $\dot{V}O_2$, $\dot{V}CO_2$ and RER at d1 while at d2 moderate individual differences were observed for EE while $\dot{V}O_2$ and $\dot{V}CO_2$ demonstrated large individual differences. Much greater variance is observed on d1 compared to d2.

Ground Reaction Forces

Table 6.5.1 Mean values and standard deviations, along with effect sizes (eta^2) when significance was observed for VGRF and APGRF variables

Variable	Group	n	Day 1		Day 2		Day 3	Eta^2
			Baseline (SD)	Post (SD)	Pre (SD)	Post (SD)	(SD)	
Loading Peak	**Unloaded**	**14**	**1.369 (0.121)**	**1.306 (0.141)**	**1.343 (0.098)**	**1.360 (0.108)**	**1.340 (0.062)**	**0.52**
	Loaded	**12**	**1.922 (0.208)**	**1.899 (0.306)**	**2.020 (0.188)*†**	**2.079 (0.270)*†**	**2.038 (0.216)***	
Force Minimum	Unloaded	14	0.473 (0.102)	0.474 (0.108)	0.486 (0.090)	0.485 (0.083)	0.487 (0.076)	
	Loaded	12	0.689 (0.221)	0.637 (0.218)	0.671 (0.173)	0.679 (0.223)	0.587 (0.118)	
Thrust Maximum	Unloaded	14	1.163 (0.111)	1.131 (0.141)	1.159 (0.083)	1.189 (0.098)	1.144 (0.082)	
	Loaded	12	1.668 (0.235)	1.635 (0.339)	1.631 (0.266)	1.761 (0.350)	1.517 (0.204)	
Average V Impulse	Unloaded	14	0.621 (0.245)	0.624 (0.266)	0.623 (0.245)	0.601 (0.192)	0.632 (0.236)	
	Loaded	12	0.730 (0.112)	0.712 (0.156)	0.741 (0.090)	0.813 (0.213)	0.849 (0.299)	
Total V Impulse	**Unloaded**	**14**	**173.549 (68.983)**	**183.226 (77.549)**	**181.330 (74.493)**	**173.298 (49.419)**	**185.080 (74.657)**	
	Loaded	**12**	**176.876 (45.848)**	**176.746 (51.596)**	**227.596 (33.008)*†**	**253.245 (75.223)*†**	**254.832 (89.716)*†**	**0.22**
First Positive Rate	Unloaded	14	7.956 (3.423)	14.427 (5.376)	14.035 (3.398)	14.506 (2.027)	15.593 (3.488)	
	Loaded	12	17.225 (9.432)	22.395 (6.490)	24.212 (5.291)	22.791 (3.917)	25.582 (5.259)	
Second Positive Rate	Unloaded	14	6.276 (3.144)	5.255 (2.634)	5.532 (2.478)	5.662 (1.765)	5.628 (2.286)	
	Loaded	12	9.235 (2.654)	9.775 (2.687)	8.778 (2.090)	10.210 (3.348)	7.774 (3.116)	
First Negative Rate	Unloaded	14	-8.164 (2.938)	-7.403 (2.791)	-7.139 (2.002)	-7.918 (2.121)	-7.226 (2.588)	
	Loaded	12	-9.206 (3.176)	-10.367 (2.514)	-10.979 (2.705)	-11.629 (3.816)	-10.496 (5.338)	
Second Negative Rate	Unloaded	14	-12.895 (4.268)	-12.366 (4.147)	-12.899 (3.958)	-13.821 (3.488)	-12.616 (4.030)	
	Loaded	12	-20.735 (3.078)	-20.051 (3.886)	-20.564 (3.896)	-20.883 (5.072)	-17.795 (5.329)	
Max Braking Force	Unloaded	14	-0.330 (0.055)	-0.305 (0.050)	-0.337 (0.072)	-0.334 (0.047)	-0.320 (0.041)	
	Loaded	12	-0.442 (0.093)	-0.444 (0.109)	-0.466 (0.061)	-0.488 (0.073)	-0.480 (0.087)	
Max Propulsive Force	Unloaded	14	0.299 (0.041)	0.277 (0.043)	0.283 (0.044)	0.292 (0.033)	0.286 (0.032)	
	Loaded	12	0.427 (0.052)	0.417 (0.070)	0.423 (0.054)	0.443 (0.058)	0.420 (0.047)	
Braking Impulse	Unloaded	14	-0.055 (0.023)	-0.052 (0.021)	-0.062 (0.033)	-0.054 (0.022)	-0.055 (0.022)	
	Loaded	12	-0.062 (0.010)	-0.061 (0.014)	-0.065 (0.006)	-0.070 (0.019)	-0.078 (0.033)	
Propulsive Impulse	Unloaded	14	0.049 (0.017)	0.049 (0.019)	0.048 (0.017)	0.047 (0.014)	0.050 (0.019)	
	Loaded	12	0.060 (0.008)	0.060 (0.011)	0.060 (0.007)	0.068 (0.017)	0.071 (0.023)	

Table 6.5.1 * Denotes statistical significance from baseline while † denotes significance from post d1. Bold text highlights a significant interaction effect to $p<0.05$. Magnitude variables are expressed as BW, while rates are explained as BW·S^{-1} and impulses are presented as BW·S.

Significant and large interactions were observed for loading peak ($p < 0.05$) with significant increases occurred in the loaded group between baseline and d2 pre and post and d3. Also changes were observed between post d1 and d2 pre and post and d3. The same profile was observed for total vertical impulse.

Table 6.5.2 Mean values and standard deviations, along with effect sizes (eta^2) when significance was observed for MLGRF variables

Variable	Group	n	Day 1		Day 2		Day 3	Eta^2
			Baseline (SD)	Post (SD)	Pre (SD)	Post (SD)	(SD)	
Mediolateral Minimum	Unloaded	14	-0.074 (0.031)	-0.072 (0.028)	-0.074 (0.028)	-0.073 (0.026)	-0.078 (0.029)	
	Loaded	12	-0.074 (0.020)	-0.077 (0.025)	-0.170 (0.275)	-0.089 (0.028)	-0.092 (0.062)	
Mediolateral Maximum	Unloaded	14	0.075 (0.018)	0.066 (0.021)	0.068 (0.016)	0.069 (0.013)	0.066 (0.015)	
	Loaded	12	0.082 (0.026)	0.076 (0.031)	0.077 (0.026)	0.087 (0.037)	0.104 (0.030)	
Medial Impulse	Unloaded	14	-0.005 (0.003)	-0.005 (0.003)	-0.005 (0.004)	-0.005 (0.002)	-0.005 (0.002)	
	Loaded	12	-0.008 (0.007)	-0.007 (0.005)	-0.009 (0.009)	-0.007 (0.004)	-0.008 (0.006)	
Lateral Impulse	Unloaded	14	0.049 (0.017)	0.05 (0.019)	0.050 (0.017)	0.047 (0.014)	0.050 (0.019)	
	Loaded	12	0.061 (0.008)	0.061 (0.011)	0.061 (0.008)	0.069 (0.017)	0.071 (0.023)	
mediolateral Impulse	Unloaded	14	-0.006 (0.011)	-0.003 (0.005)	-0.015 (0.029)	-0.008 (0.009)	-0.007 (0.008)	
	Loaded	12	-0.002 (0.007)	0.000 (0.008)	-0.005 (0.007)	-0.007 (0.006)	-0.009 (0.010)	
Medial Lateral Ratio	Unloaded	14	0.149 (0.038)	0.138 (0.028)	0.142 (0.035)	0.142 (0.023)	0.143 (0.033)	
	Loaded	12	0.156 (0.025)	0.153 (0.033)	0.168 (0.028)	0.175 (0.034)	0.196 (0.076)	

Magnitude variables are expressed as BW, while rates are explained as BW·S^{-1} and impulses are presented as BW·S.

Table 6.5.3 Mean values and standard deviations, along with effect sizes (eta^{2}) when significance was observed for absolute time (T) variables

Variable	Group	n	Day 1		Day 2		Day 3	Eta^{2}
			Baseline (SD)	Post (SD)	Pre (SD)	Post (SD)	(SD)	
T to Loading Peak	Unloaded	14	0.105 (0.023)	0.116 (0.036)	0.107 (0.030)	0.114 (0.019)	0.113 (0.025)	
	Loaded	12	0.162 (0.026)	0.184 (0.106)	0.157 (0.024)	0.169 (0.058)	0.145 (0.026)	
T to Force Minimum	**Unloaded**	**14**	**0.286 (0.023)**	**0.292 (0.027)**	**0.295 (0.034)**	**0.296 (0.029)**	**0.299 (0.033)**	**0.11**
	Loaded	**12**	**0.440 (0.030)**	**0.439 (0.031)**	**0.438 (0.035)**	**0.439 (0.040)**	**0.427 (0.028)**	
T to Thrust Maximum	**Unloaded**	**14**	**0.447 (0.032)**	**0.454(0.053)**	**0.465 (0.056)**	**0.462 (0.060)**	**0.462 (0.058)**	**0.11**
	Loaded	**12**	**0.683 (0.055)**	**0.652(0.111)**	**0.678 (0.054)**	**0.671 (0.084)**	**0.654 (0.037)**	
Stance Time	**Unloaded**	**14**	**0.575 (0.043)**	**0.596(0.062)**	**0.597 (0.069)**	**0.613 (0.066)***	**0.601 (0.068)**	**0.11**
	Loaded	**12**	**0.880 (0.069)**	**0.88(0.077)**	**0.873 (0.074)**	**0.890 (0.110)**	**0.834 (0.053)**	
T to Max Braking Force	**Unloaded**	**14**	**0.078 (0.021)**	**0.082(0.022)**	**0.082 (0.027)**	**0.083 (0.024)**	**0.082 (0.026)**	**0.12**
	Loaded	**12**	**0.131 (0.024)**	**0.124 (0.029)**	**0.120 (0.020)**	**0.125 (0.034)**	**0.105 (0.024)**	
T to Maximum Propulsive Force	Unloaded	14	0.498 (0.038)	0.514 (0.054)	0.518 (0.063)	0.520 (0.056)	0.520 (0.061)	
	Loaded	12	0.761 (0.06)	0.760 (0.066)	0.756 (0.062)	0.763 (0.079)	0.721 (0.041)	
T to ML Maximum	Unloaded	14	0.180 (0.131)	0.141 (0.065)	0.146 (0.059)	0.152 (0.051)	0.181 (0.092)	
	Loaded	12	0.420 (0.243)	0.419 (0.176)	0.257 (0.153)	0.328 (0.183)	0.219 (0.179)	
T to ML Minimum	Unloaded	14	0.051 (0.034)	0.046 (0.015)	0.063 (0.056)	0.057 (0.041)	0.046 (0.017)	
	Loaded	12	0.072 (0.074)	0.062 (0.026)	0.166 (0.199)	0.101 (0.121)	0.118 (0.148)	
T from Medial to Lateral Peak	Unloaded	14	-0.129 (0.110)	-0.093 (0.064)	-0.090 (0.055)	-0.101 (0.061)	-0.091 (0.117)	
	Loaded	12	-0.349 (0.194)	-0.357 (0.157)	-0.119 (0.112)	-0.175 (0.082)	-0.170 (0.172)	

All variables were measured in seconds. Bold text signifies significance to $p<0.05$.

Moderate interactions for stance time were observed ($p < 0.01$) which post hoc pairwise analysis highlight was signified by a maintenance of longer stance time for the loaded group through the duration of testing but an increase of stance time for the unloaded group between baseline and post d2 ($p < 0.01$).

The increase in stance time for the unloaded group was accompanied by significant increases in time to force min ($p < 0.05$) time to trust maximum ($p < 0.05$) time to max braking ($p < 0.05$) and time to max propulsive force ($p < 0.05$), post hoc analysis showed no significant changes. Numerous trends correspond to changes with stance time, demonstrating maintenance of stance time for the loaded group and a general lengthening for the unloaded group. No changes were observed for any temporal variable when considered as a percentage of stance time.

Table 6.5.4 Mean values and standard deviations, along with effect sizes (eta^2) when significance was observed for absolute temporal variables

Variable (%)	Group	n	Day 1		Day 2		Day 3	Eta^2
			Baseline (SD)	Post (SD)	Pre (SD)	Post (SD)	(SD)	
Time to loading Peak	Unloaded	14	18.123 (3.488)	18.258 (3.988)	18.385 (4.863)	18.313 (3.532)	19.213 (3.826)	
	Loaded	12	26.076 (3.507)	24.871 (4.022)	25.714 (4.007)	24.131 (4.418)	23.895 (4.057)	
Time to Force Minimum	Unloaded	14	49.684 (2.744)	49.058 (2.564)	50.690 (4.516)	50.300 (4.975)	51.176 (4.726)	
	Loaded	12	70.823 (3.098)	70.635 (3.653)	71.741 (4.460)	59.203 (20.354)	71.328 (3.583)	
Time to Thrust Maximum	Unloaded	14	77.775 (1.528)	77.309 (1.610)	80.003 (7.281)	79.424 (7.902)	78.990 (7.926)	
	Loaded	12	109.832 (5.417)	109.731 (5.095)	111.307(6.287)	99.698 (18.402)	109.280 (4.574)	
Time to Maximum Braking Force	Unloaded	14	13.516 (3.288)	13.668 (3.227)	14.050 (4.329)	14.039 (4.064)	14.045 (4.174)	
	Loaded	12	20.842 (3.282)	20.091(3.912)	19.478 (3.101)	19.957 (4.716)	17.627 (3.797)	
Time to Maximum Propulsive Force	Unloaded	14	86.484 (1.285)	86.230 (1.449)	89.018 (7.732)	88.194 (9.101)	88.855 (7.796)	
	Loaded	12	122.508 (5.407)	122.125 (5.733)	123.995 (7.553)	120.306 (6.623)	120.386 (3.960)	
Time to ML Maximum	Unloaded	14	31.430 (23.326)	25.609 (12.522)	25.913 (9.453)	26.049 (9.423)	27.206 (12.885)	
	Loaded	12	67.017 (36.858)	73.731 (34.700)	37.423 (21.259)	67.650 (43.958)	35.998 (28.596)	
Time to ML Minimum	Unloaded	14	8.903 (6.009)	7.735 (2.454)	9.698 (8.775)	10.550 (9.900)	11.713 (12.782)	
	Loaded	12	11.384 (11.479)	15.319 (13.618)	31.350 (33.324)	16.578 (20.392)	19.400 (24.234)	

All variables in the above table are presented as percentages of stance time.

Neuromuscular Function

Table 6.6 Mean values for NMF change scores, alongside statistical significance and effect sizes

Variable		Group	n	Baseline (SD) (N·M)	Day 1 Post (%)	Day 2 Pre (%)	Day 2 Post (%)	Day 3 (%)	*p*-Value	Significance	Eta^2
Knee Extension 180°s^{-1}	**Max**	**Unloaded**	**14**	**135.6 (38.7)**	**0.8 (8.2)**	**3 (8.7)**	**3.5 (12.8)**	**5.1 (10.6)**	**0.022**	**Load*Time, Load**	**0.13**
		Loaded	**12**	**166.0 (49.8)**	**-11.1 (10.4)***	**-0.9 (5.9)**	**-8.8 (14.7)*†‡**	**0.1 (10.7)**			
	Average	**Unloaded**	**14**	**126.9 (37.5)**	**2.4 (12.6)**	**6.4 (11.5)**	**6.8 (14.4)**	**7.8 (10.2)**	**0.038**	**Load*Time, Load**	**0.52**
		Loaded	**12**	**161.6 (48.9)**	**-17 (27.1)***	**-1.3 (5.6)**	**-9.3 (16.0)**	**-0.7 (9.9)**			
Knee Extension 60°s^{-1}	**Max**	**Unloaded**	**14**	**178.3 (36)**	**-1.2 (11.9)**	**-5.3 (9.0)**	**-3.3 (7.7)**	**-1.3 (9.3)**	**0.041**	**Load*Time, Load**	**0.10**
		Loaded	**12**	**228.9 (97.2)**	**-15.2 (14.3)***	**-9.6 (12.3)***	**-15.4 (10.5)*†‡**	**-11.5 (10.8)***			
	Average	Unloaded	14	169.8(38.7)	-1.1 (9.3)	-2.2 (12.9)	-1.7 (10.1)	-2.5 (8.7)	0.058	Load	
		Loaded	12	210.4 (79.8)	-12.3 (12.1)	-7.0 (9.0)	-14 (10.5)	-8.5 (7.8)			
Knee Extension 0°s^{-1}	**Max**	**Unloaded**	**14**	**222.8 (67.7)**	**-0.5 (10.2)**	**-3.3 (10.2)**	**-5 (12.9)**	**-1.2 (16.2)**	**0.009**	**Load*Time, Load**	**0.16**
		Loaded	**12**	**281.4 (116.1)**	**-9.2 (11.1)***	**-11.9 (10.4)***	**-18.7 (21.0)*†‡**	**-11.3 (12.5)***			
Knee Flexion 180°s^{-1}	Max	Unloaded	14	76.5 (29.1)	0.2 (12.1)	3.8 (18.1)	0.5 (20.1)	6.0 (20.2)	0.930		
		Loaded	12	106.8 (41.4)	-13.0 (19.1)	-7.0 (15.3)	-18.1 (18.7)	-9.6 (19.0)			
	Average	Unloaded	14	73.4 (28.4)	1.2 (13.8)	3.0 (23.2)	-0.9 (24.7)	4.4 (27.2)	0.203	Load	
		Loaded	12	100.8 (38.8)	-12.9 (20.1)	-6.4 (18.1)	-18 (19.5)	-8.0 (22.8)		p=0.065	
Knee Flexion 60°s^{-1}	Max	Unloaded	14	97.6 (33.0)	7.2 (6.7)	4.1 (7.9)	13.3 (7.5)	11.3 (7.9)	0.260		
		Loaded	12	118.4 (39.5)	8.3 (12.7)	4.0 (9.3)	11.5 (12.6)	8.2 (16.9)			
	Average	Unloaded	14	91.4 (30.2)	7.2 (7.3)	4.2 (6.9)	14.8 (9.7)	11.0 (7.5)	0.399		
		Loaded	12	112.8 (38.4)	9.3 (12.0)	3.3 (8.5)	11.9 (12.8)	8.3 (16.2)			
Knee Flexion 0°s^{-1}	Max	Unloaded	14	91.8 (32.9)	-2.4 (4.6)	-4.4 (13.5)	-4.3 (17.3)	-5.3 (11.1)	0.442		
		Loaded	12	102.0 (31.7)	-4.4 (14.2)	-0.2 (12.4)	-10.0 (19.5)	-7.2 (20.0)			

* Denotes statistical significance from baseline, while † denotes significance from post d1 and ‡ denotes significance to d2 pre. Bold text highlights a significant interaction effect to $p < 0.05$.

In table 6.6 knee extension observed significant reductions at most post d1 measurements without the exception of knee extension at 60°s^{-1} (average). Equivalent significant reductions were observed between d2 pre and d2 post change scores with the exception of Knee extension at 180°s^{-1} (average). Knee extension at 180°s^{-1} max, 60°s^{-1} max and 0°s^{-1} max observed a greater reduction in NMF at d2 post than d1 post, of these 60°s^{-1} max and 0°s^{-1} max did not return to baseline after 24 hours recovery at either d2 pre or d3.

In table 6.7 ankle plantarflexion at 120°s^{-1}(max), 60 °s^{-1} (max) and 0°s^{-1} were reduced at the d1 post, of these variables 120°s^{-1}(max) did not return to baseline. Ankle plantarflexion at 0°s^{-1} was shown to display large reductions (36.1%) at the d2 post time point. All ankle plantarflexion measures were represented by very high standard deviations.

Table 6.7 Mean values for NMF change scores, alongside statistical significance and effect sizes

Variable		Group	n	Baseline (SD) (N·M)	Day 1 Post (%)	Day 2 Pre (%)	Day 2 Post (%)	Day 3 (%)	*p*-Value	Significance	Eta^2
Ankle Plantarflexion 120°s^{-1}	**Max**	**Unloaded**	**14**	**57.7 (19.3)**	**4.4 (11.4)**	**11.5 (17.9)**	**9.4 (15.1)**	**7.5 (28.7)**	**0.016**	**Load*Time, Load**	**0.16**
		Loaded	**12**	**58.1 (24.3)**	**-15.0 (13.8)***	**-1.7(19.0)***	**-6.5 (29.7)**	**-8.1 (13.0)**			
	Average	Unloaded	14	53.7 (20.0)	7.0 (20.3)	16.4 (21.2)	13.1 (19.3)	12.8 (28.1)	0.114	Load	
		Loaded	12	53.0 (22.7)	-12.3 (13.7)	1.8 (20.6)	-4.0 (28.6)	-5.0 (12.6)			
Ankle Plantarflexion 60°s^{-1}	**Max**	**Unloaded**	**14**	**70.0 (20.4)**	**15.9 (44.1)**	**13 (29.5)**	**24.9 (34.7)**	**19.1 (10.6)**	**0.010**	**Load*Time, Load**	**0.17**
		Loaded	**12**	**86.1 (26.7)**	**-0.0 (24.1)***	**-7.9 (25.2)**	**-13.8 (26.7)**	**-20.1 (18.9)**			
	Average	**Unloaded**	**14**	**64.5 (20.2)**	**-0.3 (13.2)**	**16.7 (32.0)**	**28.3 (36.6)**	**22.9 (15.7)**	**0.023**	**Load*Time, Load**	**0.17**
		Loaded	**12**	**80.3 (25.9)**	**-14.5 (13.6)**	**-1.5 (31.9)**	**-14.6 (25.1)**	**-13.5 (26.9)**			
Ankle Plantarflexion 0°s^{-1}	**Max**	**Unloaded**	**14**	**76.9 (32.3)**	**11.5 (33.2)**	**7.8 (34.0)**	**23.6 (36.0)**	**16.1 (19.6)**	**<0.0001**	**Load*Time, Load**	**0.29**
		Loaded	**12**	**113.8 (37.7)**	**-18.4 (16.8)***	**-9.1 (24.2)**	**-36.1 (21.8)*†**	**-1.8 (29.4)**			
Ankle Dorsiflexion 120°s^{-1}	Max	Unloaded	14	17.5 (8.7)	-5.8 (19.3)	5.5 (28.6)	-30.0 (34.2)	-1.6 (52.4)	0.111		
		Loaded	12	19.4 (6.5)	-15.0 (23.7)	-14.4 (15.0)	-22.1 (30.7)	-0.1 (23.9)			
	Average	Unloaded	14	12.0 (5.8)	11.9 (46.0)	27.3 (33.8)	-8.3 (41.6)	15.9 (44.1)	0.142	Load	
		Loaded	12	18.9 (7.3)	-18.5 (21.6)	-20.6 (20.4)	-26.1 (30.4)	-0.0 (24.1)			
Ankle Dorsiflexion 60°s^{-1}	Max	Unloaded	14	19.0 (5.7)	-3.3 (26.0)	1.9 (18.0)	-8.7 (18.2)	-2.6 (15.9)	0.335		
		Loaded	12	25.6 (6.5)	-7.3 (25.5)	-15.6 (17.6)	-18.4 (23.1)	-3.8 (26.3)			
	Average	Unloaded	14	17.7 (5.6)	-7.6 (31.5)	-3.7 (13.9)	0.7 (26.7)	-5.7 (19.4)	0.302		
		Loaded	12	24.0 (6.2)	-10.5 (21.3)	-16.8 (18.3)	-18.7 (22.8)	-7.1 (23.9)			
Ankle Dorsiflexion 0°s^{-1}	Max	Unloaded	14	18.7 (10.2)	5.2 (30.3)	1.8 (34)	8.6 (28.4)	16.5 (33.1)	0.330		
		Loaded	12	26.5 (12.5)	-37.8 (68.4)	-17.6 (25.2)	-14.6 (30.7)	-26.1 (17.1)			

Figure6.4 Knee extension NMF at 180°s^{-1}(max)

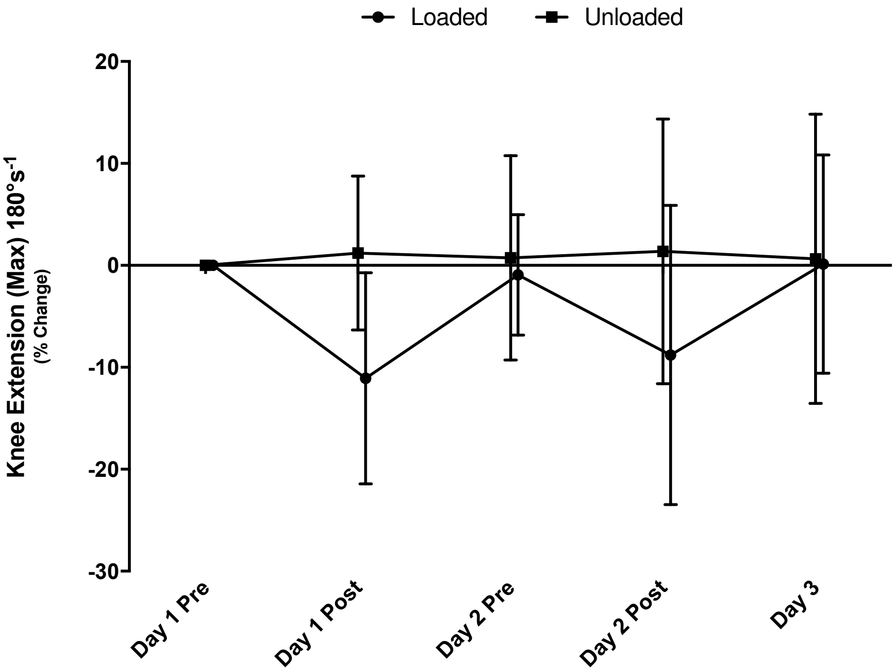


Figure displays means with standard error bars. Statistically significant differences from baseline were observed in the loaded group at day one post and day two post time points. While day two post was observed to be different from day one post and day two pre.

Figure 6.5 Knee flexion NMF 180°s^{-1} (max)

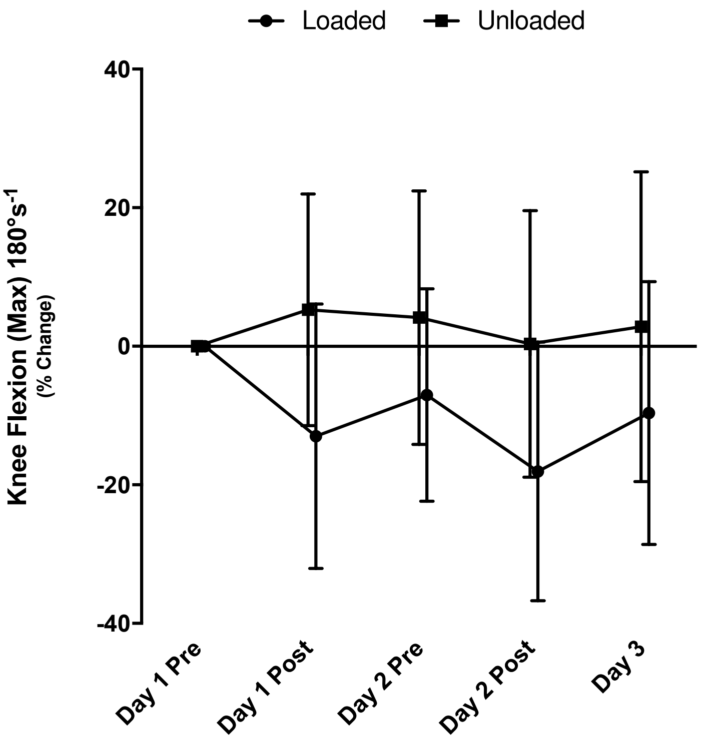


Figure displays means with standard error bars. No significant differences were observed

For knee extension at 180°s^{-1} (max)(Figure6.4), statistical significant univariate effects were observed with the loaded group experiencing a reduction in NMF. This can be further explained by an interaction effect with significance between d1 pre and post, d2 pre and post, and d2 pre and d1 post. No significant interaction effect was observed for knee flexion (Figure 6.5), however, the temporal trend follows that of the knee extensors.

Table 6.8 Individual differences for NMF variables

Variable		Day 1	Day 2	Recovery	Total Task
Knee Extension 180°s^{-1}	Max	0.25	0.13	0.26	0.27
	Average	0.22	-	0.36	0.21
Knee Extension 60°s^{-1}	Max	1.29	0.54	0.25	0.97
	Average	0.78	0.46	0.05	0.56
Knee Extension 0°s^{-1}	Max	0.28	0.27	0.14	0.44
Knee Flexion 180°s^{-1}	Max	0.44	0.34	0.30	0.34
	Average	0.45	0.19	0.25	0.30
Knee Flexion 60°s^{-1}	Max	-	0.32	0.28	0.14
	Average	0.12	0.21	0.20	-
Knee Flexion 0°s^{-1}	Max	0.37	0.31	0.20	0.48
Ankle Plantarflexion 120°s^{-1}	Max	-	-	0.36	0.29
	Average	0.16	-	0.32	0.18
Ankle Plantarflexion 60°s^{-1}	Max	-	0.38	0.25	0.24
	Average	-	0.36	0.21	0.05
Ankle Plantarflexion 0°s^{-1}	Max	0.42		0.35	
Ankle Dorsiflexion 120°s^{-1}	Max	0.57	-	-	-
	Average	0.63	-	-	0.37
Ankle Dorsiflexion 60°s^{-1}	Max	0.11	-	-	-
	Average	0.85	-	-	0.09
Ankle Dorsiflexion 0°s^{-1}		0.12	0.24	0.66	0.57

Large individual differences were observed at d1 for knee extension 60°s^{-1} (maximum and average) and ankle dorsiflexion 60°s^{-1} (average), with moderate effect sizes for ankle dorsiflexion at 120°s^{-1} maximum and minimum. A moderate effect size was observed for knee extension 60°s^{-1} (maximum). A moderate effect size was observed for ankle dorsiflexion MVC at the recovery time point, the ankle action also observed the same effect for the total task point. The recovery time was considered the difference between post d1 and pre d2. The total task was considered the differences between the d1 pre point and d3, at which point the knee extensors at 60°s^{-1} (maximum) were the only variable to observe a large effect size.

Associations

Correlations were chosen from analysis of the findings of previous chapters. All analysed correlations are presented below.

Table 6.9 Correlations between energy expenditure and GRF and NMF variables

Variable 1	Variable 2	r	VE	*p*-Value
Energy Expenditure	Loading Peak	0.39	15.08	
	Force Minimum	-0.43	18.45	
	Thrust Maximum	-0.35	12.20	
	Second Positive Rate	**-0.53**	**25.39**	**$p<0.05$**
	Max Propulsive Force	-0.39	15.36	
	Medial Impulse	0.48	22.81	
	Knee Extension 0◦s^{-1}	-0.37	13.81	
	Knee Extension 60◦s^{-1} Max	-0.37	13.76	
	Knee Flexion 0◦s^{-1}	**-0.57**	**32.20**	**$p<0.05$**
	Knee Extension 60◦s^{-1} Max	**-0.54**	**28.59**	**$p<0.05$**
	Knee Flexion 180◦s^{-1} Max	-0.44	19.57	
	Ankle Plantarflexion 0◦s^{-1}	**-0.63**	**39.47**	**$p<0.05$**
	Ankle Plantarflexion 60◦s^{-1} Max	-0.37	13.61	
	Ankle Dorsiflexion 0◦s^{-1}	-0.36	12.59	
	Ankle Dorsiflexion 120◦s^{-1} Max	0.40	15.87	

Table 6.10 Correlations between NMF variables and GRF variables

Variable 1	Variable 2	r	VE	*p*-Value
Ankle Dorsiflexion 60◦s^{-1} Max	Stance Time	0.44	19.34	
	Thrust Maximum	0.34	11.59	
Knee Flexion 60◦s^{-1} Max	Second Negative Rate	0.43	19.14	
Knee Extension 60◦s^{-1} Max	**Force Minimum**	**0.71**	**49.89**	**$p<0.01$**
Ankle Plantarflexion 60◦s^{-1} Max	**Thrust Maximum**	**0.93**	**85.92**	**$p<0.001$**
	Average Vertical Impulse	**-0.72**	**52.26**	**$p<0.01$**
	Second Positive Rate	**0.84**	**71.25**	**$p<0.001$**
	First Negative Rate	0.51	26.30	
	Second Negative Rate	**-0.91**	**83.08**	**$p<0.001$**
	Maximum Braking Force	**-0.93**	**85.99**	**$p<0.001$**
	Maximum Propulsive Force	**0.95**	**89.42**	**$p<0.001$**

For all significant findings follow-up analysis was conducted on the unloaded group. No significant findings were observed for any measure.

Secondary Analysis

Table6.11 Metabolic change scores for d1 and d2 presented concurrently

Variable	Group	Day 1		Day 2		*p*-Value
		Baseline (SD)	Change Score (SD)	Baseline (SD)	Change Score (SD)	
EE ($cal·kg·min^{-1}$)	Unloaded	5.96 (1.14)	1.21 (3.40)	5.95 (0.93)	0.02 (4.18)	0.332
	Loaded	8.91 (1.96)	8.49 (7.23)	9.30 (2.06)	8.94 (6.31)	
VO_2 ($ml·kg·min^{-1}$)	Unloaded	16.28 (1.89)	2.69(3.30)	16.33 (1.45)	1.43 (4.98)	0.291
	Loaded	23.26 (3.06)	9.56 (7.14)	24.23 (3.47)	10.96 (6.43)	
VCO_2 ($ml·kg·min^{-1}$)	Unloaded	13.98 (1.80)	-4.37 (6.43)	13.64 (1.58)	-5.20 (6.31)	0.383
	Loaded	20.53 (3.20)	0.96 (5.25)	21.15 (3.63)	0.33 (7.40)	
RER	Unloaded	0.86 (0.04)	-6.66 (5.40)	0.84 (0.06)	-6.40 (6.87)	0.351
	Loaded	0.88 (0.05)	-8.15 (0.05)	0.87 (0.04)	-9.49 (4.78)	

When compared by non-corrected T-test, change scores between both days were not significantly different for any parameter.

6.4 Discussion

The primary finding of this study is that EE was shown to not return to baseline 24 hours after day one, this lead to an elevation in EE throughout day two which was higher than day one, which enables the positive conclusion of the main hypothesis and of secondary hypothesis (1). This section will further discuss this change and possible mechanisms of the change in EE. In terms of secondary hypothesis (2) this chapter did find partial support that two days of load carriage instigates a greater reduction in NMF than a single day load carriage for some variables, however large variance in the findings were observed suggesting that while the hypothesis should be partially accepted in this instance, the findings should be taken with caution.

As with the two previous chapters and previous work (Bennett et al., 2013, Coombes and Kingswell, 2005, Grenier et al., 2012b, Lyons et al., 2003) this study observed load carriage to elicit an EE response approximately 40% greater than the unloaded group. This study demonstrates that there is greater energy expenditure at baseline for the loaded group compared to unloaded walking, these findings are in agreement with chapter 4, providing further support the previous studies. Furthermore the change in energy expenditure as a result of load carriage in d1 was shown to be comparable to previous studies (Epstein et al., 1988, Mullins et al., 2015, Patton et al., 1991) , which observed respiratory drift between 10 and 18% from baseline, and the previous chapter which observed an increase of 9.2%. At the start of d2 (24hours from the start of d1) energy expenditure was shown to be significantly elevated compared to baseline (4.4%). This suggests that while there is recovery in the 24hours after a load carriage task, participants were starting d2 in a less economical state, and as a consequence at the completion of d2 participants were significantly less economical (d1post 8.48% v d2 post 13.68%) than at the completion of d1.

Secondary analysis suggests that there were no differences between change scores for either day, suggesting that while the task required significantly greater energy expenditure on d2, the does not appear to be an exponential (the magnitude of d2 change was not larger than then d1 change) increase in energy expenditure. In fact, the post d2 changes appear to be proportional to the elevation above baseline at the start of d2. $\dot{V}O_2$ showed a temporal profile very similar to energy expenditure, however at the d2 pre measurement $\dot{V}O_2$ was found to be nearing statistically significance in comparison to baseline (p= 0.078). These findings are novel; this study is the first to report that repeated day activity causes increased energy cost on consecutive days.

$\dot{V}Co_2$ was shown to remain relatively stable through all timepoints, mixed methods ANOVA observed significant difference with a small effect size. Post hoc pairwise analysis suggests a significant change of -6.23% for unloaded and 3.06% for the loaded group between baseline and post d2. The apparent difference in response between $\dot{V}O_2$ and $\dot{V}Co_2$ values suggests that there is a change in whole body substrate oxidation. This can be observed in the RER values which demonstrated a main effect for time.

Participants' diets were not controlled between groups; consequently conclusions drawn from substrate oxidation must be taken with caution. However, participants arrived in the laboratory in a rested state on d1 and did not consume food and only drank water, testing was usually conducted early morning. Both days displayed a similar response of a reduction from a predominantly carbohydrate substrate utilisation to fat utilisation during the two hours unloaded and loaded walking with a complete recovery 24hours post d1.

Findings in this study differ from Blacker et al. (2009b) but are in agreement with the previous chapter, while Blacker (2009) observed no difference in RER through the duration of testing, this study observed an effect as a result of time, suggesting a gradual change from carbohydrates to fats during two hours of walking. Reduced glycogen stores have been associated with lower running economy (Rapoport, 2010) and as such may have an effect of the observed $\dot{V}O_{2drift}$. However, there was no interaction effect observed, and differences were still observed in energy expenditure when substrate change accounted for in the estimates of EE. The recovery to baseline at least over two days of RER suggests that change in substrate oxidation does not account for the failure of energy expenditure to recover to baseline 24hours post activity.

In response to research objective one it can be stated that load carriage on d2 does increase energy expenditure compared to d1. This elevation is due to an increased starting baseline score, due to participants not recovering to d1 baseline. There were no differences observed in change scores, for each day even when examined via paired uncorrected T-test, suggesting that the change from d1 baseline to d2 baseline is a guide of EE elevation, however further research needs to be conducted to explore whether it can be used as a predictor of d2 energy cost.

When the NMF pairwise comparisons are considered along with d_{Cohens} and d_{Glass}, it becomes clear that there are small and moderate individual effects demonstrated within the data (Smith and Hopkins, 2011). When the data is considered broken down into each day of activity, recovery and total duration, the effect sizes appear to be roughly comparable to d1 activity, there appears to be no change in individual differences. Namely d1 variance is not larger or smaller than d2.

While all measures show strong incidences of individual differences in EE and $\dot{V}O_2$ there does not appear to be evidence that individual differences get larger over consecutive days. Interestingly, this study observed the opposite, as the second day exhibited moderate and large individual differences, rather than the extremely large sizes observed as a result of d1.

Considering all individual differences were taken from the same control SD, this cannot be due to increased variance at the start of d2. While this work is unable to provide any reason for this finding it does suggest that significantly less variation in consecutive day responses than there is in a single bout of exercise. Therefore, the second research objective cannot be affirmed for all variables, as individual variability did not increase through the second testing period. While conversely, energy expenditure for d2 was noticeably higher than d1. This can be further characterised by a significant increase in $\dot{V}O_2$. It is also clear that the cause of this elevated response is the fact that EE did not return to baseline 24hours post activity. There was no evidence of a cumulative increase in energy cost, with the increase approximately proportional to the elevation above baseline at the start of d1.

It has previously been demonstrated that ankle and knee extension is significantly reduced during two hours of load carriage (Clarke et al., 1955, Blacker et al., 2013). This study identified approximately the same change scores were experienced during d1 (between 9-11%). While all knee extension measures demonstrated statistically significant differences post d1 and d2. Knee extension at $60^{\circ}s^{-1}$ max was shown to not recover to baseline 24hours post d1, while other knee extension measures suggest trends which supported this finding. It is quite plausible that the reason for not observing difference in the other measures is the large CVs which are reported. No differences were observed between the change scores of d1 and d2 in alignment with the previously discussed metabolic scores. As knee extension did not recover to baseline, the d2 post scores were seen to be elevated to greater than post d1 for the loaded participants, suggesting that there is a cumulative effect on NMF. D3 was then shown to be significantly elevated over post d1 and non-significantly higher than post d2, suggesting subsequent day tasks would elicit similar responses in line with this trend.

No significant interaction effects were observed in the knee flexors. The change scores are similar to those observed in the previous chapter, reductions in knee flexors appeared to be roughly comparable to the knee extensors which would not be expected during normal locomotion (Millet et al., 2003). This may be due to the need of the knee flexors to activate to maintain pelvis position to resist against the forward lean which is widely accepted to occur as an acute effect of load carriage (Lloyd and Cooke, 2011) or as a result of a central loss of function.

No significant changes were observed in the ankle dorsiflexor measurements, this was surprising, given that reductions were observed in the previous chapter and published research (Clarke et al., 1955, Blacker et al., 2010). It is possible that this change may be due to the different statistical tests as Blacker et al. (2010) completed a pre-planned series of adjusted T-tests which while reducing possible type two errors increases the chance of a type one error. While Clarke et al. (1955) only reported T values, and the previous chapter used an ANOVA with fewer time points, all of which would imply smaller alpha levels. While there is a clear trend which suggests that the loaded group induces greater reduction in NMF than the unloaded group during both load carriage tasks, and again there appears to be no differences between the change scores of each day again, scores appear to not to return to baseline for the load group, at the end of d1 and d3 appears to be elevated beyond those at d2 pre.

Significant interaction effects were observed for ankle plantarflexor variables. It needs to be acknowledged that the was more unexplained variance in the ankle measurements than the knee variables due to the shorter range of movement, and the reduced distance to achieve target velocity. While the participant set up was completed according to BASES guidelines (Baltzopoulos et al., 2012), it is possible that due to the limb position participants were conceivably able to activate larger muscles of the quadriceps to increase the force exerted through the plate and lever arm. It is clear that both days load carriage instigates a reduction in neuromuscular output compared to unloaded walking, it is also noticeable that the ankle shows much less of a recovery between trials between groups than compared to the knee extensors and flexors. These appear to be largely in line with Clarke et al. (1955) but in contrast with Millet et al. (2011) who observed 34% and 39% change for knees and ankles respectively. However, this may be due to the greater involvement of the ankle plantarflexors required for running compared to loaded walking. Although given the numerous associations between these measures and GRF measurements during push off, this would suggest a more important role in the gait cycle during load carriage for the ankle plantarflexors than previously thought, especially when compared to unloaded walking, which observed no significant correlations.

In response to research objective 3, it is clear that d2 generated NMF changes which were greater than d1 for the knee extensors and ankle plantar flexors this was characterised by an inability to recover to baseline 24 hours after the first bout, and activity change scores which were not statistically different, suggesting that the change 24hours post d1 is an indication of elevation post d2. For measures of the knee flexors and ankle dorsiflexors there are clear trends suggesting increased demands, however there are no statistically significant findings to support this further.

While there is no research which has observed multiple bouts of load carriage performance in this manner, a number of studies have examined changes in vertical jump height as a result of military activity which contained military load carriage. Reductions in NMF have been rather small (Welsh et al., 2008), with observed changes of 5.2% to vertical jump height, which is roughly comparable to the range between 5% and 22% as a result of 2 days load carriage. This suggests that repeated days activity may not produce a globally large change. Nindl et al. (2002) suggested by taking repeated measures at 0, 24, 48 and 72 hours of simulated high-stress military exercise that VJT was reduced significantly (5.7%) between days in a similar manner to that observed in this study.

A noteworthy and novel finding is that while large to extremely large individual differences were observed for the activity phases, the recovery phases showed small and occasionally moderate individual differences. This suggests that while individual participants may have experienced different levels of NMF loss as a result of the load carriage, most participants experienced more homogenous recovery patterns. It can, therefore, be inferred that participants who experience greater reductions are less likely to fully recover to baseline, placing them in a more vulnerable position for activity on the following day. The only study to observe similar findings, beyond the current thesis, can be observed during three days of military exercise (Nindl et al., 2002) which observed increasing standard deviations for each testing bout.

This study is the first to biomechanically examine load carriage over consecutive days of prolonged load carriage. The previous chapter demonstrated a decrease in force minimum as a result of load carriage. While this study observed a similar increase between groups at baseline and through the task, no interaction effect was observed.

Interaction effects were observed for total vertical impulse as the load instigated an increase as the participants underwent load carriage. This is likely to be a function of the increase in stance time which was also observed, as discussed in the previous chapter such an increase has been observed as a result of field base load carriage (Rice et al., 2016). It is clear from these and previous acute studies (Tilbury-Davis and Hooper, 1999, Birrell et al., 2007) that stance time is lengthened in order to increase the time in order to safely decelerate the load (Rice et al., 2016) and this continues over repeated days of exercise.

In order to increase stance time while maintaining a constant walking speed changes must occur within the gait cycle, it is likely the stance time being a function of many gait parameters is a global symptom of a summation of a number of changes which cannot be observed after comparatively short walking bouts. While this study is likely to induce changes that are symptomatic of fatigue, fatigue was not deliberately induced, meaning physically demanding field studies may observe greater changes. For example when fatigue was induced by a running task to a threshold rating of perceived exertion (RPE) (Qu and Yeo, 2011) observed increases to step width, hip and trunk ROM even with low loads of 15kg. While other work has used computational modeling after a fatiguing task to suggest peroneous longus fatigue can result in greater mediolateral deviations (Gefen, 2002) can occur as a result of fatigue, while Bennett et al. (2013) observed an increase in first positive rate when participants underwent an adapted loaded Bruce protocol max test.

In response to research question 4 no change during force minimum was observed, however changes for stance time and vertical impulse were observed, these changes tend to be global markers of change which suggest other small changes may have occurred. As such, these parameters need to either be studied via induced fatigue or through substantial and physically demanding field based studies, the next chapter will attempt to address this issue.

This chapter does support the simple effects for VGRF as a result of load observed within chapters 5 and 6. Increases in vertical variables were demonstrated to be roughly proportional to the effect of the load, again this was with the exception of force minimum.

Earlier in the section EE was shown increase significantly as a result of load carriage, this was shown to occur with large individual differences between participants with participants starting d2 activity in a pre-fatigued state. Estimates of substrate utilisation suggested that this was not a cause of such changes. Significant reductions in the ankle plantarflexors and knee extensors were observed, given that these reductions only occur in two of the four muscle groups examined it is likely that this change is due to the roles these muscle groups play within locomotion, furthermore the same three way correlation between NMF, GRF, and EE variables.

Energy expenditure was shown to share moderate correlations with knee extension and ankle plantarflexion, two variables which were discussed in chapter 5 to relate to movement economy. This chapter adds further strength to that suggestion by highlighting notably strong correlations between the ankle plantarflexors and second positive rate, maximum breaking and maximum propulsive force. These relationships provide a mechanistic link between the NMF loss and energy expenditure increase. Finally this triangle is again completed by the observance of second positive rate sharing a significant association with EE.

These findings suggest that there is a strong argument for biomechanical changes accounting for a large part of $\dot{V}O_{2drift}$. That ankle strength is very important to maintaining an economical movement as the second positive rate also indicates the rate of force development in the push off phase of the gait cycle, which suggests that reduced ankle plantarflexion force is related to less economical gait push off, meaning that there is less force propelling of the body forward, meaning reduced movement economy. In order to counter these training programmes should focus on developing plantarflexor muscle and importantly the dorsiflexor muscles to maintain muscle balance.

Also, correlations to thrust maximum, average vertical impulse and max brake and propulsion can all suggest a less efficient gait patterns due to an inability to propel the body forwards in the latter stages of gait (Saunders et al., 2004). In response to research question 5, these findings suggest that reduced neuromuscular output has a substantial effect on gait and as such energy expenditure.

6.5 Conclusions

This chapter demonstrates that repeated bouts of load carriage on consecutive days instigates increased NMF demand in the knee extensors and ankle plantarflexors, which in turn can have effects on gait and EE. The chapter is the first to show that EE can increase significantly as a result of consecutive days activity, and that those changes can be indicated by elevations from baseline at the start of the second activity.

While this and previous chapters have highlighted changes in biomechanical measurements, these changes were supported by small effect sizes, therefore, some caution needs to be taken when assessing their occupational relevance. However, onus should be placed on the correlations which have been observed. As such the next chapter is going to observe biomechanical changes in a field based setting during a prolonged load carriage task. The increased relevance of the overground walking and increased load carriage time will provide a more relevant model to examine subtle biomechanical parameters.

Physiological and Biomechanical Responses of Greek Special Forces Soldiers to 43km Load Carriage in the Field

7.1 Introduction

Previous chapters within this thesis have observed load carriage in a laboratory based setting, this has enabled examination of variables such as knee extension NMF and ankle plantarflexion NMF in relation to movement economy. This has produced some interesting and valuable findings, further highlighting the importance of ankle plantarflexors in movement economy during load carriage. However, the level surface of the treadmill may not accurately reflect over ground load carriage, where participants may have to navigate uneven surfaces. The previous chapters have suggested that there may be some ML changes as a result of load carriage, however due to the level treadmill and the examination of NMF in the sagittal plane it is possible the studies have underestimated ML findings. This chapter will overcome this issue by studying load carriage in a field based environment.

The most accurate assessment of neuromuscular output is the measurement of the force producing capability of a muscle or muscle group (Warren et al., 1999). In a laboratory this is normally conducted via isokinetic dynamometry, however such complex set up is not available for field based research. The maximal vertical jump test (VJT) has been found to be a useful measure of neuromuscular performance in the field, due to its low skill component, easy repeatability and minimal equipment requirements, in fact it has previously been used in military physiology research (Welsh et al., 2008, Fallowfield et al., 2012, Nindl et al., 2002).

Generally, overuse injury has been understood to occur as a result of the deterioration of the muscular ability to produce force eccentrically to mitigate the effect of the vertical load, and therefore the ability to effectively reduce the magnitude of the foot-ground impact (Milgrom et al., 1991, Gefen, 2002, Ghori and Luckwill, 1985), over prolonged periods of load carriage these elevated bone stresses can accumulate into stress fractures (Hunt et al., 2001). A commonly used method of evaluating such impact forces is by studying the VGRF either directly via force platform or indirectly using a pressure plate.

Plantar pressure measurement has been demonstrated to be reliable in test-retest reliability (Hafer et al., 2013) when using software with a masking algorithm which associates anatomical reference points to the plantar pressure data (Bryant et al., 1999). Plantar pressure measured by insoles has been shown to share good intra class correlation coefficients with force plate comparisons (Low and Dixon, 2010). Within a military research setting pressure plates have been used in previous work (Rice et al., 2014, Rice et al., 2015) to evaluate load carriage tasks, and to generate predictors of injury risk (Franklyn-Miller et al., 2014).

To date the Institute of Naval Medicine has explored plantar pressures during walking and running post load carriage tasks (Rice et al., 2016, Rice et al., 2013b), and when examining anthropometric differences between an injured cohort and an uninjured control (Rice et al., 2013b). Recently as part of a programme identifying risk factors for metatarsal stress, Rice et al. (2016) demonstrated fatigue of the peroneus longus (PL) (signified by a reduction in mean EMG frequency), as a result of a 19.3km load carriage task by Royal Marine recruits. This change was attributed as a risk factor for increased impact force through the lower leg as a result of reduced plantar flexion strength.

Several conflicting roles have been suggested for the PL. It is described principally in biomechanical literature as a plantarflexor (Hunt et al., 2001). However in clinical research the PL is more commonly referred to as the strongest rear foot everter (Serrafian, 1983), which provides protection of the ankle joint to spraining by returning the foot from an inverted position early in the stance phase (Gefen, 2002), to a neutral position by mid stance and then stabilising the whole foot during the later stages of ground contact (Hunt et al., 2001). As such, ankle sprain has been viewed as the result of insufficient ankle control by the PL for some time (Hunt et al., 2001, Gefen, 2002, Milgrom et al., 1991, Mitchell et al., 2008, Karlsson and Andreasson, 1992, Konradsen and

Ravn, 2009) this is further supported by observations in the unpublished Institute of Naval Medicine paper which observes increased speed of rear foot eversion post load carriage, hinting at a lack of instability (Rice et al., 2016).

A step up protocol designed to intentionally fatigue (defined by a VJT score of 80% max) the Pl muscle has shown that when fatigued, participants experienced greater lateral centre of pressure (CoP) shift signifying greater instability of the ankle (Gefen, 2002). Research has shown that when fatigued the PL activates approximately 60ms later (Stacoff et al., 1996) suggesting that at heel contact there may be reduced support for the ankle. When it is considered that athletes with a prolonged PL reaction time (84ms) compared to a normal control group (69ms) experienced a reduced response to sudden inversion (Konradsen and Ravn, 2009) it is possible to postulate that any delay in PL response could result in increased injury risk.

The novel aspects of this study were that it is the first study to observe lateral changes in CoP as a result of prolonged military load carriage. At a distance of 43km, it will be by far the longest load carriage study to assess biomechanical parameters as such increasing the chance of inducing fatigue within the participants.

Research Objectives

1) Investigate whether field based prolonged load carriage causes a significant reduction in NMF of the lower limbs
2) Examine whether prolonged load carriage prompts the development of increased amplitude in impact VGRF parameters
3) Investigate whether prolonged load carriage instigates increased instability of the ankle, observed by increased medial/ lateral rate or displacement variables
4) Investigate whether greater impact amplitudes and ML instability occur through the ankle and foot system as a result of reduced NMF.

Hypothesis

As a result this chapter will test the primary hypothesis that prolonged load carriage over uneven ground will instigate a statistically significant increase in x axis deviations of the CoP variables. The secondary hypothesis is that any change in x axis deviation will be statistically significantly greater at heel contact.

7.2 Methods

Trial Design

This chapter employs an observational design without control group, measurements were taken before and after a load carriage task.

Participants

Twenty-three Special Forces Soldiers provided their informed consent to participate in the study. The soldiers had served in the military for a minimum of two years. Ethical approval for all procedure and protocol was provided by Canterbury Christ Church University Research Ethics Committee (16/SAS/264) and the Greek Military Medical Ethics Committee. All protocols were performed in accordance with the ethical standards proclaimed in the 2013 declaration of Helsinki and BASES guidelines (Winter et al., 2006), while this chapter was written in line with CONSORT guidelines (Schulz et al., 2010). Participants provided written informed consent in both Greek and English and were free from musculoskeletal injury.

Table 7.1 Table presenting participant descriptive data.

Condition	Body Mass (kg)	Stature (cm)	Age (yrs)	Males (n)	Females (n)
Loaded	82.26 (35.41)	180.54 (15.21)	27(9)	20	3

Mean values presented in table with ranges presented in brackets

The following inclusion criteria were used:

- Participants must be over 18 years old
- Participants must be free from musculoskeletal disorder which may visibly alter gait
- Participants must be declared physically fit by their commanding officer

Sample Size Calculations

G*Power (G*power: Germany) was used after data collection to confirm the sample size required was suitable for this study.

Effect size estimates were based on key variable change scores after data collection:
Vertical jump test (height) (n=3)
First lateral displacement (n=5)

Experimental Protocol

All aspects of this research were conducted by the author in the medical station at Volos military camp.

Participants were monitored during the 43km load carriage event (duration 817min). Participants carried a total external load of at least 32Kg, consisting of a bergen (27kg), M16 assault rifle (3.5kg) and boots (1.5kg). The load carriage event started at 18:00 approximately 1.5hours after participants had consumed dinner. The event was conducted at night to ensure participants were not exposed to extreme heat. All participants walked as a group with the pace dictated by the Non-Commissioned Officer in charge.

Participants carried a Global Positioning System (GPS) (Garmin ®, Garmin International Inc, Kansas, USA) for the duration of the load carriage, which recorded the participants position every second. Data were downloaded on completion of the load carriage task using activity tracking software (Garmin connect). Speed of movement, altitude and distance covered were calculated in excel.

VJT and pressure plate trials were conducted before and after the load carriage event. Due to the military demands (participants underwent a test shoot after the load carriage) post measurements were taken between one and four hours after the load carriage task and the participants wore combat trousers, top and boots, they were unloaded when they completed all measurement protocols.

Heart rate was recorded every second using downloadable heart rate monitors (Garmin ®, Garmin International Inc, Kansas, USA). Heart rates were expressed as absolute values.

Interim Analysis

No interim analysis was conducted due to the acute nature of the study.

Preliminary Measures

Stature (Seca, Seca Ltd., Birmingham, UK) (± 0.005 m) and body mass (Seca Model 880, Seca Ltd., Birmingham, UK) (± 0.01 kg) were measured whilst wearing military issue combat jacket, trousers and underwear.

Vertical Jump Test

The VJT was completed before and after the load carriage event. The jump started with the participants standing in a neutral position with their hands on their hips, they squatted down into a squat position without moving their feet, after a slight pause at the bottom of the movement, they jumped vertically with maximum effort. The vertical jump technique was demonstrated by the investigator individually to the participants before each testing session. Participants performed three practice submaximal jumps during pre-testing (previous work has explained this has no negative effect on VJT scores (Fallowfield et al., 2012). The participants then completed three maximal effort jumps. The participant's score was taken as the average of the three maximal vertical jumps.

A camera filmed the participant’s lower limbs, in the sagittal plane. Jump height was calculated as the total time that the participant’s feet were off the ground. This method was chosen due to the minimum equipment set up required.

Vertical jump height and power were calculated using the following equations:

$$VJT\ Height = \frac{(9.81 \times s)^2}{8} \tag{4}$$

Equation 7.1 Used to calculate VJT Height (cm) from time record off the ground(s).

$$VJTPower(w) = (60.7 \times cm) + (45.3 + BM) - 2055 \tag{5}$$

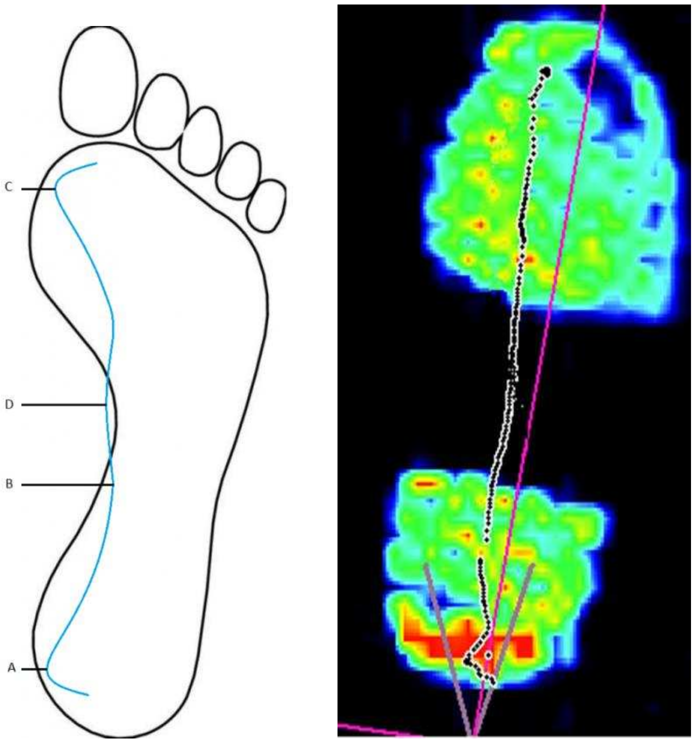
Equation 7.2 Equation used to calculate VJT power (w) derived from jump height (cm) and BM(Kg), adapted from (Sayers et al., 1999).

Pressure Plate

The participants were required to walk at a pace of 6.5km·h^{-1}±10% across a pressure platform (RSscan International, Belgium, 1068mm x 418mm x 12mm, 7192 sensors), in the middle of a 20m runway. Participants were instructed to walk naturally and to not think about hitting the platform. Participants were not instructed to “look forwards” as is common in gait trials, this was to reduce the chance that participants manipulated their gait and posture. Five successful trials were collected at 256Hz. The participants wore military issue boots, combat jacket and trousers.

Data was collected in RS Footscan software (RSscan International, Belgium), where the location of the foot strike was defined by the manual designation of masks within the software. Raw CoP co-ordinates (mm) and raw estimations of force (N) were then exported for analysis in Excel.

Figure 7.1 A typical centre of pressure (CoP) line of progression, along with a diagram presentation of key points



Markers were extracted from the raw data via excel: A) 1st maximum lateral CoP displacement, B) maximum medial CoP displacement, C) 2nd maximum lateral displacement, D) maximum Y displacement (as measured by the largest space between two measurement points on the Y axis).

These positions were then used to calculate amplitude differences, such as A-B for the lateral CoP difference. The time of each marker was then calculated to allow the assessment of temporal changes, by absolute time, percentage of total stance time and to study the rate of CoP change (Δ displacement/ Δ time). Displacement was calculated using Pythagoras theorem and the sum of all relevant co-ordinates.

The following VGRF variables were studied: A) loading peak, B) force minimum, C) thrust maximum. The known frame rate was then used to calculate the temporal characteristics of the positions as well as the average and total vertical impulse.

It is important to highlight that VGRF parameters collected from a pressure plate are estimated parameters of force. As such, while the pressure plate and its associated software was calibrated and used in line with the manufacturer's recommendations.

Environmental Conditions

Ambient temperature (°C) and humidity (%) data were obtained during data collection and at two hour intervals during the load carriage task. Average ambient temperature and humidity were recorded at 25.3°C, 45% respectively.

Statistical Analysis

SPSS for windows V23 (SPSS Chicago, Illinois) and Excel (Microsoft: USA) was used for statistical analysis. Shapiro-Wilk test was used to check the data was normally distributed. If any time points were found to be in violation of normality, then a non-parametric test was also run. In all circumstances T-tests were shown to be robust enough to withstand any violation of normality. Subsequently, differences in means were assessed using paired T-tests with an alpha level set at 0.05. Relationships between any variables were examined using Pearson correlations. d_{Cohen} and d_{Glass} were used to examine the effect size of any significant difference between means. Two effect size measurements were used as d_{Glass} uses standard deviation drawn from the control condition while d_{Cohen} uses a pooled standard deviation, as such any difference between outcomes can be a guide to individual differences in response. However such differences should only be used an estimate of individual difference.

Before change scores were compared and GRF were normalised to body mass the data were log transformed and plotted to ensure that it did not violate the previously proposed scaling guidelines (Nevill et al., 1992, Davies and Dalsky, 1997, Atkinson and Batterham, 2012).

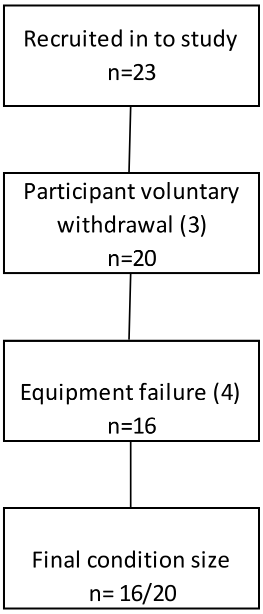
7.3 Results

Adverse Events

The researcher was not exposed to any risk or danger during this research. While the soldiers were supervised by senior officers during the march and had full medical cover, three soldiers experienced injuries, with one carried off the route.

Sample Size Profile

Figure 7.2 Flow diagram displaying participant drop out



Twenty-three participants were recruited into the study, with three failing to complete the load carriage task due to lower limb injuries and did not attend the post march testing. Due to failure of the heart rate/GPS monitors to record data for heart rate comparisons were made using n=16.

GPS

GPS recorded 43.203±0.093km of the load carriage route, with no missing data. Average speed was recorded as 4.1±0.24km·h^{-1} including rest stops, while average speed excluding rest stops was 4.2±0.18km·h^{-1}. The march was conducted between 57m and 478m above sea level which consisted of a total gain in altitude of 1048±92.3m. From a hybrid of GPS and HR data, a total distance of 17.275±0.42km was covered uphill and 14.678±0.56km was covered downhill, identified by >5min periods, while no consistent level walking was highlighted. The activity lasted 818±32min while stationary time was recorded at 78.2min±22min. During uphill walking the average speed was recorded at 3.17±0.23 km·h^{-1} with downhill walking faster at 4.4±0.73 km·h^{-1}.

Mean HR during the load carriage was 122±13beats min^{-1} and was observed to be 3.55% higher when rest stops are excluded (124±12 beats·min^{-1}) ($p<0.001$). Further analysis shows that HR was between 60beats·min^{-1} and 80 beats·min^{-1} for 8.52% of the activity, 80-100beats·min^{-1} for 27.84%,100-120beats·min^{-1} for 46.38%, 120-140beats·min^{-1} for 15.68%, 140-160beats·min^{-1} for 1.53% and >160beats·min^{-1} for 0.04%. By using the GPS classified uphill, downhill and stationary segments HR was observed to be higher for uphill 140±5 beats·min^{-1} ($p<0.001$) and lower for downhill 118±11 beats·min^{-1} ($p<0.001$) and lower again for stationary periods (111± 5beats·min^{-1}) $p<0.001$).

VJT height decreased by 18.62%±16.85% (0.304±0.08m to 0.243±0.07m) which can be used to calculate a reduction in power of 10.34±10.6% (3429.9±758.3W to 3060±717.2W).

Table7.2 Pre and post means and SD supported by standardised effect sizes and significance levels for VGRF values

Variable	n	Condition	Lower CI	Mean (SD)	Upper CI	d_{cohens}	d_{glass}	*p*-Value
Stance Time (ms)	20	Pre	650.727	679.446 (77.839)	708.164			0.232
		Post	663.019	695.909 (89.145)	728.799			
Total COP Displacement (mm)	**20**	**Pre**	**302.630**	**309.085 (17.493)**	**315.539**	**0.70**	**0.94**	***P*<0.001**
		Post	**315.831**	**325.487 (26.171)**	**335.143**			
Loading Peak (BW)	**20**	**Pre**	**1.812**	**1.949 (0.371)**	**2.086**	**0.39**	**0.44**	**0.035**
		Post	**1.950**	**2.114 (0.439)**	**2.273**			
Force Min (BW)	**20**	**Pre**	**0.853**	**0.964 (0.300)**	**1.075**	**0.44**	**0.45**	**0.015**
		Post	**0.985**	**1.1 (0.313)**	**1.216**			
Thrust Maximum (BW)	20	Pre	1.490	1.64 (0.422)	1.800			0.362
		Post	1.570	1.73 (0.423)	1.890			
Time to loading Peak (%)	**20**	**Pre**	**21.199**	**22.076 (2.379)**	**22.954**	**0.57**	**1.00**	**0.037**
		Post	**17.771**	**19.699 (5.23)**	**21.629**			
Time to Force Min (%)	20	Pre	51.384	52.839 (3.947	54.296			0.356
		Post	48.658	50.972 (6.272)	53.286			
Time to Thrust Max (%)	20	Pre	78.483	79.311 (2.245)	80.140			0.265
		Post	72.531	75.925 (9.201	79.320			
Average Vertical Impulse (BW·S)	**20**	**Pre**	**964.483**	**1062.131 (264.666)**	**1159.780**	**0.37**	**0.41**	**0.032**
		Post	**1051.036**	**1170.869 (324.794)**	**1290.703**			
Total Vertical Impulse (BW·S)	20	Pre	165142.710	189558.552 (66176.340)	213974.394			.052
		Post	185550.051	211488.299 (70302.650)	237426.548			

Bold text signifies significance to at least $p<0.05$.

Following the load carriage there was no change in stance time. As such time markers are presented only in relative terms (% stance time). Loading peak and force minimum were observed to be significantly increased (2.588±0.509 to 2.810±0.606; 1.279±0.401 (p=0.350) to 1.459±0.409 (p=0.015) respectively). These changes were accompanied by a significant shortening of the time to loading peak (p=0.016) supported by a large effect size.

Figure 7.3 Displacement of the CoP before and after load carriage

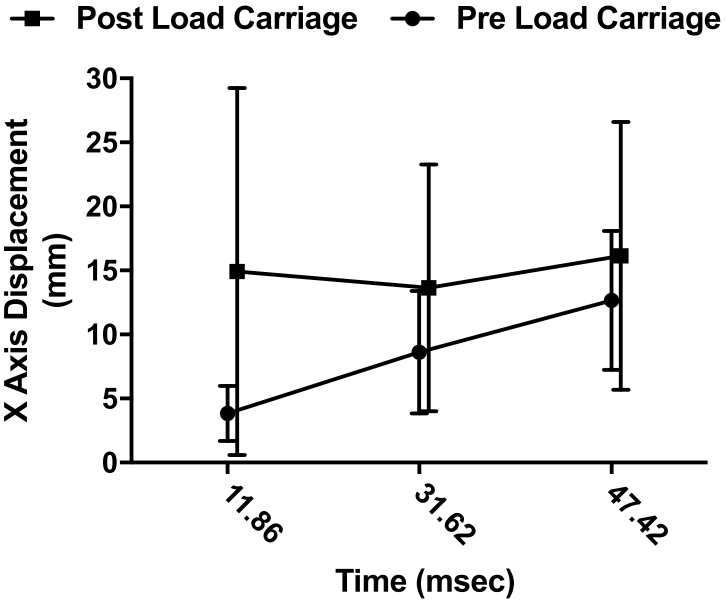


Figure presents means with standard error bars. Statistically significant differences were observed post load carriage for all three time points compared to pre load carriage.

It is notable that the pre load carriage task in figure 7.3 shows a progressive change in CoP through heel strike, however after load carriage the CoP change is no longer progressive, starting at its most lateral point. Standard deviations are clearly larger at all-time points post load carriage task, suggesting greater variance in the findings.

Variable	n	Condition	Lower CI	Mean (SD)	Upper CI	d_{cohens}	d_{glass}	*p*-Value
1st Maximum Lateral COP Displacement (mm)	**20**	**Pre**	**13.304**	**14.641 (3.62)**	**15.977**	**0.59**	**0.64**	**0.029**
		Post	**15.512**	**16.966 (3.942)**	**18.420**			
Maximum medial COP displacement (mm)	**20**	**Pre**	**-4.840**	**-2.729 (5.719)**	**-0.619**	**0.45**	**0.63**	**0.049**
		Post	**-9.910**	**-6.336 (9.692)**	**-2.759**			
ML Amplitude Difference (mm)	**20**	**Pre**	**14.491**	**17.024 (6.866)**	**19.557**	**0.61**	**0.77**	**0.007**
		Post	**19.749**	**23.355 (9.770)**	**26.960**			
2nd Maximum Lateral Displacement (mm)	**20**	**Pre**	**12.077**	**14.811 (7.410)**	**17.545**	**0.64**	**0.57**	**0.022**
		Post	**17.201**	**19.064 (5.049)**	**20.926**			
Maximum Y Displacement (mm)	20	Pre	249.269	264.264 (40.642)	279.259			0.074
		Post	272.12	282.292 (82.143)	292.464			
Time to 1st Maximum Lateral COP Displacement (%)	20	Pre	8	10.6 (8.10)	14			0.322
		Post	7	12.4 (1.48)	18			
Time to 2nd Maximum Lateral Displacement (%)	20	Pre	86	89.8 (9.80)	93			0.054
		Post	91	93.2 (6.30)	96			
Time to Maximum Y Displacement (%)	20	Pre	89	92.6 (9.80)	96			0.234
		Post	84	89.4 (14.54)	95			

Table7.3.1 Pre and post means and SD supported by standardised effect sizes and significance levels for CoP measurements

Bold text signifies significance to at least $p<0.05$.

Table7.3.2 Pre and post means and SD supported by standardised effect sizes and significance levels for CoP measurements

Variable	n	Condition	Lower CI	Mean (SD)	Upper CI	d_{cohens}	d_{glass}	*p*-Value
X Displacement at 11.86ms (mm)	**20**	**Pre**	**3.043**	**3.839 (2.157)**	**4.635**	**0.94**	**5.22**	**0.001**
		Post	**9.269**	**14.923 (15.324)**	**20.577**			
X Displacement at 31.62 (mm)	**20**	**Pre**	**6.847**	**8.616 (4.796)**	**10.386**	**0.63**	**1.05**	**0.029**
		Post	**10.084**	**13.640 (9.640)**	**17.196**			
X Displacement at 47.42 (mm)	**20**	**Pre**	**10.666**	**12.673 (5.440)**	**14.681**	**0.63**	**1.01**	**0.023**
		Post	**14.287**	**16.147 (10.463)**	**22.008**			
Rate of X Displacement at 11.86ms (BW·S^{-1})	**20**	**Pre**	**0.413**	**0.475 (0.168)**	**0.537**	**0.71**	**2.98**	**0.015**
		Post	**0.631**	**0.976 (0.936)**	**1.322**			
Rate of X Displacement at 31.62 (BW·S^{-1})	**20**	**Pre**	**0.432**	**0.485 (0.144)**	**0.538**	**0.72**	**1.89**	**0.015**
		Post	**0.579**	**0.757 (0.483)**	**0.935**			
Rate of X displacement at 47.42 (BW·S^{-1})	**20**	**Pre**	**0.464**	**0.521 (0.155)**	**0.578**	**0.70**	**1.20**	**0.014**
		Post	**0.589**	**0.708 (0.320)**	**0.826**			

Bold text signifies significance to at least $p < 0.05$.

Significant increases were observed in total CoP displacement, explained by significant increases in both medial and lateral CoP displacement, with notably large increases supported by large effect sizes at the onset of foot strike.

Secondary Analysis

Secondary analysis was conducted correlating BM, age, BMI, stature and rank to key CoP variables. No significant correlations were observed. When jump height, jump power or BM were correlated to CoP parameters no significance was observed.

7.4 Discussion

The primary hypothesis of this study was that prolonged load carriage would instigated greater x axis deviations of the CoP. This chapter observed ML deviations for all variables measured, confirming the first hypothesis. This is further supported by very large changes in x axis deviation at the start of heel contact with smaller deviations observed temporally, this section will discuss that this suggests strongly that the ankle instability occurs from delayed activation from muscles such as the PL.

Participants completed the task with a mean HR of 122±13beats$\cdot$min^{-1}. When water stops were excluded the HR increased by 3.55% (124±12beats$\cdot$min^{-1}). While the stops provide a crucial point to consume water, food, remove bergens and allow a short term reduction in HR (stationary HR 111±5beats$\cdot$min^{-1}) the stops only marginally reduced the mean HR experienced by the participants. Previously, the study of a 19.3km loaded march by Royal Marine recruits observed a mean HR of 147±10beats$\cdot$min^{-1} which equated to a HRR of 73%HR_{max}, this was used to classify the task as 'hard' using Howley (2001) classification, given that intensity is a function of time and magnitude and that this current study was conducted over 43km then it is easy to state that this study represents a considerable physiological stress to the participants.

HR was shown to be greater than the total march mean during uphill walking and lower than the mean during downhill walking, regardless of the reduction of speed during uphill and the increase of speed during downhill walking. These findings are in agreement with Fallowfield et al. (2012) who observed similar changes in Royal Marine recruits as well as treadmill based studies which have observed corresponding HR increases and decreases with gradient during load carriage (Lloyd and Cooke, 2011, Blacker, 2009). This is worthy of note, this thesis previously discusses that downhill walking may require a greater eccentric input from the supporting muscles to maintain body position (Armstrong, 1990, Eston et al., 1995) and that such contractions cause increased muscle damage beyond concentric and isometric muscle contraction (Eston et al., 2000). As participants perceive reduced physiological stress, they may be choosing to increase their speed during the descents, this could mean the soldiers are exposed to greater skeletal muscle damage.

VJTs have previously been shown to be a practical and useful method of estimating the functional impairment of the lower limb muscles (Warren et al., 1999). This study found an 18.62% reduction in VJT height which corresponds to a 10.34% reduction in vertical jump power following the load carriage event. These findings indicate an even greater reduction in NMF than the 8±9% reported by Fallowfield et al. (2012), almost certainly as a result of the longer duration of the activity.

In response to the first research objective, this study suggests prolonged load carriage does instigate a significant reduction of NMF of the lower limbs even at a relatively modest intensity, this has been observed to be far greater than previous studies, which is to be expected considering the greater distance involved.

The reductions in vertical jump height attributed to a loss of NMF in the lower limbs is further supported by the estimated VGRF findings, most notable is the increase in the amplitude of the impact peak and the shortening of the time to impact peak (first positive rate was not observed due to the estimated nature of the force measurement) which is frequently demonstrated to be synonymous injury risk through increased stress through the lower limb (Rice et al., 2013a).

The findings in this study for force minimum differed from chapters 5 and 6 within this thesis but are in agreement with (Boozari et al., 2013) as this study observed an increase as a result of time. This thesis has previously discussed that the reduction during load carriage as a result of time is due to the body attempting to reduce impact forces by increasing knee flexion during the stance phase, this is further supported by observed increases in quadriceps activation during landing as a result of fatigued box jumps (James et al., 2006). Where-as the findings from this chapter suggest that no increase in knee flexion was observed, conversely there was a significant increase in force at midstance. These findings are interesting, as it may suggest that once the LCS is removed the participants do not need to flex their knees to resist the effect of the load, however this would only explain a maintenance of NMF, but not an increase in estimated force minimum. A more likely reason for this observed change is that the knee extensors have experienced substantial NMF loss as observed by VJT height loss of >18.62%, so once the load carriage has stopped knee flexion occurs less to reduce the eccentric loading on the quadriceps as a protective mechanism from further fatigue to help aid recovery and project from injury.

This observed reduced knee flexion during mid-stance, as a result of the quadriceps muscles impaired ability to work eccentrically to mitigate the effects of the vertical load (Wright and Weyand, 2001), is novel, as it contradicts findings observed in non-loaded studies and has real world impact as both changes and the assumed increase in first positive rate are commonly cited as biomechanical risk factors for lower limb extremity overuse injuries (Zadpoor and Nikooyan, 2011, Christina et al., 2001, Ferber et al., 2002).

As a result of the increase in force and shortened time over which the mechanical load is applied to the major bone structures of the shank and foot. These findings mean that not only do the lower limb muscles have to control greater forces during walking they also have to do so while producing less force. As a result of these changes it is possible to answer the second research objective and conclude the reductions in NMF prompts changes in VGRF parameters indicative of lower limb over use injury.

Total CoP displacement was seen to be increased in this study, while there was no corresponding increase in stance time observed, suggesting a reduction in global stability of the ankle (Palmieri et al., 2002). This can be further characterised as a significant increase in the 1st maximum lateral CoP displacement, signifying a loss of control of the ankle at heel contact (Gefen, 2002). The novel aspect of these findings is that the greatest change in CoP rate and displacement was observed very early in the gait cycle with an increase in displacement of 288.7% at 11.86ms, 56.5% at 31.62ms and 43.2% at 47.42ms. While there is an increase in post walk SDs the large effect sizes observed suggest that the changes can still be considered with confidence.

While activation of the PL was not observed within this study, the reduction of VJT height and the findings of Hunt et al. (2001) and Rice et al. (2016) show that PL fatigue is likely. As such it is possible to speculate that the change in displacement early on in the gait cycle is due to a delayed activation of the PL as a result of fatigue from the load carriage task, this means there is almost no resistive force during initial contact.

In response to the third research objective, an increase in ML amplitude between the first lateral peak and the medial peak was observed; this was represented by an increase in both lateral and medial deviations of the CoP. As there was no temporal change in the peaks to accompany the increase in peak magnitude, the rate of change must have increased, both parameters give reason to believe there is an increased instability within the stance phase. It is possible to speculate that this reduction in stability could be due to an over-compensation resulting from reduced activation of the PL attempting to recover from the first lateral shift of CoP, most likely from reduced neural control or late onset of the PL activation. To suggest any further mechanisms behind the change further research would need to be completed.

In response to the fourth research objective no significant correlations were observed between VJT parameters and CoP or VGRF variables. This is despite studies which have observed links between reductions in PL mean frequency EMG and plantar pressure (Hunt et al., 2001), and computational studies which linked PL fatigue to increased ML eccentricities (Gefen, 2002). Despite this, all participants which displayed increased ML displacement or increase ML rate also showed a reduction in NMF. It should be acknowledged that the VJT is a basic measure of NMF and as such may not be sensitive enough to relate NMF of specific muscles or muscle groups. In summary, this study has not found any direct support for NMF relating to ML eccentricities, however further research should be conducted to consider the point with more precise measures of NMF.

Reductions to lower limb NMF have been shown to last up to a duration of 72hours after a two hour bout of load carriage on a treadmill (Blacker, 2009), however due to the restraints of the military programme it was not possible to explore the recovery profile of the participants. While it is likely that reductions in the force producing capability of the lower limbs will have an effect on gait characteristic, no significant correlation was observed between VJT height and power and CoP and VGRF parameters, it is likely that this is due to the simplistic nature of the VJT especially considering strong correlations which have been observed between push off variables, such as second positive rate and thrust maximum with ankle plantarflexors observed in the previous chapters.

Due to military requirements participants were not able to undergo the post testing immediately after the end of load carriage and they also were not able to complete the protocol with their bergens on, meaning that changes of gait were not representative of possible gait changes with the load considered. However, the significant alterations to unloaded gait following the removal of the external load highlight that the possibility for injury due to load carriage is not confined to the duration over which the load is carried. Conversely, it appears there is significant impact on normal function even after the load is removed, findings of note for any practitioners in the applied arena.

Another limitation of this study is that a control condition was not included in this study (walking with no load). As such while the findings are relevant to the soldier as it accurately depicts the stress they are placed under, it is not possible to determine whether the changes occur as a result of the additional carrying of the load or the walking task. However, the previous two chapters have observed reductions in knee extensors and flexors during 120minutes of treadmill walking load carriage compared to unloaded. As such it is reasonable to hypothesise that reductions in the vertical jump performance can be due to the load carriage task. However further controlled studies are required to explore whether changes in the VGRF parameters are as a result of the load or walking task.

7.5 Conclusion

The findings of this study provide a better understanding of the physiological stress Special Forces soldiers experience during a substantial and prolonged load carriage task by presenting a number of novel findings, chiefly, the early onset of significant CoP shift and the increased impact forces as a result of the load carriage task. The physiological demand was deemed to be very high and to have caused a significant reduction in NMF. Simultaneously, changes in CoP and VGRF were observed which are commonly associated with shank stress fractures and ankle sprains. However it was not possible to associate these changes directly with reduced NMF due to the general nature of the VJT, however, this was likely due to the basic nature of the vertical jump test. As there was no control group it is not possible to discern whether the changes occurred as a result of the load carriage task or the load itself.

General Discussion

8.1 Overview

The purpose of this thesis was to investigate the mechanisms and responses to cumulative day load carriage, with particular reference to energy cost, neuromuscular function and ground reaction forces. This was completed by the study of individual differences in response, analysis of difference in means and correlation analysis.

The earlier studies within this thesis served several purposes. Initially, chapter 4 examined the acute impact of load carriage on the physiological and biomechanical demands of the task. This served to assist in the refining of variables for chapters 5 and 6, of particular note was the associations between strength, GRF's at push off and EE, but more importantly it was the first to examine individual differences in response to load carriage. Chapter 5 attempted to manipulate key variables by using a prolonged (2 hour) load carriage task, identifying that participants experience substantial individual differences in performance, particularly in terms of NMF and EE. Again, correlations were observed between NMF and energy cost, this was further supported by associations between these variables and GRF which served to triangulate the findings. Significant individual differences were observed in this chapter, possibly as a result of the absolute load which reflects the occupational nature of the task. This was the first study to examine torque produced by the knee extensors at specific joint angles, making it the first study to profile changes in muscle function.

Chapter 6 was the first study to examine load carriage completed on cumulative days. This produced a number of novel findings which suggested participants experienced higher energy cost when completing load carriage on d2 compared to d1. Moreover, it explored whether these individual differences were translated through to a second day of load carriage activity. This provided insight into how cumulative day exercise affects the participants, both as a single cohort, through the assessment of means and in terms of individual differences. It also provided an opportunity to establish associations over a number of time points, considering both recovery and exercise. These meant associations were considered via repeated measures through the single study, but also through the two preceding studies.

Chapter 7 studied load carriage in a highly trained population (Greek Marines) in an occupational setting, performing an occupational task (>12 hours load carriage). The study served to validate the findings of the laboratory based studies, observing changes in GRF as a result of the load carriage and observing NMF loss via a field based vertical jump test. The study further explored and observed a number of parameters informed by a study on a similar population and load (Royal Marines recruits) (Rice et al., 2016). This highlighted a number of substantial mediolateral deviations, which were contrary findings within the laboratory studies. Suggesting that the level treadmill, while representative in the sagittal plane, may not reflect the destabilising effect of cross country over ground walking.

8.2 Metabolic changes due to load carriage

Acute examination of load carriage observed findings which were largely in line with previous research (Lloyd and Cooke, 2000b, Hinde et al., 2017, Quesada et al., 2000). The load carriage group was shown to experience greater estimated energy expenditure and $\dot{V}O_2$ than the unloaded group; this was supported by an increased HR after 10 minutes of walking with the external load. These were supported by large effects sizes. Comparable outcomes were also observed in the prolonged load carriage studies which observed simple effects for load at each time point. Moreover, there was a large difference between effect sizes calculated via Cohen's D compared to Glass's D, suggesting that substantial individual differences exist between participants even over a short period of load carriage.

When metabolic measures were considered during prolonged load carriage a substantial increase in $\dot{V}O_2$, HR and EE were observed during two hours of load carriage, again these were supported by large effect sizes. These findings are in keeping with previous literature (Blacker et al., 2009b, Mullins et al., 2015), as effect sizes for individual differences were explored classifying $\dot{V}O_2$ change as extremely large. These findings suggest participants are exposed to differing levels of energy cost, the next section will attempt to explore mechanisms for this large individual difference.

The final laboratory based study observed two prolonged load carriage tasks. This study observed novel findings as EE did not return to baseline 24 hours post d1 while $\dot{V}O_2$ showed a trend which further supported the finding. Significant interaction effects were supported by large effect sizes for EE (η^2=0.33) and $\dot{V}O_2$ (η^2=0.29) and follow up tests showed that during load carriage participants experienced the same amount of EE and $\dot{V}O_2$ change for d1 and d2. This infers that any change above baseline 24hours post load carriage d1 can be used as an indicator for energy cost at the end of d2, however the time points were not observed to be significantly correlated.

8.3 Ground Reaction Forces During Load Carriage

When studied acutely vertical parameters of GRF were shown to be increased, namely, loading peak, force minimum and thrust maximum, this was shown to be maintained through all subsequent studies, supported by large effect sizes. These findings are in agreement with previous studies for short duration (Birrell et al., 2007, Lloyd and Cooke, 2011) and prolonged load carriage (Harman et al., 2000). Loading peak and thrust maximum was shown to increase in proportion to the load in agreement with the previous studies. However, while force minimum was shown to be increased as a result of the external load, this change was not in congruence with the previously referenced studies, suggesting that the change is not simply as a result of the static effect of the load. It has previously been observed that this effect occurs as a result of increased knee flexion during the stance phase (Rice et al., 2016) performed to enable a greater distance and time for the load to be decelerated over. This postulation finds further support as the first negative rate is the only measured rate to not observe an increase as a result of load carriage, suggesting the body maintains its ability to decelerate the load.

These finding suggest that increased knee flexion during the stance phase was successful in maintaining normal rate, however it is likely that such an increase in flexion from basal gait would be a challenge to maintain. When GRFs are studied as a result of prolonged load carriage, a reduction in force minimum was observed after 2hours of treadmill load carriage. It is likely that the change is as a result of the observed reduced NMF from the knee extensor, which is further supported by correlations in the final laboratory based study. This change again is likely to be as a result of increased knee flexion. Support for this can be observed in the maintenance of the first negative rate.

An increase in first positive rate was observed acutely; suggesting that greater force is placed through the lower limb system, alongside the elevation in impact peak which suggests an increase in injury risk (Christina et al., 2001, Ferber et al., 2002, Zadpoor and Nikooyan, 2011). When considered as a result of prolonged load carriage in both chapters 5 and 6, an interaction effect for impact peak was observed, suggesting that the body lost its capacity to mitigate the force at heel contact as result of both load and time. Further support for these findings were observed in chapter 7, where as a result of >12hours of load carriage increases loading peak, force min and time to loading peak (%) while time to force minimum (%) was shown to be maintained (rates were not extracted), while this suggests that treadmill based load carriage is representative of field based load carriage with regards to vertical ground reaction forces, it should be noted that the testing pre and post was conducted unloaded compared to the loaded GRF trials in the laboratory studies.

When acute AP variables are considered the findings again appear to be in agreement with previous work, (Lloyd and Cooke, 2011, Birrell et al., 2007) by observing an increase in maximum breaking force and maximum propulsive force, supported by large effect sizes. Interestingly, these findings were supported by large individual differences, considering there is a known link between AP forces and movement economy (Saunders et al., 2004),it is possible these findings may account for some of the individual differences observed in EE and $\dot{V}O_2$.

No changes were observed for AP variables as a result of prolonged load carriage and no change in CoP displacement or rate along the Y axis was observed in chapter 7. This suggests that while the AP acute response was irregular compared to normal gait, the participants were able to maintain the change, suggesting that while AP changes may reduce movement economy they do not necessarily increase injury risk.

Lateral impulse was the only ML variable to show any change as a result of acute load carriage, again this is in agreement with previous research which has observed few changes in MLGRF variables, with most studies, not reporting ML findings (Kinoshita, 1985, Kinoshita and Bates, 1981, Lloyd and Cooke, 2011). As discussed previously it is likely that this increase in impulse is due to a be a progressive change as a result of carriage of a rifle, anteriorly, due to the rifle carriage reducing arm swing (Birrell et al., 2007). This finding was also observed as a simple effect in chapters 5 and 6, however, no change was observed as a result of time.

Treadmill based load carriage has a number of significant advantages, as it provides an opportunity to study steady state performance, and the use of complex data collection methods, such as isokinetic dynamometry, a limitation is that the level surface and constant speed may not accurately replicate the overground walking involved in occupational load carriage. Moreover, a number of unexplained ML correlations were observed in chapter 4. In order to examine this, chapter 7 examined a number of ML CoP deviations. As a result of prolonged field based load carriage an increase in ML CoP deviation was observed, characterised by increases in both maximal lateral and medial CoP displacement; these findings are an indication of instability of the ankle. This was further explored by extracting CoP displacement at serial time points, to provide a temporal description of the differences. These findings demonstrated that participants experience very rapid CoP shift at the start of the movement. It has been demonstrated that after prolonged load carriage, the peroneus longus observed a shift in EMG frequency and a delay in muscle activation time (Gefen, 2002, Rice et al., 2016). It has been demonstrated previously that the delay of 60ms can occur as a result of fatigue (Stacoff et al., 1996) and is reflective of unstable control (Gefen, 2002). These findings make it possible to speculate that such rapid excursion of the CoP is due to fatigue of the PL specifically but also likely the rest of the inverter and everter muscle groups. These findings are supported via large differences in effect sizes, which suggest individual differences in response; as such future research should explore any anthropometric predictors of lateral injury. This research would need to be covered in an overground setting to accurately reflect the demands of the task.

8.4 Neuromuscular Function

In response to a >12 hour military march, vertical jump height was shown to be reduced by 18.62%±16.85% which was which was used to calculate a reduction in vertical jump power, from 3429.9±758.3W to 3060±717.2W. It is not possible to compare findings to an unloaded control group, and as such it is not possible to deduce whether this change is as a result of the load. Previous reductions in vertical jump height of 8±9% and power 5±5% have been observed in Royal Marine recruits following a 19.3 km load carriage task (Fallowfield et al., 2012). These findings suggest substantial lower limb NMF loss as a result of load carriage however it is not possible to determine how these changes may affect gait or energy cost due to the general nature of the measurement.

When NMF change was observed after 2hours of treadmill load carriage in chapter 5, a reduction in knee flexion was observed at 180°s^{-1} for maximum and average variables, supported by large effect sizes, however no individual differences were observed in the performances. Change score reductions of 9.81% (maximum) and 10.91% (average) were observed for the loaded group, while the non-significant reductions in the knee flexors at 60°s^{-1} were 10.34% (maximum) and 12.22% (average), again suggesting a substantial reduction in the participants capacity to generate force, however due to differences in the response in the unloaded control group no statistically significant interaction effect was observed.

Chapter 5 was the first load carriage study to observe changes in torque through the whole joint action. Unfortunately it was not possible to examine ankle action, due to the very short range of movement of the joint. Significant interaction values were observed for knee 180°s^{-1} between 95°-125°. These were supported by effect sizes (Appendix 4-7) which suggested the greatest differences occurred at the optimum muscle length for force. This suggests that while NMF reduction does occur, when the muscle is working at a length which represents a walking angle there is no change as a result of load carriage. When studied at 60°s^{-1} a similar change was observed however the window was slightly smaller at 95°-105°, with the findings still supporting the assertion that NMF reduction occurs at muscle lengths not associated with angles achieved while walking. Similar effects were observed for knee flexion with interaction effects observed between 95°-125° and again effect sizes increased towards the optimum angle for force however no significant effects were observed for knee flexion at 60°s^{-1}.

No significant effect was observed for knee flexion as a result of two days load carriage in chapter 6 partially due to the large CVs which were observed in the data. Typically there is a very clear trend in the data which suggest particularly at the higher velocity NMF is reduced following load carriage, and may not recover to baseline 24hours post d1. Given these findings while no change was observed during two days of load carriage it is likely that the data analysis was not sufficiently powered to observe some temporal changes, particularly during the recovery phases were the magnitude of reduction will be very small compared to the CV of the data collection methods, so a study with substantially larger sample size may observe changes, however studying knee flexor change was not the primary aim of chapter 6.

No statistically significant effect was observed for ankle dorsiflexion as a consequence of load carriage, however trends were observed which suggest that participants experienced a reduction in NMF during both walking and load carriage groups with the load carriage group experiencing a greater reduction in NMF than the unloaded group. When observed over two days there is a clear trend which demonstrates that for most ankle dorsiflexion variables at most time points, the loaded group experienced a greater reduction in NMF than the unloaded. As a result of d1 load carriage, reductions were observed to be between 7.3% and 37.8%, while statistically no differences were observed 24hours post d1 activity, while scores showed reductions between 14.4% and 20.6% from baseline which suggested very little recovery occurred 24 hours post the load carriage task. The trend then demonstrated a reduction for four out of five variables as a result of load carriage on d2.

Statistically significant reductions in NMF were observed as a result of load carriage for all measures of knee extension over one day, with reductions between 9.12% and 15.04%, supported by large effect sizes but small individual differences. The reduction in extensor NMF is likely to be in response to the increased knee flexion during the stance phase. It is likely that as the knee extensors experience NMF reduction, their capacity to reduce the effect of the external load is reduced making it likely that extra work is required distally along the kinetic chain. These findings were replicated within chapter 6 with reductions in NMF between 9.2% and 17%. Measures at 24 hours post d1 of the knee extensors at 60°s^{-1} were shown to have not fully recovered with a reduction of 9.6% with the isometric extension showing a non-significant reduction of 11.9%. This prompted further reductions post d2, with the extensors showing statistical difference from baseline and pre d2 scores, at 180°s^{-1} and 60°s^{-1} with all other variables showing reductions greater than d1 reductions. Interestingly, most variables were shown to have returned to baseline 24 hours post d2, however knee extension at 60°s^{-1} was observed to still be reduced 24hours post d2 load carriage.

Significant reduction in NMF is observed in the ankle plantarflexors for all measures supported by moderate and large effect sizes, suggesting a distal shift in the kinetic chain. As a result of one day load carriage, reductions in NMF output were observed to be between 10.97% and 19.91%. These findings were reinforced in chapter 6 which observed losses between 12.3% and 18.4%. Ankle plantarflexion at 120°s^{-1} was observed to still be reduced 24hours post d1, with a reduction of 1.7% for the loaded participants and an increase of 11.5% for the unloaded participants. Interestingly while very large differences between groups as a result of the d2 load carriage were recorded, no statistically significant differences were observed.

This study observed no evidence of cumulative NMF loss between d2 and d1. While NMF was shown to be reduced for ankle plantarflexion and knee extension at 60◦s^{-1} at the start of d2 suggesting the participants had not fully recovered between trials, no summative effect was observed.

8.5 Mechanisms of movement economy

A number of studies have attempted to define predictors of load carriage performance, using applied tasks (Rayson et al., 2000) and anthropometric characteristics (Mello et al., 1988, Bilzon et al., 2001). This thesis aimed to explore any possible mechanistic changes behind metabolic drift by correlating biomechanical and neuromuscular variables to energy expenditure, in chapter 4 and 7 this was done by simple Pearson correlations, while chapter 5 and 6 were performed by repeated measures correlation.

Chapter 4 observed a number of correlations between lower limb strength and energy expenditure, particularly ankle plantarflexion which observed significant associations with EE for both 60°s^{-1} measurements and near significance at 120°s^{-1}. Moreover, significant associations were observed between EE and the knee extensors for all measurements, while the correlations for all measurements were weak to moderate in strength ($r=0.423$ to $r=0.463$, $p<0.05$) the findings were observed across a number of measurements points and variables, providing triangulation of the findings. No significant correlations were observed for the ankle dorsiflexors and knee flexors. This suggests that associations may be due to changes in gait as stronger participants are more able to resist the changes in gait associated with the external load as opposed to a more general association between participants strength.

These initial findings suggest that strength, as recorded as NMF, relates to EE, as such chapters 5 and 6 aimed to explore whether this correlation held once variables were manipulated. When the associations are examined via repeated measures as a result of one day load carriage, knee extension and ankle plantarflexion variables were shown to be related to $\dot{V}O_2$. It has been suggested that this association is due to the increased recruitment of muscle fibres which require greater oxygen demand(Blacker, 2009). While it is possible that muscle fibre recruitment may account for some level of drift, it has already been explained that it is unlikely that it will have a substantial role (Blacker, 2009). When correlations were explored in chapter 6, findings supported the previous chapters, with knee extension (60°s^{-1} and MVC) and ankle plantarflexion (MVC) being moderately correlated to EE. Given the number of correlations observed and more importantly, the lack of correlation between the antagonistic muscles and EE it is possible to suggest that reductions in NMF of the knee extensors and ankle plantarflexors affect EE of load carriage.

This thesis has used GRF to attempt to explain the observed association between NMF and EE. This has previously be done acutely between EE and GRF variables, which observed relationships with energy cost and force at first lateral impact peak, maximum braking force and lateral first peak, for a double pack system and second lateral peak force, the time to the same force and a moderate but non-significant relationship for time to maximum braking force for a back pack system (Lloyd and Cooke, 2011).

The acute study within this thesis observed contrasting findings, possibly due to the larger sample size. For example observing a correlation between first positive rate and EE. These findings are not surprising given the acute nature of the testing, and the relatively small changes in GRF involved. The acute study highlighted associations between knee extensors, ankle plantarflexors and braking impulse as well as the aforementioned NMF variables and braking maximum. While there is some variance in the findings in studies which have attempted to relate braking GRF variables to movement economy it is logical that these associations may provide a link between NMF loss and changed EE (Saunders et al., 2004, Barnes and Kilding, 2015).

Chapter 5 examined these variables again as a result of prolonged load carriage, in an effort to manipulate NMF in an occupationally relevant setting. When associations were examined in terms of one day performance, significant correlations with EE were observed for all measures of knee extension and ankle plantarflexion at either moderate or high levels, while no associations were observed for knee flexion or ankle dorsiflexion. This provides further support to the difference in means which were reported; as the observed reductions in NMF occur as a peripheral fatiguing mechanism, which in turns effects metabolic and cardiovascular drift as a result in change of gait; as opposed to central mechanisms which instigates reduction of NMF. These findings can be further triangulated by correlations between ankle plantarflexion and second positive rate, knee extension variables and thrust maximum within the vertical measurement and associations between propulsive impulse and ankle plantarflexion and knee extension within the AP measurement. These observations within chapter 4 suggest that reduced NMF of the lower limbs reduces the push off force in the gait cycle. This is a likely contributor of the reduced economy, given the previously discussed association between NMF variables and EE and a moderate but statistically significant relationship between energy cost and the second positive rate.

Chapter 6 observed correlation through the whole testing period. As such, for two variables to be correlated they would have to share characteristics between two exercising bouts and two 24hour recovery periods. This study found further support for the mechanisms of cardiovascular drift with, ankle plantarflexion and all knee extension parameters and second positive rate all sharing associations with EE. This is further supported by high correlation between ankle plantarflexion at 60°s^{-1} and thrust maximum, second positive rate, and second negative rate.

When significant associations were observed within the loaded group the equivalent unloaded cohort was examined for correlation, no relationships were examined in the unloaded group, these findings are contrary to Lloyd and Cooke (2011). These findings suggest that the increased demand which occurs from external load carriage instigates gait changes which reduce movement economy significantly.

These findings suggest that the ankles plantarflexors are critical to maintaining an economical gait pattern, as such programmes should focus on increasing both ankle plantarflexor strength and endurance and also to increase knee extensor strength and endurance to avoid the distal shift in work along the kinetic chain.

8.6 NMF and Injury

As a secondary aim, this thesis wanted to examine whether NMF can be associated with injury risk. Research has already been conducted examining the effect of peripheral muscle fatigue on injury via stress fracture, focusing principally on stress fracture injury through increased impact forces in the sagittal plane (Rice et al., 2016, Rice et al., 2013b). Less research has studied the effects of reduced NMF on instability and therefore ankle sprain and falls risk (Wang et al., 2013, Gefen, 2002).

It has previously been discussed that this thesis observes an acute increase in VGRF parameters, specifically in this instance, loading peak and first positive rate. These have previously been demonstrated to be predictors of injury risk (Dixon et al., 2000). Over a prolonged period of treadmill load carriage, loading peak was shown to be increased as a result of both load and time effects, suggesting that prolonged load carriage instigates an increased injury risk, beyond the effect of the load in of itself. In the acute study, it was observed that participants with stronger knee extensors and ankle plantarflexors displayed reduced loading peak so physical training programmes should look to increase strength in these areas to reduce the risk of impact fracture on the lower limb.

The acute laboratory based study showed changes in MLGRF as a result of load carriage which were in agreement with Birrell et al. (2007), namely increases in ML impulse, this was largely attributed to the carriage of a rifle, these findings suggest a slight increase in instability of the participants and a possible increase in falls risk. Despite this, no significant correlations between ML variables and any other studied variables existed when studied acutely. However when changes in ML variables were examined as a result of one day load carriage, while no significant interaction effect was observed for any parameter a large number of correlations were observed, between all measured NMF variables and most ML variables. These findings were surprising considering that the NMF variables were measured in the sagittal plane. However, it is likely that most of the muscles involved in extension and flexion movements are likely to have secondary roles preventing inversion or eversion of the ankle during foot strike (Baumhauer et al., 1995). This is further supported by the large correlation coefficients which are observed, suggesting large changes in NMF variables is required to instigate a large change in ML markers.

The laboratory based studies provided a clue that reduction of NMF may instigate change in ML variables which could be indicative of fatigue. However due to the measurements not being specifically targeted to examine ML change and the level nature of treadmill based walking. It is likely that the studies may have missed ML change which occurs during over ground walking in an occupational setting. This is further supported, by finding which demonstrated PL fatigue during prolonged load carriage in Royal Marine recruits (Rice et al., 2015, Rice et al., 2016). It is frequently cited in literature that the PL serves to reduce ankle eversion during walking (Hunt et al., 2001, Kelikian and Sarrafian, 2011, Winter, 1991), with work demonstrating it cannot sufficiently support propulsion (Jones, 1941). As such the field based study set out to incorporate an examination of ML variations of CoP.

The study observed, significant displacement of CoP characterised by a change in ML amplitude which can further be characterised by changes in both lateral and medial displacements of CoP. This change in CoP has been associated with PL fatigue in previous research (Wang et al., 2013). Previous research has shown that fatiguing exercise of the PL is associated with a delay in onset of activation which in turn is associated with instability of the ankle. This study’s findings support the observed increased reduction in vertical jump height. While also observing changes in displacement showing that instability was increased for 47.42ms suggesting a delay in muscle activation in agreement with Stacoff et al. (1996). As such this has shown that while PL fatigue may instigate increased vertical impact forces associated with metatarsal fracture (Rice et al., 2016), it can also be associated with increases in ML CoP displacement which can be associated with ankle eversion injury (Gefen, 2002).

8.7 Future Research

The laboratory studies within this thesis studied load carriage of 120 minutes, this has been shown to be a relevant occupational model for metabolic, cardiovascular and neuromuscular responses to load carriage (Blacker, 2009), however this research has found that mediolateral components of GRF may not be accurately portrayed by 2hours of load carriage on a level treadmill. As such future research should consider biomechanical changes during overground walking when ML variables are the topic of investigation.

This study examined load carriage over consecutive days, however due to the small changes involved for a repeated measures trial, possible type II errors may have occurred. This research suggests that consecutive day exercises has a cumulative effect on NMF reduction, this study has not been able to refine the nature of the change. As such future research can pursue one of two avenues, either exploring mechanistic physiological changes through specific protocols designed to instigate NMF loss, or it can pursue large, field based studies, using simple measures of NMF but with large sample sizes, to describe cumulative effect on performance of large groups of soldier, this approach would maintain ecological validity of the research.

8.8 Practitioner Impact

This thesis has highlighted a link between NMF and movement economy. By suggesting that loss of NMF output of the knee and ankle extensors produces a less economical movement pattern. As such training should focus on increasing the strength of these muscle groups, as well as the reciprocal muscle groups in order to reduce loss of movement economy and an increase in injury risk.

This study has highlighted that exercise on consecutive days has an accumulative effect on NMF reduction and energy cost. As such when conducting exercise on consecutive day’s consideration needs to be given to dietary requirements to meet the increased energetic cost.

8.9 Conclusion

The research presented in this thesis has shown that load carriage in an occupational and simulated occupational setting causes changes in NMF which can cause $\dot{V}O_{2Drift}$. This work has found the knee flexors and particularly ankle plantarflexor NMF to be of high importance when trying to maintain $\dot{V}O_2$. Support for these links were observed in changes in GRF parameters, changes in force minimum correlated with previous work and findings to suggest increased knee flexion during walking to place greater stress on the knee extensors and a number of GRF variables at push off were shown to have strong correlations to ankle plantarflexion, which in turn provided further support for the ankle role in locomotion. Interestingly no significant correlations were observed during unloaded testing suggesting that load carriage increases the role of the ankle plantarflexors and knee extensors beyond that of normal unloaded walking.

Field based work used an occupational task of >12 hours walking by Greek Special Forces Soldiers to highlight that soldiers may be exposed to much greater ML fatigue and injury risk than initially thought. This work suggests that further work needs to be done in a field based setting to study NMF loss from multiple planes of movement.

This thesis observed extremely large individual differences in metabolic measures as a result of load carriage, interestingly these were not observed in d2 of load carriage and while it is possible to say it is unlikely that this variance is not due to differences in NMF. This is the first work to examine individual differences as a result of load carriage. It is an avenue of further exploration given the impact individual difference will have on injury rates.

Finally, this thesis observed load carriage during an occupational task on consecutive days, this study observed increased energy cost as a result of load carriage on d2 compared to d1. Moreover, it can further clarify that the energy cost increase on d2 was roughly proportional to the elevation above baseline and the start of d2. No similar effect was observed for NMF however, further more statistically powerful work would need to focus specifically on NMF change to confirm that there is no cumulative change in NMF.

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Appendix

1) Example participant information sheet

2) Example participant consent form

3) Knee joint angle

4) Max knee extension torque (180°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.
5) Max knee extension torque (60°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.
6) Max knee flexion torque (180°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.
7) Max knee flexion torque (60°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.

1. Example participant information sheet

Canterbury
Christ Church
University

Physiological and biomechanical markers of load carriage performance.

Participant information sheet

Background:

Research is being carried out at Canterbury Christ Church University (CCCU) by James Scales, Dr Mathew Brown and Dr Damian Coleman. This study is looking at how your muscles and heart react to long duration exercise. This study may not benefit you directly, but the findings from the research will help develop training protocols for the military which will reduce the amount of injuries experienced by soldiers.

What you will be required to do:

- Come in to the laboratories on three days back-to-back.
- On the first two days you will be in the laboratories for 3 hours, and on the third day you will be in for 1 hour
- On the first two days you will walk on a treadmill for 2 hours, covering 6.7 miles carrying a loaded bergen(military backpack).
- On the third day you will only undergo the tests, and not walk on a treadmill, the test requirements are as follows:
- Have body measures taken: Height, weight
- Have blood samples taken before and after each treadmill walk and once on day 3
- Allow electrodes to be attached on your legs in order to measure electrical activity in your muscles
- Walk over a platform that will allow measurements of your feet to be taken
- You will to fill out a sheet describing what food you have eaten during the testing period.

To participate in this research you must:

- Be aged between 18 and 45 years old
- Be free from any injury that may be made worse by participating in the study
- Must not be using any performance improving substances or be willing to stop using them.

Feedback:

A summary of the findings will be made available to you at the end of the study. This summary will not contain any personal identification.

Confidentiality:

All data and personal information will be stored securely within CCCU premises in accordance with the Data Protection Act 1998 and the University's own data protection requirements. Data can only be accessed by James Scales, Dr Coleman and Dr Brown. The only time your name is recorded is when you sign the consent form, after which all data collected including blood samples will be referred to by an ID number.

Publication of results

The results of this study will be presented at conference via a research paper and shall be published in an academic journal. The result may also be referred to in a blog available at http://sportslabcccu.wordpress.com/, at no time will you be referred to or identifiable by name.

Deciding whether to participate:

If you have any questions or concerns about participation do not hesitate to contact me. Should you decide to participate, you will be free to withdraw at any time without having to give a reason.

Any questions?

Please contact James Scales on E-mail: J.Scales895@Canterbury.ac.uk,
Tel: 01227767700 ext. 3145

2. Example participant consent form

Canterbury
Christ Church
University

CONSENT FORM

Study 1: Physiological and biomechanical markers of load carriage performance.

Name of Researcher: James Scales

Address:

AF50
North Holmes campus
Canterbury Christ Church University
North Holmes Road
Canterbury
Kent
CT1 1QU

Email: J.Scales895@Canterbury.ac.uk
Phone: 01227 767700 Ext 3145

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.
3. I understand that any personal information that I provide to the researchers will be kept strictly confidential.
4. I agree to take part in the above study.

_________________________	_________________	_____________________
Name of Participant	Date	Signature
__________________________	_________________	_____________________
Name of Person taking consent (if different from researcher)	Date	Signature
James Scales_______________	_________________	_____________________
Researcher	Date	Signature

3. Knee joint angle

4. Max knee extension torque (180°s^{-1}) at values at specific joint angles. Data pertains to chapter 5

	Loaded						Unloaded					
	Pre Load Carriage			Post Load Carriage			Pre Load Carriage			Post Load Carriage		
Angle (°)	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n
85	118.3	49.1	13	117.7	48.3	12	108.7	32.1	15	110.1	32.5	15
90	133.7	44.1	13	129.0	42.8	12	114.5	36.8	16	115.0	44.1	17
95	138.4	44.2	13	127.4	49.4	13	114.2	36.3	18	121.0	44.2	18
100	145.1	46.1	13	132.7	48.9	13	124.0	34.1	18	125.2	46.1	18
105	148.1	45.9	13	136.8	45.4	13	130.8	34.7	18	131.5	45.9	18
110	146.8	43.4	13	134.6	40.6	13	131.8	34.1	18	132.4	43.4	18
115	144.2	39.4	13	128.6	37.0	13	129.8	32.5	18	128.8	39.4	18
120	139.8	34.6	13	123.2	33.9	13	124.6	33.1	18	122.6	34.6	18
125	130.6	31.7	13	114.4	31.8	13	116.0	31.0	18	115.7	31.7	18
130	119.4	27.6	13	102.8	29.4	13	107.3	30.4	18	105.7	27.6	18
135	107.9	23.7	13	89.0	28.8	13	98.2	29.8	18	93.4	23.7	18
140	93.1	21.5	13	75.6	28.4	13	90.4	22.4	17	79.6	21.5	18
145	78.5	20.7	13	62.0	29.0	13	78.3	21.8	17	68.3	20.7	16
150	64.0	22.7	12	51.6	30.5	11	66.5	22.8	17	59.3	22.7	15
155	55.3	23.9	8	51.1	18.2	9	56.3	19.6	13	50.5	23.9	13

5. Max knee extension torque (60°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.

	Loaded						Unloaded					
	Pre Load Carriage			Post Load Carriage			Pre Load Carriage			Post Load Carriage		
Angle (°)	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n
80	147.5	65.0	10	130.9	70.8	10	133.8	43.6	13	139.4	37.0	13
85	163.9	69.6	12	144.8	63.2	11	144.1	44.4	14	135.4	69.6	16
90	178.5	75.6	12	157.2	57.7	11	140.7	51.7	16	145.8	75.6	18
95	191.3	76.3	12	163.0	53.1	11	156.8	36.9	17	160.6	76.3	18
100	200.4	69.9	12	161.4	50.5	12	166.9	33.9	17	166.8	69.9	18
105	198.9	62.2	12	161.9	48.5	12	170.3	36.3	17	164.5	62.2	18
110	187.9	54.3	12	161.2	50.8	12	170.0	37.6	17	157.8	54.3	18
115	177.0	48.3	12	156.5	51.6	12	162.8	37.6	17	148.7	48.3	18
120	161.8	40.7	12	143.4	51.2	12	152.0	38.7	17	137.9	40.7	18
125	149.7	33.9	12	123.3	45.0	12	137.4	41.8	17	134.1	33.9	17
130	136.6	27.0	12	110.3	46.8	12	130.9	32.1	16	121.9	27.0	17
135	120.6	21.4	12	105.0	36.0	11	118.8	28.7	16	108.2	21.4	17
140	103.6	17.8	12	90.2	36.2	11	104.8	25.1	16	94.3	17.8	17
145	84.8	24.7	12	73.7	35.6	11	88.8	19.4	16	74.6	24.7	17
150	69.8	16.6	11	63.3	29.8	10	72.6	17.9	16	65.5	16.6	15
155	48.9	19.7	10	48.8	25.8	7	53.4	16.9	14	53.3	19.7	13

6. Max knee flexion torque (180°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.

	Loaded						Unloaded					
	Pre Load Carriage			Post Load Carriage			Pre Load Carriage			Post Load Carriage		
Angle (°)	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n
95	69.9	24.0	13	58.2	30.2	13	54.8	23.0	18	57.9	21.8	18
100	75.3	24.6	13	62.3	33.9	13	59.3	24.0	18	61.8	24.6	18
105	79.1	27.0	13	67.0	34.9	13	61.8	24.6	18	65.3	27.0	18
110	82.2	27.9	13	70.0	35.5	13	64.4	25.2	18	66.2	27.9	18
115	85.1	29.5	13	74.3	37.3	13	65.4	25.5	18	68.3	29.5	18
120	86.5	28.6	13	75.6	36.9	13	66.4	25.4	18	69.4	28.6	18
125	86.3	35.4	13	75.5	38.6	13	66.9	25.3	18	69.3	35.4	18
130	83.6	31.4	13	77.4	38.9	13	66.8	25.2	18	68.1	31.4	18
135	82.7	30.0	13	77.2	35.3	13	67.3	24.6	18	66.6	30.0	18
140	85.2	43.4	13	70.9	41.4	13	61.3	23.3	18	61.9	43.4	18
145	74.3	36.8	13	66.2	44.9	13	62.0	30.8	18	59.8	36.8	16
150	75.5	27.2	11	68.3	22.1	10	59.0	29.1	18	55.0	27.2	15

7. Max knee flexion torque (60°s^{-1}) at values at specific joint angles. Data pertains to chapter 5.

	Loaded						Unloaded					
	Pre Load Carriage			Post Load Carriage			Pre Load Carriage			Post Load Carriage		
Angle (°)	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n	Torque (N·M)	SD	n
80	45.9	25.1	11	52.3	23.7	9	43.7	11.5	9	39.2	15.2	13
85	61.7	26.9	12	58.4	25.9	10	51.9	19.8	13	48.2	26.9	15
90	75.2	28.5	12	64.7	27.0	11	56.9	25.2	15	53.8	28.5	18
95	82.8	30.4	12	71.5	29.8	11	61.8	24.8	17	60.1	30.4	18
100	88.4	31.3	12	72.4	34.6	12	70.9	22.6	17	64.1	31.3	18
105	92.8	30.5	12	80.9	32.8	12	76.6	25.7	17	66.9	30.5	18
110	96.4	31.9	12	85.8	35.7	12	80.3	28.2	17	72.4	31.9	18
115	99.5	32.0	12	90.5	37.8	12	82.2	28.8	17	74.8	32.0	18
120	103.1	34.2	12	91.7	40.3	12	82.8	29.8	17	75.5	34.2	18
125	105.4	36.7	12	93.8	42.0	12	84.7	32.2	17	79.2	36.7	17
130	106.8	38.5	12	92.7	44.3	12	82.9	36.8	17	79.4	38.5	17
135	105.1	38.4	12	97.3	41.1	11	86.9	33.2	16	78.9	38.4	17
140	99.9	37.7	12	93.7	38.9	11	85.6	33.2	16	74.9	37.7	17
145	91.8	38.6	12	86.7	37.9	11	80.3	31.4	16	68.6	38.6	17
150	87.8	39.4	11	73.4	36.3	11	71.1	29.7	16	66.8	39.4	15
155	82.4	42.1	9	57.9	25.0	8	59.9	26.5	14	53.2	42.1	13