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The effect of loaded work on cardiopulmonary function, maximum acceptable work duration, and repeated sprint ability

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THE EFFECT OF LOADED WORK ON CARDIOPULMONARY FUNCTION,  
MAXIMUM ACCEPTABLE WORK DURATION, AND REPEATED SPRINT  
ABILITY

A thesis submitted in partial fulfilment of the  
requirements for the award of the degree

MASTER OF SCIENCE – RESEARCH

from

UNIVERSITY OF WOLLONGONG

by

Daniel S. Lee, BExScRehab

SCHOOL OF HEALTH SCIENCES  
FACULTY OF HEALTH AND BEHAVIOURAL SCIENCES  
2012
I, Daniel S. Lee, declare that this thesis, submitted in partial fulfilment of the requirements for the award of Master of Science, in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Daniel S. Lee

6 December 2012
ACKNOWLEDGEMENTS

I would not have completed this work without the encouragement of the other postgraduate students who I have worked with. Therefore, I would like to thank Sean, Brooke, Laura, and Hugo. I have enjoyed working with you, and your assistance in the lab and advice over the past two years is greatly appreciated. I would also like to mention Jo and Anne, who were always happy to discuss ideas and assist in the lab.

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This work would not have been possible without human subjects. Thanks to all those who participated. Your time and effort is appreciated. Finally, I want to thank Rachel, Mum, and Kate. It has been difficult at times, but you have continued to support me during my time at university.
Load carriage is a requirement of certain occupations such as the military and fire and rescue services. The nature of work within these occupations may be exhaustive, submaximal, and repetitive. It is therefore necessary to quantify the physiological demand of load carriage during both exhaustive and submaximal work, and to provide workplace recommendations on task duration for work involving load carriage. Considering that restricting the chest wall affects pulmonary mechanics, load carriage may influence the contractile performance of the diaphragm. Since repetitive, high intensity work is also common in these occupations, it would be useful to determine if load carriage influences the performance of subsequent high intensity work. As a result, three laboratory experiments were conducted. Firstly, exhaustive treadmill exercise was performed under three experimental conditions: control (unloaded), load (22 kg weighted vest), and restricted (chest strapped). Second, submaximal treadmill exercise with a 22 kg external load was performed under five exercise conditions: 30, 50, 60, 70, and 80% of peak oxygen uptake. Finally, repeated sprints were performed on a cycle ergometer immediately following each of the five submaximal exercise conditions. During exhaustive exercise combined with load carriage, exercise tolerance was significantly reduced ($P<0.05$), and the degree of this reduction was a function of body mass. Furthermore, loading or restricting the chest caused significant reductions in maximum voluntary ventilation, inspiratory time, and expiratory time ($P<0.05$). However, diaphragmatic contraction velocity and excursion were not influenced by exhaustive exercise with external load or restriction. During submaximal exercise with load, peak heart rate was the most appropriate measure of acceptable work duration. Therefore, load carriage at 30% of peak oxygen uptake may continue for up to 3.5 hours, whereas work at 80% of peak oxygen uptake should not exceed 6 minutes. Finally, prior activity beyond 60% of peak oxygen uptake affects the performance of subsequent high intensity work. Therefore, where repetitive sprint ability is required, prior activity should not exceed 60% of peak oxygen uptake.
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CHAPTER ONE:
INTRODUCTION

1.1 CONCEPTUAL INTRODUCTION

Certain occupations require workers to perform tasks in different environments and at varying intensities. The infantry soldier is a good example of such a worker. They may have to work in hot environments, carry a significant amount of equipment, perform moderate intensity tasks, such as a pack march, or high intensity work, such as sprinting to obtain cover. These activities contribute to the level of physiological strain experienced by the worker, and may affect task performance (Figure 1.1). It is therefore important to determine the duration a task can be performed. This will ensure that workers are able to perform their duties competently with minimal risk of injury and fatigue. For the purpose of this research, this duration will be referred to as the maximum acceptable work duration. Of course, other factors exist which may influence task performance, such as age, training status, and the complexity of the task at hand. However, this research will focus on the physiological determinants of acceptable work duration.

In addition to identifying this duration for a specific task, the current study will also quantify the physiological strain associated with loaded maximal and submaximal exercise. Continuing with our current example, it is mandatory for soldiers to be equipped with body armour, backpack, ammunition when deployed in potentially hostile theatres, and several other items. This equipment is placed on the torso, and may be carried over great distances, difficult terrain, and in extreme climates. In addition, tasks may be repetitive, and performed immediately following a prior activity. For instance, soldiers may have performed a pack march before coming under fire. Sprinting may be performed to obtain cover. To further understand the physiological requirements of a soldier, it is often necessary to perform tasks across several intensities. This will identify the maximum physiological response which is required to perform a task. In addition, performing several submaximal intensities will allow predictions of physiological responses across a range of intensities to be made, and the purpose of this is to provide estimations of physiological stress regardless of exercise intensity.

Consider Figure 1.2, where the ordinate represents a physiological variable of interest, such as heart rate or oxygen consumption, with exercise intensity as the independent variable. If
Figure 1.1: Factors which influence task performance. A variety of factors such as environmental temperature and exercise intensity, may affect the performance of a task. These in turn may also influence the duration that tasks can be performed.
Figure 1.2: Relationship between exercise intensity and a physiological variable. Such a relationship can allow for accurate predictions of the physiological response associated with specific workloads. If the independent variable was replaced with time, then the time taken to reach a certain heart rate, for example, can be predicted.
each data point represents the mean of a population sample of interest, then the relationship between this variable and exercise intensity can be explained mathematically, and the resulting relationship can be used to predict physical strain associated with various unmeasured work rates. The ability to predict these physiological responses would be very useful in many occupational settings, but is of particular importance to occupations in which work rates and operational capability are vitally important. Furthermore, if there was a physiological upper limit which represents an appropriate end-point for work, then specific work intensities can be prescribed with the knowledge on how long a given task can be performed, without compromising either safety or capability.

Whilst the aforementioned tasks may relate to a military scenario, the current research has a much broader physiological application relating to loaded maximal and submaximal exercise, and its impact upon cardiopulmonary function. For example, load carriage on the torso may restrict the movement of the chest wall during breathing. This could increase the work of breathing and cause the individual to experience heightened breathing discomfort. During exercise, this may pose a significant limitation as increases in ventilation are necessary to meet the oxygen demands of the working body. Furthermore, an external load may place greater demand on the inspiratory muscles, which may lead to premature fatigue. Therefore, in this study, diaphragmatic contractile performance will be evaluated with respect to loading or restricting the chest wall during exhaustive exercise.

1.1.1 Load carriage

Traditionally, research has focussed on the energy cost of load carriage (Goldman & Iampietro, 1962; Soule et al., 1978), and more specifically on predicting the energy cost of load carriage (Epstein et al., 1987; Pandolf et al., 1977). However, the objective of this research was not to predict the energy cost of load carriage, but to quantify the physiological strain associated with loaded exhaustive and submaximal work.

Many occupations require workers to carry loads. In Australia for example, soldiers are required to carry a minimum of 22 kg, and loads in excess of 50 kg have been reported (Knapik et al., 2004, Treloar & Billing, 2011). In addition, firefighters utilise a breathing apparatus, protective footwear, and heavy clothing as protection from heat and smoke. In total, this equipment weighs 19.86 kg (Taylor et al., 2012). Since the purpose of this research is to quantify the physiological strain associated with, and to identify acceptable working
times for loaded whole-body exercise, it is important to understand the physiology of load carriage.

1.1.1.1 Load carriage and resting physiological function

Even without the stress of physical work, load bearing has significant effects on human function. For instance, resting energy expenditure increases significantly when carrying heavy backpack loads of up to 50 kg (Pandolf et al., 1977). Alterations in pulmonary function are also observed with loads less than 10 kg. For example, forced vital capacity, peak expiratory flow, and forced expired volume in one second are reduced at rest due to increasing load (Legg, 1988; Majumdar et al., 1997).

The increase in resting oxygen consumption with heavy load may be partially explained by trunk muscle activity, which has been shown to be elevated during load carriage (Hong et al., 2008). Indeed, restricting the chest wall without the presence of load has a significant effect on total lung capacity, vital capacity, forced expired volume, tidal volume, and breathing frequency at rest (Gonzalez et al., 1999; Miller et al., 2002). Accordingly, load carriage may cause restriction of the chest wall and therefore impair pulmonary function. Furthermore, load carriage has also been shown to increase the overall contact area of the foot and, depending on the position of the load, cause either flexion or extension of the spine, and pelvic tilt (Chow et al., 2010; Pau et al., 2011; Thomas et al., 1959).

1.1.1.2 Load carriage during submaximal work

The physiological response to submaximal levels of work is well established. During exercise which is below 50% of peak aerobic power, there is an initial linear increase in oxygen consumption until a steady state is reached. It has been reported that exercise below this threshold may continue for durations of up to 8 hours (Saha et al., 1979). However, when exercise intensity is progressively increased, oxygen consumption will continue to increase until exhaustion (Hill & Lupton, 1923). Furthermore, minute ventilation increases in proportion to exercise intensity and, as with oxygen consumption, the initial increase in ventilation is linear. However, when exercise intensity is above 65% peak aerobic power, ventilation will increase exponentially until exhaustion (Owles, 1930). These relationships may vary considerably depending on a variety of factors such as the age and training status of subjects (Davis et al., 1979; Posner et al, 1987).
The research relating to physiological function during submaximal exercise and load carriage is extensive. Load conditions up to 70 kg have been studied, with various load positions, load carriage devices, exercise intensities, and physiological variables measured (Abe et al., 2004; Beekley et al., 2007; Bambhani & Maikala, 2000; Das & Saha, 1966; Duggan & Haisman, 1992; Kram, 1991; Legg et al., 1992; Manning & Griggs, 1983; Pandolf et al., 1977; Sagiv et al., 1994). Selected variables have been summarised in Table 1.1.

When a load is carried, physiological variables such as heart rate and oxygen consumption increase to a greater extent when the load is carried in a distal position compared to a more central position (Abe et al., 2004; Balogun, 1986). When load is carried on the shoulders, this may be explained by static muscular contractions of the upper limbs to support the load position. The addition of mass to the extremities must also be accelerated and decelerated during gait which would increase the work done by limb muscles (Legg et al., 1992; Taylor et al., 2012). It also appears that load carriage has an effect on pulmonary function as tidal volume is reduced during submaximal exercise with load (Goslin & Rorke, 1986; White & Hodous, 1987). Furthermore, there is evidence that postural muscle activity is elevated during load carriage tasks, which may explain the increase in oxygen consumption which occurs during load carriage (Hong et al., 2008).

In addition to these physiological effects, one may confidently assume that load bearing, whether on the torso, head, or limbs, is accompanied by a degree of discomfort, depending on the mass and duration of carriage. In support of this, perceived exertion increases linearly with the mass carried, and significant shoulder discomfort has been reported with loads of 50 kg (Goslin & Rorke, 1986; Patton et al., 1991). This may explain why exercise time is reduced with loads up to 93 kg. For example, with a 73 kg load, treadmill exercise continued for 41 minutes, whereas when the mass was increased to 93 kg, exercise was terminated after 18 minutes (Koerhuis et al., 2009).

1.1.1.3 Load carriage during exhaustive work

Whole-body exercise to voluntary exhaustion is well studied in humans. In trained individuals, peak oxygen consumptions exceeding 5 L.min\(^{-1}\) have been reported (Burtscher et al., 2011). During incremental exercise, physiological variables will continue to increase until exhaustion, and, due to the increasing intensity, a physiological steady state is not reached (Wyndham et al., 1959). During peak exercise, it is believed that performance is partially
Table 1.1: Load carriage and its effect on selected physiological variables during submaximal exercise

<table>
<thead>
<tr>
<th>Variable</th>
<th>Load</th>
<th>Result</th>
<th>Author/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen consumption</td>
<td>Unloaded – 25.6 kg</td>
<td>Elevated with load compared to no load or lighter load</td>
<td>Balogun (1986), Duncan et al. (1979), Goslin &amp; Rorke (1986), Li &amp; Hong (2010), Lloyd &amp; Cooke (2000)</td>
</tr>
<tr>
<td></td>
<td>Unloaded – 40% body mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6-27 kg, 10-70% body mass</td>
<td>Increased when load carried distally compared to proximal position</td>
<td>Abe et al. (2004), Das &amp; Saha (1966), Legg et al. (1992), Lloyd et al. (2010), Stuempfle et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>18 kg</td>
<td>Relative oxygen consumption is negatively correlated with body mass</td>
<td>Bilzon et al. (2001)</td>
</tr>
<tr>
<td></td>
<td>15% body mass</td>
<td>Reduced when walking with load at slow speeds compared to no load</td>
<td>Abe et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>30-50 kg</td>
<td>Equation developed to predict energy expenditure of load carriage during rest and exercise</td>
<td>Pandolf et al. (1977)</td>
</tr>
<tr>
<td>Heart rate</td>
<td>Unloaded – 25.6 kg</td>
<td>Increases with load compared to no load or lighter load</td>
<td>Balogun (1986), Duncan et al. (1979), Goslin &amp; Rorke (1986), Lloyd &amp; Cooke (2000), Louhevaara et al. (1985)</td>
</tr>
<tr>
<td></td>
<td>26 kg</td>
<td>Increased when load carried distally compared to proximal position</td>
<td>Legg et al. (1992)</td>
</tr>
<tr>
<td>Minute ventilation</td>
<td>Unloaded – 30 kg</td>
<td>Elevated with load compared to no load or lighter load</td>
<td>Balogun (1986), Bhambhani &amp; Maikala (2000), Majumdar et al. (1997), Louhevaara et al. (1985), Sykes (1993)</td>
</tr>
<tr>
<td>Variable</td>
<td>Load</td>
<td>Result</td>
<td>Author/s</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>25% body mass</td>
<td>Increased when load carried distally compared to proximal position</td>
<td>Stuempfle et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>Tidal volume</td>
<td>Unloaded – 15.5 kg</td>
<td>Decreased at rest with load compared to no load</td>
<td>Louhevaara et al. (1985)</td>
</tr>
<tr>
<td></td>
<td>3.8 – 23.1 kg</td>
<td>Increased with load compared to no load or lighter load</td>
<td>Goslin &amp; Rorke (1986), White &amp; Hodous (1987)</td>
</tr>
<tr>
<td>Breathing frequency</td>
<td>Unloaded – 15.5 kg</td>
<td>Increased with load compared to no load</td>
<td>Gordon et al. (1983), Li &amp; Hong (2010), Louhevaara et al. (1985)</td>
</tr>
<tr>
<td></td>
<td>Unloaded – 50% body mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceived exertion</td>
<td>Unloaded – 70% body mass</td>
<td>Increased with load compared to no load or lighter load</td>
<td>Beekley et al. (2007), Gordon et al. (1983), Goslin &amp; Rorke (1986), Quesada et al. (2000), Simpson et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>25.9 – 50 kg</td>
<td>No change with heavier load compared to no load or lighter load</td>
<td>Sagiv et al. (1994)</td>
</tr>
<tr>
<td></td>
<td>25% body mass</td>
<td>Increased when load carried distally compared to proximal position</td>
<td>Stuempfle et al. (2004)</td>
</tr>
<tr>
<td>Core Temperature</td>
<td>3.8 – 23.1 kg</td>
<td>Increased with heavier load compared to lighter load</td>
<td>White &amp; Hodous (1987)</td>
</tr>
<tr>
<td>Muscle activity</td>
<td>Unloaded – 20% body mass</td>
<td>Postural muscle activity increased</td>
<td>Hong et al. (2008)</td>
</tr>
</tbody>
</table>
limited by oxygen delivery to the working muscles. In support of this theory, it has been shown that peak blood flow to exercising muscle exceeds that which can be delivered by the heart (Saltin, 1985). In contrast, the pulmonary system is said to be developed to a greater extent than that necessary for maintaining ventilation at peak work rates (Aaron et al., 1992). However, since arterial hypoxemia and respiratory muscle fatigue may occur in some cases, it is possible that this system may pose significant limitations to performance (Bye et al., 1984; Loke et al., 1982; Romer et al., 2006).

There are few studies which combine peak exercise and load carriage (Louhevaara et al., 1995; Simpson et al., 2010; Raven et al., 1977; Taylor et al., 2012). The findings from these studies are summarised in Table 1.2. For the purpose of this research, exercise tolerance will be defined as the duration (min) of exercise until volitional fatigue, and exhaustive treadmill exercise will refer to exercise which is terminated due to volitional fatigue. Indeed, occupations such as firefighting may require near maximal levels of exertion whilst subjects are wearing heavy clothing and carrying equipment. Consequently, much of the literature combining load carriage and high intensity work has been applied to firefighting (Louhevaara et al., 1995; Raven et al., 1977; Taylor et al., 2012).

It is clear that combining high intensity work and load carriage is not well-tolerated. Accordingly, the potential to perform physical work is reduced since peak relative oxygen consumption is limited by load carriage. However, it appears that peak physiological responses such as absolute oxygen consumption, minute ventilation, and heart rate remain unchanged despite the addition of loads between 19 and 26 kg (Table 1.2). To explain this, it has been suggested that, since peak absolute oxygen consumption is not affected, oxygen consumption is partitioned to that required to perform physical work, and that necessary to bear the load (Taylor et al., 2012). Therefore, less oxygen is available to perform work compared to that which is available during unloaded work. As a consequence, the peak physiological response is reached sooner, therefore reducing exercise duration.

1.1.2 Maximum acceptable work duration

It is important, from both scientific and occupational perspectives, to quantify the physiological demand of loaded work. Scientifically, by measuring physiological function, we will enhance our understanding of human physiology under stressful conditions. Furthermore, this will define the physical nature of specific load carriage tasks within an
**Table 1.2:** Load carriage during exhaustive exercise

<table>
<thead>
<tr>
<th>Authors</th>
<th>Load</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raven et al. (1977)</td>
<td>Unloaded, 15.8 kg breathing apparatus</td>
<td>Exercise tolerance reduced by 22%, peak heart rate reduced by 4.6%</td>
</tr>
<tr>
<td>Louhevaara et al. (1995)</td>
<td>Unloaded, 25.9 kg fire protective clothing and breathing apparatus</td>
<td>Exercise tolerance reduced by 27%, no change in absolute oxygen consumption, heart rate, minute ventilation, or perceived exertion</td>
</tr>
<tr>
<td>Simpson et al. (2010)</td>
<td>20 kg British Army backpack</td>
<td>Peak oxygen consumption 4.33 L.min⁻¹, 54.5 mL.kg⁻¹.min⁻¹</td>
</tr>
<tr>
<td>Taylor et al. (2012)</td>
<td>Unloaded, 19.86 kg protective clothing, boots, helmet, and breathing apparatus</td>
<td>Exercise tolerance reduced by 56%, no change in peak absolute oxygen consumption, heart rate, minute ventilation, or perceived exertion</td>
</tr>
</tbody>
</table>
occupation. From this, one may then decide if an individual is capable of performing specific tasks. However, quantifying the physical demands may not necessarily enable us to predict how long a task may be performed. This is the next step of the current research.

One could reasonably hypothesise that the time a person can sustain continuous physical work is a function of the intensity at which that work is performed, and the type of activity involved. For example, the average person cannot sustain a power output of 800 watts for greater than 15 seconds, whereas an output of approximately 250 watts can be maintained for over 10 minutes (Wilkie, 1985). However, we must consider the consequences of performing physically demanding work. For example, consider a bricklayer who is required to construct a straight wall by laying 1000 bricks in one day. Does this workload carry a greater risk of injury or fatigue compared to laying 500 bricks per day? Furthermore, can the worker perform this task just as effectively at the higher workload, and, if necessary, can further work be completed? It would be analogous to ask “is the wall straight, and, is the worker physically capable of working overtime?” It is therefore important to identify an acceptable duration a worker can perform certain duties. Furthermore, defining an acceptable workload, or duration, is necessary to reduce the risk of injury in the workplace, as it has been shown that over exhaustion, high workloads, and fatigue are causes of occupational and sport-related injury (Craib et al., 2007; Dennis et al., 2005; Fisman et al., 2007).

Previous research has recommended the use of oxygen consumption to determine appropriate workloads. For example, one third of maximum aerobic power has been suggested as the limit for physical work performed over an 8-hour period (Michael et al., 1961). During this study, three male subjects exercised on a treadmill or cycle ergometer for up to 8 hours. When subjects were exercising at equivalent levels of oxygen uptake, higher heart rates were recorded during cycle ergometry. Furthermore, treadmill exercise was better tolerated when the workload was matched with cycle ergometry. Therefore, the exercise mode must be considered when calculating acceptable work duration, especially if it is determined by heart rate. Furthermore, humans consume oxygen to perform physical work. Thus, it is logical to use this as a determinant of work duration. However, the measurement of oxygen consumption in the field may not be appropriate, and is also restricted by equipment costs. An alternative would be to use a surrogate measure of oxygen consumption such as heart rate. This may be more appropriate since equipment costs are low and devices, unlike those for
measuring oxygen consumption, are not cumbersome. Work in this area is currently being carried out (Notley, 2012).

We are aware of three studies concerning maximum acceptable work duration (Saha et al., 1979; Wu & Wang, 2001; Wu & Wang, 2002) (Table 1.3). There are several limitations to these studies, including the use of cycle ergometry. This exercise mode is not a good representation of common tasks which are performed in physically demanding jobs. In addition, these studies have not considered load carriage, which is also performed in many occupations. Furthermore, several different methods to calculate acceptable work duration have been utilised. For instance, locating the time point at which heart rate is several beats higher than that during the initial hours of work seems appropriate, considering that this may indicate non steady state conditions. However, if the work intensity is such that a steady state does not exist, then this calculation cannot be performed. Therefore, this method is useless during non steady state conditions. In addition, using an absolute value for heart rate as an indicator of acceptable work time is simple, and logical. Despite this, having two values of heart rate as measures of work time is not. Thus, one method for calculating acceptable work duration, which involves whole-body exercise, a variety of exercise intensities, and load carriage, is needed. The use of absolute heart rate as the limit to work is also a limitation to these studies. Depending on factors such as age, gender, and training status of the worker, an absolute heart rate may elicit a different relative workload (Andrews, 1969; Harms, 2006; Swain et al., 1998). However, these are the only published methods we are aware of for calculating acceptable work duration.

1.1.3 Repeated high intensity work
Continuing with our previous example of the firefighter and soldier, repetitive high intensity work is common to these occupations. During certain firefighting tasks, heart rates exceeding 180 b.min\(^{-1}\) have been observed (Samspon et al., 2012). Within the military, repetitive high intensity work is also common. Consequently, a specific assessment was developed to evaluate the effect of load on infantry soldier sprint performance (Treloar & Billing, 2011). In addition, research has also explored repetitive sprint ability in sport as this is performed in many disciplines. For example, soccer players completed 30-metre sprints before, during, and after a 90-minute game. It was shown that 30-metre sprint performance was reduced following, but not during the game (Krusrup et al., 2006; Krusrup et al., 2010). Where repeat sprints have been performed on a cycle ergometer, performance also declines with
Table 1.3: Literature concerning maximum acceptable work duration

<table>
<thead>
<tr>
<th>Authors</th>
<th>Exercise mode</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saha et al. (1979)</td>
<td>Treadmill 20 – 70% peak aerobic power</td>
<td>Maximum acceptable work duration 35% peak aerobic power for 8-hour work day</td>
</tr>
<tr>
<td>Wu &amp; Wang (2001)</td>
<td>Cycling 60 – 70% peak power</td>
<td>18.8 and 6.5 min suggested as acceptable work times for 60 and 70% peak power, respectfully</td>
</tr>
<tr>
<td>Wu &amp; Wang (2002)</td>
<td>Cycling 20 – 70% peak aerobic power</td>
<td>Maximum acceptable work duration negatively correlated with relative oxygen consumption and relative heart rate</td>
</tr>
</tbody>
</table>
successive sprints (Mendez-Villanueava et al., 2008; Racinais et al., 2005). Further research confirms that prior activity may affect the performance of subsequent exercise. For instance, submaximal exercise was performed on a cycle ergometer prior to high intensity leg extensions on an isokinetic dynamometer (Hitchcock, 1989). The decrement in power output during leg extensions was greater when the intensity of prior exercise was higher. Consequently, it has been suggested that prior exercise which exceeds 60% of peak oxygen uptake will affect sprint performance (Capelli et al., 1993; Ferretti et al., 1987).

1.2 AIMS AND HYPOTHESES
The overall purpose of this project was to determine how loaded work influences human physiological function, and to provide workplace recommendations related to the performance of tasks involving load carriage. Furthermore, this research will determine how load carriage combined with submaximal work affects the performance of repetitive high intensity exercise. In order to accomplish this, three separate studies were conducted.

1.2.1 Study one
The purpose of this study was to examine the combined effects of external load and exhaustive exercise on physiological function and diaphragm performance. To evaluate this, two experimental conditions were developed: load carriage, and chest wall restriction. These conditions were studied during incremental treadmill exercise to voluntary exhaustion, with several physiological and physical variables measured during experiments.

1.2.1.1 Aims
(i) Quantify the physiological demands of exhaustive exercise combined with load carriage
(ii) Determine if pulmonary function is altered by load carriage or chest wall restriction
(iii) Examine diaphragm performance following exhaustive exercise

1.2.1.2 Hypotheses
(i) Peak measures of oxygen uptake, minute ventilation, and heart rate will not be affected by the experimental conditions
(ii) Load carriage, but not chest wall restriction, will reduce exercise tolerance
(iii) Load carriage and chest wall restriction will reduce maximum voluntary ventilation
(iv) Diaphragmatic contraction velocity will be reduced following exhaustive exercise, with more profound reductions being present in the experimental conditions
1.2.2 **Study two**

The purpose of this study was to identify acceptable work times across a range of submaximal intensities for whole-body work combined with load carriage. To investigate this, five experimental conditions were established, each varying by intensity only: 30, 50, 60, 70, and 80% of peak oxygen uptake. Each condition consisted of treadmill exercise combined with load carriage.

**1.2.2.1 Aims**

(i) Quantify the physiological demands of submaximal exercise combined with load carriage across several exercise intensities

(ii) Provide acceptable work durations based on previously established methods using heart rate, across a variety of work intensities

(iii) From the established methods for calculating acceptable work time, suggest the most appropriate method for whole-body exercise involving load carriage

**1.2.2.2 Hypotheses**

(i) Voluntary exhaustion will occur at workloads above 30% peak oxygen uptake

(ii) Acceptable work time will be significantly different between each of the experimental conditions

(iii) Several methods for calculating acceptable work time will be utilised, and these will produce significantly different work times for each condition

(iv) Load carriage performance will be significantly correlated with body mass

1.2.3 **Study three**

The purpose of this study was to determine if submaximal exercise combined with load carriage influences the performance of subsequent high intensity work, and, if this is dependent on the intensity of prior exercise. To evaluate this, five experimental conditions were established, each varying by intensity only: 30, 50, 60, 70, and 80% of peak oxygen uptake. Each condition consisted of treadmill exercise combined with load carriage, followed by repetitive high intensity exercise on a cycle ergometer.

**1.2.3.1 Aims**

(i) Quantify the physical demands of high intensity work which is preceded by submaximal work at varying intensities
(ii) Determine if there is a threshold where submaximal exercise combined with load carriage begins to affect the performance of subsequent high intensity work

1.2.3.2 Hypotheses

(i) Power output will be significantly reduced following exercise which exceeds 60% peak oxygen uptake
(ii) The recovery of sprint performance will be significantly correlated with peak oxygen uptake.
1.3 REFERENCES


CHAPTER TWO: THE COMBINED EFFECTS OF THORACIC LOAD CARRIAGE AND EXHAUSTIVE EXERCISE

2.1 INTRODUCTION
A traditional approach to studying load carriage focused on quantifying the energy cost of different tasks. From the present study, we intended to highlight the physiological effects of load carriage during peak, whole-body exercise. Accordingly, there is limited evidence in this field. Furthermore, studies have been applied to firefighting, as this is an occupation which demands both high intensity work and load carriage. For instance, exhaustive treadmill exercise was performed without load, and with a self-contained breathing apparatus with a total mass of 15.82 kg (Raven et al., 1977). During the loaded condition, there was a 22% reduction in exercise tolerance. This is similar to other findings, where there was a 27% reduction during exhaustive exercise with a load of 25.90 kg (Louhevaara et al., 1995). In addition, peak relative oxygen consumption was reduced by 26%. However, peak physiological responses were not different between the loaded and unloaded conditions.

These results have been confirmed recently (Taylor et al., 2012). Exhaustive treadmill exercise was performed with no load, and with a standard firefighter ensemble consisting of protective clothing, boots, breathing apparatus, and helmet, with a combined mass of 19.86 kg. Peak values for absolute oxygen consumption, minute ventilation, and heart rate were not different between trials. However, the peak response was reached much sooner, and at a lower external work rate when subjects wore the ensemble. Furthermore, exercise tolerance and peak relative oxygen consumption were reduced by 56% and 15%, respectively, as a result of the ensemble.

Load carriage not only influences the ability to perform work, but also affects pulmonary function. For example, forced vital capacity and maximum voluntary ventilation are significantly reduced when the load is carried on the torso (Legg et al., 1988; Majumdar et al., 1997). Other studies suggest that these effects are not due to load carriage per se, but are the result of restricting the thoracic cage (Gonzalez et al., 1999; Harty et al., 1999). Furthermore, there is evidence that the respiratory muscles may become fatigued following exhaustive and prolonged exercise (Coast et al., 1990; Guenette et al., 2010; Loke et al., 1982). With the addition of a thoracic load, it seems logical that the work performed by the
inspiratory muscles would increase, possibly causing fatigue. Therefore, we also investigated diaphragmatic contraction velocity and excursion to determine if diaphragm fatigue is exacerbated by load carriage.

Several studies have demonstrated that the respiratory muscles may become fatigued. This has been shown using methods such as phrenic nerve stimulation and measuring respiratory pressures (Black & Hyatt, 1969; Guenette et al., 2010; Johnson et al., 1993; Martyn et al., 1987; Nickerson & Keens, 1982). The former technique allows observation of diaphragm performance only, whilst the latter includes accessory muscles of respiration. The muscles responsible for inspiration appear to fatigue following exhaustive exercise and prolonged endurance activity (Coast et al., 1990; Guenette et al., 2010; Loke et al., 1982). However, it is unknown whether the magnitude of respiratory muscle fatigue which occurs following exhaustive exercise is affected by load carriage. Furthermore, restricting the chest wall during exercise affects pulmonary function and increases oxygen consumption (Coast & Cline, 2004; Gonzalez et al., 1999; Harty et al., 1999). As previously stated, these effects are also observed when body armour is worn (Legg et al., 1988; Majumdar et al., 1997). The combined effects of load carriage and chest wall restriction may place greater demand on the inspiratory muscles, possibly leading to fatigue. Thus, it is important to consider the function of the diaphragm during tasks involving load carriage and exhaustive exercise.

Ultrasonography may be an alternative, non-invasive method of evaluating diaphragmatic performance. This method involves locating the right hemidiaphragm and recording the activity using motion modulation ultrasonography (Boussuges et al., 2009). However, to our knowledge, the use of this technique as a measure of diaphragmatic fatigue is not well documented. This method was based on animal models which have demonstrated changes in the pressure generated by the diaphragm during paced contractions (Davis, 1967; Planas et al., 1985). A study was conducted to reveal if ultrasound could identify changes in diaphragm movement when fatigue was present (Kocis et al., 1997). Fatigue was identified as a significant decrease in transdiaphragmatic pressure. The velocity of diaphragm contraction during inspiration was significantly reduced when fatigue was present, suggesting that ultrasound may be a useful measure of diaphragm performance.

Respiratory muscle fatigue is not the only concern when high intensity exercise is combined with load carriage and chest wall restriction. For example, increasing the work of breathing
reduces blood flow to working muscles, and research suggests that this is caused by elevated sympathetic output during high intensity exercise (Harms et al., 1997; St Croix et al., 2000). It is reasonable to suspect that thoracic load carriage alone, or combined with chest wall restriction, would create a situation in which the work of breathing is increased. Accordingly, minute ventilation and perceived exertion increase significantly with loading, suggesting that breathing effort and whole-body exertion are affected (Beekley et al., 2007; Borghols et al., 1978; Gordon et al., 1983; Quesada et al., 2000; Sagiv et al., 1994). Identifying a threshold where pulmonary function is impaired due to loaded exercise would be valuable where predictions of work performance are sought. Physical work could then be carried out at a level below this threshold, and work may continue for a longer period of time.

2.2 AIMS AND HYPOTHESES

The aim of this study was to quantify the physiological demands of exhaustive exercise combined with load carriage. In addition, this study will determine if pulmonary function, and diaphragm performance are influenced by load carriage or chest wall restriction during exhaustive exercise.

There were several hypotheses concerning this study. First, peak physiological measures would not be affected by the experimental conditions. Second, both load carriage and chest wall restriction would influence pulmonary function. Third, exercise tolerance would be reduced following load carriage. Finally, diaphragm performance would be affected by load carriage and chest wall restriction.

2.3 METHODS

2.3.1 Subjects

Thirteen healthy and physically active male subjects were recruited who were current and past students within the School of Health Sciences at the University of Wollongong (Table 2.1). Subjects were asked to refrain from strenuous exercise the day before attending the laboratory and to avoid smoking, caffeine, and alcohol in the 12 hours prior to an experiment. Experimental procedures were approved by the Human Research Ethics Committee, University of Wollongong (HE10/400).
<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (y)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>VO$_{2peak}$ (mL.kg$^{-1}$.min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>64.78</td>
<td>168.10</td>
<td>48.98</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>76.02</td>
<td>171.80</td>
<td>58.58</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>78.14</td>
<td>186.00</td>
<td>53.43</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>65.92</td>
<td>179.20</td>
<td>67.92</td>
</tr>
<tr>
<td>5</td>
<td>34</td>
<td>78.26</td>
<td>180.00</td>
<td>67.40</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>80.70</td>
<td>186.60</td>
<td>72.60</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
<td>63.12</td>
<td>174.90</td>
<td>62.11</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
<td>71.06</td>
<td>183.90</td>
<td>65.53</td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>85.42</td>
<td>180.90</td>
<td>54.15</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>80.24</td>
<td>183.60</td>
<td>68.31</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>84.58</td>
<td>173.00</td>
<td>48.90</td>
</tr>
<tr>
<td>12</td>
<td>21</td>
<td>74.30</td>
<td>173.90</td>
<td>66.94</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>69.06</td>
<td>178.00</td>
<td>58.67</td>
</tr>
<tr>
<td>Mean</td>
<td>22.31</td>
<td>74.74</td>
<td>178.45</td>
<td>61.04</td>
</tr>
<tr>
<td>S.D.</td>
<td>4.07</td>
<td>5.80</td>
<td>7.42</td>
<td>7.85</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>1.13</td>
<td>1.61</td>
<td>2.06</td>
<td>2.18</td>
</tr>
</tbody>
</table>
2.3.2 Study design and overview

This study had a within-subjects design with each subject acting as his own control. Subjects attended the laboratory on five separate occasions. During the first visit, subjects were familiarised with all experimental procedures, completed a medical screening questionnaire, and provided their written, informed consent to participate in the study. Baseline measurements were taken during the second visit, and the experimental protocol was performed during the remaining three sessions.

2.3.3 Experimental conditions

Subjects were required to perform exhaustive treadmill exercise. Three experimental conditions were used in this study: condition 1 (control), condition 2 (load), and condition 3 (restricted) (Figure 2.1). In all subjects, condition 1 occurred first, followed by conditions 2 and 3, which were presented in a balanced order. All experiments were performed in a laboratory environment (22°, 35% relative humidity).

Military fatigues (long-sleeved shirt and pants) and running shoes were worn for all conditions (combined mass 1.66 kg). In addition, subjects donned a 22 kg weighted vest (MIR Pro Weighted Vest, Mir Vest Inc., CA, USA) for the load condition. This was to simulate the minimum load that Australian soldiers are required to carry. The primary researcher was responsible for fitting the vest to each subject. To standardise the thoracic wall compression applied by the vest, a pressure bio-feedback unit was used (Chattanooga Group Inc., TN, USA) (Figure 2.2). The unit was positioned at the level of the zyphoid process and inflated to 20 mmHg. The weighted vest was then placed on the subject, who was asked to “breathe normally, and indicate with your hand each time you are about to inhale”. The vest was fastened until a pressure of 80-90 mmHg was achieved following a normal exhalation. The pressure was checked on three consecutive breaths to ensure the correct tension was applied. The pressure bio-feedback unit was then deflated and removed.

Finally, a chest wall restriction was applied for condition 3 (Figure 2.1). This was achieved by strapping the chest using three crepe bandages (Handy Crepe Heavy T, 7.5cm x 2.3m, BSN Medical Pty. Ltd., Victoria, Australia). The position and direction of the bandages was chosen to apply pressure to the same areas of the chest wall as condition 2. That is, to attempt to restrict both anterior-posterior and lateral movements of the thoracic cage. The purpose of this condition was to simulate the same level of chest wall restriction as condition 2, however
Figure 2.1: Experimental conditions. **A** – Condition 1 (control), **B** – Condition 2 (load), **C** – Condition 3 (restricted). In **C**, the shirt was removed for the purpose of displaying the chest wall restriction. The bandages were arranged in this manner in order to apply pressure to the same areas of the chest wall as condition 2. That is, to attempt to restrict both anterior-posterior and lateral movements of the thoracic cage.
Figure 2.2: Pressure bio-feedback unit. In the load and restricted conditions, the unit was positioned at the level of the ziphoid process and inflated to 20 mmHg. The weighted vest or chest strapping were then placed on the subject and fastened until a pressure of 80-90 mmHg was achieved following a normal exhalation. The pressure bio-feedback unit was then deflated and removed.
without the load. The level of restriction was standardised using a pressure bio-feedback unit, according to the method described for the load condition.

2.3.4 Experimental protocol
Subjects performed incremental treadmill exercise to voluntary exhaustion on three occasions, but under three treatment conditions: control, load, and restricted. The exercise protocol was based on a previously established method (Davies et al., 1984) which was modified during a pilot study. The test began with 5 minutes of seated rest, followed by 5 minutes of standing rest, and 5 minutes of walking at 5 km.hr⁻¹ and a gradient of 1%. The treadmill speed was then increased to 9 km.hr⁻¹ and further increases of 1 km.hr⁻¹ occurred each minute until a perceived exertion of 16/20 was achieved (Borg 1962a, 1962b). At this point, treadmill speed remained constant and the gradient was increased by 1% every minute until voluntary exhaustion. Subjects performed this protocol under three different experimental conditions, with at least 72 hours of recovery between each experiment. The protocol is summarised in Table 2.2.

2.3.5 Measurements

2.3.5.1 Maximum voluntary ventilation
This was performed as a baseline measurement when subjects initially attended the laboratory for familiarisation. A subset of 5 subjects from the sample population participated in this measurement. The test was performed in a seated position for each condition (Figure 2.1), which were presented randomly. Subjects were connected to a two-way non-rebreathing valve (Model 2700B, Hans Rudolph Inc., KS, USA) which was connected to a pneumotachometer (Model 3813, Hans Rudolph Inc., KS, USA), and asked to breathe as forcefully as possible for 12 seconds. Expired volume was recorded on a computer program (OUSW 4.3, TrueOne 2400 metabolic measurement system, ParvoMedics Inc., UT, USA) for each breath during this period, and multiplied by a factor of five to achieve the calculated maximum voluntary expired ventilation (L.min⁻¹). Subjects performed the test three times for each condition, with 5 minutes of rest between tests. Maximum voluntary ventilation was taken as the highest value recorded from the three replicate measurements.

2.3.5.2 Oxygen consumption
Subjects breathed through a two-way non-rebreathing valve (Model 2700B, Hans Rudolph Inc., KS, USA) and expired air was directed to a metabolic system (TrueOne 2400 metabolic
Table 2.2: Exhaustive exercise protocol

<table>
<thead>
<tr>
<th>Subject arrival</th>
<th>Subject dresses in military fatigues and running shoes. Primary researcher fits weighted vest or chest strapping.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10 min</td>
<td>Resting data collection</td>
</tr>
<tr>
<td>10-15 min</td>
<td>Walking at 5 km.hr⁻¹, 1% grade</td>
</tr>
<tr>
<td>15 – 16 min</td>
<td>Running at 9 km.hr⁻¹, 1% grade</td>
</tr>
<tr>
<td>17 min</td>
<td>Speed increased by 1 km.hr⁻¹ every minute until whole-body RPE ≥ 16/20</td>
</tr>
<tr>
<td>Whole-body RPE ≥ 16/20</td>
<td>Grade increased by 1% per minute until exhaustion</td>
</tr>
</tbody>
</table>
measurement system, ParvoMedics Inc., UT, USA). Data were averaged for each breath over a 15-second period to determine oxygen consumption, carbon dioxide production, expired minute ventilation, tidal volume, breathing frequency, inspiratory time, and expiratory time. The metabolic system was calibrated with a 3-litre calibration syringe (Model 5530, Hans Rudolph Inc., KS, USA) with known concentrations of oxygen (15.97%), carbon dioxide (4.03%), and nitrogen (80%) prior to each use.

2.3.5.3 Heart rate
Heart rate was obtained at 15 second intervals based on R-wave detection during ventricular depolarisation using a heart rate monitor (Model PE3000 and Advantage, Polar Electro Sport Tester, Finland).

2.3.5.4 Perceived exertion
Perceived exertion was recorded at 2 minute intervals using a 15-point rating of perceived exertion scale (where 6 = very, very light, 20 = very, very hard) (Borg, 1962a, 1962b). Subjects were asked “How hard are you exercising” with reference to the whole body, chest, and legs.

2.3.5.5 Diaphragmatic contractile performance
Diaphragmatic displacement and velocity were recorded during the familiarisation visit to the laboratory (baseline). In addition, these measurements were taken at three time points during the experimental protocol (5, 10, and 15 minutes following voluntary exhaustion). The following technique was based on the methods of Boussuges et al. (2009). Clothing, weighted vest, and crepe bandages were removed to access the lateral chest wall for this measurement.

The right hemidiaphragm was imaged using a curved array transducer (C4-2 Broadband Curved Array, ATL Ultrasound Inc., WA, USA) which was connected to an ultrasound system (HDI3000 Ultrasound System, ATL Ultrasound Inc., WA, USA). The right costal margin, the mid-clavicular, and anterior axillary lines were located whilst the subject was in a standing position. The transducer was placed here and directed dorsally, medially, and cranially (Figure 2.3). If the right hemidiaphragm was not located in this position, the transducer was moved superiorly or inferiorly to the next intercostal space until it was located. When a clear image of the right hemidiaphragm was displayed, the position of the
**Figure 2.3:** Location of the right hemidiaphragm. The right costal margin, the mid-clavicular (A), and anterior axillary (B) lines were located whilst the subject was in a standing position. The transducer was placed here and directed dorsally, medially, and cranially.
A transducer was marked to ensure that further measurements were taken at the same site. Locating the right hemidiaphragm was performed in two-dimensional mode (Figure 2.4A).

Once the diaphragm was located, subjects were asked to perform a maximal voluntary sniff. This inspiratory sniff manoeuvre required the subject to inhale through the nose as rapidly as possible. Five inspiratory sniff manoeuvres were performed during baseline testing and three at 5, 10, and 15 minutes following each experimental trial. Only three were performed following experimental trials as several minutes were required to analyse the ultrasound trace. Each manoeuvre was performed from residual volume and separated by one tidal breath. All inspiratory sniff manoeuvres were performed in three-dimensional mode (Figure 2.4B) with the horizontal and vertical axes representing time (sec) and diaphragmatic displacement (cm), respectively. A marker was placed by hand at the base and the peak of each curve to allow measurement of diaphragmatic displacement and speed of contraction (Figure 2.4B). These two indices were taken as measures of diaphragmatic contractile performance.

2.3.6 Statistical analyses
All data are reported as means with standard deviations or standard errors of the means. To determine statistical differences, one and two-way repeated measures analysis of variance (ANOVA) were performed with Bonferroni’s post hoc analysis. Statistical significance was accepted if $P<0.05$. It was anticipated that certain individuals would exercise for a longer period than others. To allow for appropriate comparisons, physiological variables were expressed relative to each subject’s percentage of peak oxygen uptake ($\%$ VO$_{2\text{peak}}$). In addition, exercise time was also the independent variable for selected comparisons. Linear regression analysis was performed to determine correlations between selected variables.

2.4 RESULTS
2.4.1 Baseline data
Subject 9 was excluded from the study due to an injury which was not sustained during this study. Twelve subjects successfully completed the three conditions. When subjects were resting prior to commencing exercise, there were no significant differences between conditions for absolute or relative oxygen consumption, heart rate, minute ventilation, tidal volume, or breathing frequency (Table 2.3).
Figure 2.4: Viewing the diaphragm using ultrasound. Panel A shows the right hemidiaphragm in two-dimensional mode. Panel B shows the right hemidiaphragm in three-dimensional mode. A maximal voluntary sniff is shown on the far left and a normal breath is in the centre. Note that the $x$ and $y$ axes represent time (sec) and distance (cm), respectively, and were measured using markers. The speed of diaphragmatic contraction was calculated as $y/x$. 
Table 2.3: Baseline data (N=12). Data represents each subject in seated rest for a period of 5 minutes. Values are means with standard errors of the means.

<table>
<thead>
<tr>
<th>Baseline data</th>
<th>Control</th>
<th>Load</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (beats.min(^{-1}))</td>
<td>84.42 ± 3.78</td>
<td>83.75 ± 2.70</td>
<td>83.58 ± 2.85</td>
</tr>
<tr>
<td>Tidal volume (L)</td>
<td>0.89 ± 0.06</td>
<td>0.75 ± 0.04</td>
<td>0.79 ± 0.05</td>
</tr>
<tr>
<td>Breathing frequency (breaths.min(^{-1}))</td>
<td>14.98 ± 0.72</td>
<td>18.56 ± 0.72</td>
<td>17.51 ± 0.63</td>
</tr>
<tr>
<td>Minute ventilation (L.min(^{-1}))</td>
<td>12.84 ± 0.60</td>
<td>13.87 ± 0.64</td>
<td>13.13 ± 0.38</td>
</tr>
<tr>
<td>Oxygen consumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>absolute (L.min(^{-1}))</td>
<td>0.41 ± 0.02</td>
<td>0.41 ± 0.02</td>
<td>0.38 ± 0.01</td>
</tr>
<tr>
<td>relative (mL.kg(^{-1}).min(^{-1}))</td>
<td>4.49 ± 0.21</td>
<td>4.30 ± 0.17</td>
<td>4.37 ± 0.15</td>
</tr>
</tbody>
</table>
2.4.2 Exercise tolerance
Exercise tolerance was reduced by 21% with load compared to control and restricted conditions \( (P<0.05) \). This is reflected in all graphs with time as the independent variable. However, there were no differences in exercise tolerance between control and restricted conditions (Table 2.4). This suggests that load carriage, and not restriction of the chest wall, is responsible for reducing exercise tolerance. In addition, performance decrement was calculated as the percentage change in exercise tolerance from the control condition. Accordingly, performance decrement was significantly correlated \( (N=12, r^2 = 0.76, P<0.05) \) with body mass, suggesting that an individual’s ability to carry a 22 kg load is largely associated with body mass (Figure 2.5).

2.4.3 Maximum voluntary ventilation
Maximum voluntary ventilation was reduced by 15% with the external load and 10% with the chest wall restriction \( (P<0.05) \). The maximum values were 164.30 ± 3.82, 139.70 ± 6.94, and 147.10 ± 7.32 L.min\(^{-1}\) for control, load, and restricted conditions, respectively (Figure 2.6). The peak values for minute ventilation during exercise for this subset of the sample population were 143.80 ± 6.04, 141.20 ± 5.72, and 139.60 ± 3.56 L.min\(^{-1}\) for control, load, and restricted conditions, respectively. Furthermore, peak ventilation during exercise was 12% lower than the maximum voluntary ventilation for the control condition \( (P<0.05) \). However, there were no significant differences between maximum voluntary ventilation and peak ventilation during exercise for the experimental conditions.

2.4.4 Oxygen consumption
Whilst subjects were walking at 5 km.hr\(^{-1}\), there were no differences in oxygen consumption between the conditions (Table 2.5). At the commencement of incremental exercise, both absolute and relative oxygen consumption increased linearly with exercise intensity and there were no significant differences between conditions at any exercise intensity (Figure 2.7A). However, when subjects were at peak exercise, relative oxygen consumption was reduced by 25% \( (P<0.05) \) with load compared to both control and restricted conditions (Table 2.5). In addition, relative oxygen consumption was consistently lower with load \( (P<0.05) \) from 30% peak oxygen consumption until voluntary exhaustion (Figure 2.7B). Although an expected outcome, this confirms that despite either loading the body with a 22 kg mass, or providing an equivalent restriction of the chest wall (strapping), an equivalent amount of oxygen will be
Table 2.4: Exercise tolerance (min) during incremental treadmill exercise to voluntary exhaustion for three conditions (control, load, and restricted). This duration includes the initial 5 minutes of walking at 5 km.hr\(^{-1}\). Subjects are listed in ascending order according to body mass. * = Significantly different compared to control and restricted conditions ($P<0.05$). The decrement in performance was calculated as the percentage change in exercise time from the control condition.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Mass (kg)</th>
<th>Control</th>
<th>Load</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (min)</td>
<td>Time (min)</td>
<td>$\Delta$ vs. Control (%)</td>
<td>Time (min)</td>
</tr>
<tr>
<td>7</td>
<td>63.12</td>
<td>18.50</td>
<td>12.75</td>
<td>-31.08</td>
</tr>
<tr>
<td>1</td>
<td>64.78</td>
<td>13.50</td>
<td>10.50</td>
<td>-22.22</td>
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<tr>
<td>4</td>
<td>65.92</td>
<td>21.50</td>
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<td>13</td>
<td>69.06</td>
<td>17.50</td>
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<td>-24.29</td>
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<td>8</td>
<td>71.06</td>
<td>19.00</td>
<td>14.50</td>
<td>-23.68</td>
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<td>12</td>
<td>74.30</td>
<td>18.25</td>
<td>13.50</td>
<td>-26.03</td>
</tr>
<tr>
<td>2</td>
<td>76.02</td>
<td>14.75</td>
<td>12.00</td>
<td>-18.64</td>
</tr>
<tr>
<td>3</td>
<td>78.14</td>
<td>13.00</td>
<td>10.50</td>
<td>-19.23</td>
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<td>5</td>
<td>78.26</td>
<td>16.00</td>
<td>13.50</td>
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<td>80.24</td>
<td>21.00</td>
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<td>6</td>
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<td>21.00</td>
<td>17.00</td>
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<td>11</td>
<td>84.58</td>
<td>12.50</td>
<td>11.00</td>
<td>-12.00</td>
</tr>
<tr>
<td>Mean</td>
<td>73.85</td>
<td>17.21</td>
<td>13.44*</td>
<td>-21.46</td>
</tr>
<tr>
<td>S.D.</td>
<td>6.98</td>
<td>3.22</td>
<td>2.35</td>
<td>5.89</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>2.02</td>
<td>0.93</td>
<td>0.68</td>
<td>1.70</td>
</tr>
</tbody>
</table>
Figure 2.5: Relationship between body mass and the percentage change in exercise time (performance decrement) from unloaded exercise during loaded (22 kg) incremental exercise to voluntary exhaustion. Line represents the linear fit ($N=12$, $r^2 = 0.76$, $P<0.05$).
Figure 2.6: Maximum voluntary ventilation (filled bars) and peak minute ventilation (open bars) during incremental treadmill exercise to voluntary exhaustion for control, load, and restricted conditions \( (N=5) \). Values are means with standard errors of the means. * = \( P<0.05 \)
Table 2.5: Oxygen consumption whilst walking for 5 minutes, and at peak exercise for control, load, and restricted conditions (N=12). * = significantly different compared to control and restricted conditions (P<0.05). Values are means with standard errors of the means.

<table>
<thead>
<tr>
<th>Oxygen consumption</th>
<th>Control</th>
<th>Load</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking (5 km.hr⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>absolute (L.min⁻¹)</td>
<td>1.02 ± 0.04</td>
<td>1.20 ± 0.04</td>
<td>1.00 ± 0.03</td>
</tr>
<tr>
<td>relative (mL.kg⁻¹.min⁻¹)</td>
<td>13.83 ± 0.57</td>
<td>12.85 ± 0.46</td>
<td>13.62 ± 0.45</td>
</tr>
<tr>
<td>Peak exercise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>absolute (L.min⁻¹)</td>
<td>4.55 ± 0.22</td>
<td>4.36 ± 0.17</td>
<td>4.43 ± 0.16</td>
</tr>
<tr>
<td>relative (mL.kg⁻¹.min⁻¹)</td>
<td>61.61 ± 2.28</td>
<td>45.42 ± 1.41*</td>
<td>59.99 ± 1.61</td>
</tr>
</tbody>
</table>
Figure 2.7: Relationship between exercise intensity and absolute (A), or relative (B) oxygen consumption during incremental treadmill exercise to voluntary exhaustion for control —, load —, and restricted — conditions (N=12). * = load condition significantly different to control and restricted conditions (P<0.05). Values are means with standard errors of the means.
consumed during incremental exercise. However, when the external load and the mass of the subject are accounted for, significantly less oxygen is consumed during work.

As anticipated, there was a marked difference when expressing oxygen consumption in relation to time. For example, during the first 5 minutes of incremental exercise, absolute oxygen consumption was significantly higher ($P<0.05$) with load compared to the control and restricted conditions (Figure 2.8A). Immediately following this 5 minute period, relative oxygen consumption was significantly lower ($P<0.05$) with load compared to control and restricted conditions (Figure 2.8B). Therefore, although the same amount of oxygen was consumed despite subjects carrying an external load, or having their chest wall restricted, peak oxygen consumption is obtained much sooner during load carriage. Furthermore, this was caused by a 22 kg external load, and not by restricting the chest wall.

Accordingly, peak oxygen consumption was significantly correlated with body mass during all conditions ($P<0.05$). However, these correlations did not appear to be different between conditions (Figure 2.9). In addition, performance decrement was poorly correlated with peak oxygen consumption ($P>0.05$), and, since some subjects were highly trained (peak oxygen uptake > 5 L.min$^{-1}$), this suggests that well-trained individuals may not possess greater load carrying ability than those who are less trained (Figure 2.10).

2.4.5 Minute ventilation
There were no differences in minute ventilation during walking (23.31 ± 0.60, 29.49 ± 0.65, and 24.74 ± 0.50 L.min$^{-1}$), nor was there a difference in peak ventilation (154.20 ± 6.91, 150.20 ± 6.48, and 149.30 ± 6.47 L.min$^{-1}$) for control, load, and restricted conditions, respectively. Furthermore, minute ventilation increased linearly until approximately 60% of peak oxygen consumption during incremental exercise (Figure 2.11A). From this point, ventilation increased exponentially with exercise intensity. There were no differences in minute ventilation between conditions at any exercise intensity up to voluntary exhaustion (Figure 2.11A). However, minute ventilation was different when expressed relative to time (Figure 2.11B). Accordingly, minute ventilation was significantly higher during exercise with load compared to both the control and restricted conditions ($P<0.05$). This is consistent with the elevated oxygen uptake at any given time point whilst subjects are exercising with load, confirming an increased physical demand during load carriage, and further explaining the reduced exercise tolerance which accompanies load carriage.
Figure 2.8: Absolute (A) and relative (B) oxygen consumption with respect to time during rest (0-5 min), walking at 5 km.hr⁻¹ (5-10 min), and incremental treadmill exercise to voluntary exhaustion (10 min onwards) for control ▬, load ▬, and restricted ▬ conditions (N=12). * = load significantly different to control and restricted conditions after 5 minutes of incremental exercise (P<0.05). Values are means at 15 sec intervals with standard errors of the means.
**Figure 2.9:** Peak oxygen consumption as a function of body mass during incremental treadmill exercise to voluntary exhaustion for control (A), load (B), and restricted (C) conditions. Symbols represent data for individual subjects \((N=12)\). Lines represent the linear fit for control (A) \((r^2 = 0.35)\), load (B) \((r^2 = 0.42)\), and restricted (C) \((r^2 = 0.44)\) conditions. Correlations were significant for all conditions \((P<0.05)\).
Figure 2.10: Relationship between the percentage change in exercise time from the control condition to the load condition (performance decrement), and the peak oxygen consumption obtained during the control condition. Each symbol represents values from individual subjects, and the line represents the linear fit (N=12, $r^2 = 0.06$, $P > 0.05$).
Figure 2.11: Minute ventilation with respect to exercise intensity (A) and time (B), during treadmill exercise to exhaustion for control —, load —, and restricted — conditions. Values are means with standard errors of the means (N=12). In B, values are at 15 second intervals during rest (0-5 min), walking at 5 km.hr⁻¹ (5-10 min), and during incremental exercise to exhaustion (10 min onwards). * = significantly different to control and restricted conditions (P<0.05).
2.4.5.1 Tidal volume
There were no differences in tidal volume whilst subjects were walking at 5 km.hr\(^{-1}\) (1.24 ± 0.02, 1.24 ± 0.02, and 1.11 ± 0.02 L) for the control, load, and restricted conditions, respectively. During incremental exercise to exhaustion, tidal volume increased linearly with exercise intensity until approximately 75\% of peak oxygen consumption. Furthermore, consistently lower values were observed during exercise with load and restriction compared to control (Figure 2.12A). However, peak tidal volume was reduced by 8\% with load, and 9\% with restriction (Figure 2.13A), compared to the control condition (\(P<0.05\)). These findings suggest that loading or restricting the chest wall limits the peak tidal volume that can be achieved during incremental exercise to exhaustion.

2.4.5.2 Breathing frequency
When subjects were walking at 5 km.hr\(^{-1}\), breathing frequency was not different between control, load, and restricted conditions, respectively (19.85 ± 1.09, 24.87 ± 1.39, and 23.15 ± 0.85 breaths.min\(^{-1}\)). During incremental exercise to exhaustion, breathing frequency increased linearly with exercise intensity until approximately 60\% of peak oxygen consumption (Figure 2.14A), with no difference at exhaustion (55.08 ± 1.70, 59.58 ± 1.65, and 58.17 ± 1.97 breaths.min\(^{-1}\)) for control, load, and restricted conditions, respectively. However, the peak breathing frequency was increased by 7\% (\(P<0.05\)) with load (64.40 ± 2.60 breaths.min\(^{-1}\)) compared to the control condition (60.22 ± 1.85 breaths.min\(^{-1}\)) (Figure 2.13B). This increase in breathing frequency accounts for the unchanged peak ventilation, since peak tidal volume was significantly reduced by a similar amount (8\%) with load.

Furthermore, there was a significant interaction between experimental condition and time (\(P<0.05\)). Specifically, breathing frequency was significantly higher with load following 4 minutes of incremental exercise compared to control (Figure 2.14B). Since tidal volume was not affected by the experimental conditions during the first 5 minutes of incremental exercise, the increase in minute ventilation which was observed can be attributed to an elevated breathing frequency.

2.4.6 Heart rate
During 5 minutes of walking at 5 km.hr\(^{-1}\), the average heart rate was not different between conditions (99.84 ± 0.55, 108.00 ± 0.89, and 96.79 ± 0.49 beats.min\(^{-1}\) for control, load, and restricted conditions, respectively). Accordingly, at the commencement of incremental
Figure 2.12: Tidal volume with reference to exercise intensity (A), and time (B), during treadmill exercise to exhaustion for control — , load — , and restricted — conditions. Values are means with standard errors of the means (N=12). In B, values are at 15 second intervals (N=12) during rest (0-5 min), walking at 5 km.hr\(^{-1}\) (5-10 min), and during incremental exercise to exhaustion (10 min onwards).
Figure 2.13: Peak tidal volume (A) and peak breathing frequency (B) during treadmill exercise to exhaustion for control ■, load ■, and restricted ■ conditions. Values are means with standard errors of the means. * = P<0.05
Figure 2.14: Breathing frequency with reference to exercise intensity (A) and time (B), during treadmill exercise to exhaustion for control ▼, load ▲, and restricted ▼ conditions. Values are means with standard errors of the means (N=12). In B, values are at 15 second intervals during rest (0-5 min), walking at 5 km.hr⁻¹ (5-10 min), and during incremental exercise to exhaustion (10 min onwards). * = significantly different to the control condition (P<0.05).
exercise, heart rate increased in a linear fashion with respect to exercise intensity, with peak values of 195.30 ± 2.45, 188.80 ± 2.82, and 193.50 beats.min⁻¹ for control, load, and restricted conditions, respectively (Figure 2.15). The peak heart rate which was obtained during the load condition was significantly lower compared to both control and restricted conditions (P<0.05). Thus, exercise with load may not be limited by cardiovascular performance, but by some other mechanism such as local muscle fatigue or discomfort.

2.4.7 Perceived exertion
Perception of whole body exertion was significantly greater (P<0.05) for the load condition compared to the control and restricted conditions. For instance, treadmill speed was 16.67 ± 0.48, 14.83 ± 0.61, and 16.58 ± 0.51 km.hr⁻¹ when whole body perceived exertion was 16/20 for the control, load, and restricted conditions, respectively. Therefore, higher values of exertion were observed much sooner during the load condition as treadmill speed increased proportionally with time. This threshold value of exertion was selected as it represents the point at which treadmill speed remained constant and further increments in workload were achieved by increasing treadmill grade. Following 5 minutes of incremental exercise, subjects reported significantly higher (P<0.05) exertion for the chest whilst carrying the load (15.42 ± 0.65) compared to the control condition (12.58 ± 0.77). Furthermore, perceived exertion for the legs during the load condition (15.75 ± 0.65) was significantly higher (P<0.05) than that reported during the restricted condition (12.67 ± 0.68) (Figure 2.16). Therefore, since heightened perceptions of physical strain were reported for the chest and legs whilst carrying a load, it is possible that whole body exhaustion did not occur with load, and performance was limited by local muscle fatigue or discomfort. However, subjects did not rate their physical exertion for whole body, chest, or legs to be any different between conditions when they were exhausted (Table 2.6).

2.4.8 Respiratory time
2.4.8.1 Inspiratory time
At rest, inspiratory time was significantly lower (P<0.05) with load (3.30 ± 0.14 s) compared to the control condition (4.18 ± 0.23 s). Accordingly, the inspiratory time decreased linearly with exercise intensity (Figure 2.17A), and at a very light workload (5% peak oxygen uptake), lower values (P<0.05) were observed for load (2.79 ± 0.18 s) and restricted (2.81 ± 0.14 s) conditions compared to control (3.71 ± 0.37 s) (Figure 2.18A).
Figure 2.15: Absolute heart rate with respect to exercise intensity (A), or time (B), during treadmill exercise to exhaustion for control —, load —, and restricted — conditions. Values are means with standard errors of the means (N=12). In B, values are at 15 second intervals during rest (0-5 min), walking at 5 km.hr⁻¹ (5-10 min), and during incremental exercise to exhaustion (10 min onwards).
Figure 2.16: Rating of perceived exertion (6-20 scale) for whole body, chest, and legs after 5 minutes of incremental exercise for control ■, load ▲, and restricted ■ conditions. Values are means with standard errors of the means. * = $P<0.05$
Table 2.6: Perceived exertion at exhaustion for control, load, and restricted conditions. Values are means with standard errors of the means.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>Load</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived exertion (6-20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole body</td>
<td>18.42 ± 0.29</td>
<td>18.25 ± 0.37</td>
<td>18.42 ± 0.31</td>
</tr>
<tr>
<td>Chest</td>
<td>18.25 ± 0.33</td>
<td>18.25 ± 0.37</td>
<td>18.67 ± 0.28</td>
</tr>
<tr>
<td>Legs</td>
<td>18.33 ± 0.28</td>
<td>18.50 ± 0.31</td>
<td>18.67 ± 0.23</td>
</tr>
</tbody>
</table>
Figure 2.17: Inspiratory (A) and expiratory (B) time with respect to exercise intensity during treadmill exercise to exhaustion for control □, load ▲, and restricted ▼ conditions. Values are means with standard errors of the means (N=12). Significant differences were observed at rest and during light exercise (P<0.05). These are shown in Figure 2.18.
Figure 2.18: Inspiratory (A) and expiratory (B) time at rest and during light treadmill exercise (5% peak oxygen uptake) for control ■, load ■, and restricted ■ conditions. Values are means with standard errors of the means (N=12). * = P<0.05
2.4.8.2 Expiratory time
Expiratory time also decreased linearly from rest to peak exercise (Figure 2.17B). A similar pattern was observed in that there were significant differences at rest and during exercise (Figure 2.18B). Expiratory time was significantly lower ($P<0.05$) at rest during load (1.65 ± 0.07 s) compared to the control condition (2.04 ± 0.10 s). Furthermore, during light exercise (5% peak oxygen consumption), expiratory time was significantly lower ($P<0.05$) for the load (1.43 ± 0.09 s) and restricted (1.46 ± 0.08 s) conditions compared to control (1.90 ± 0.18 s).

2.4.8.3 Total breathing time
Whilst subjects were resting, total breathing time was significantly lower ($P<0.05$) during load (4.95 ± 0.20 s) compared to the control condition (6.22 ± 0.32 s). Once exercise began, total breathing time decreased linearly with exercise intensity. Furthermore, total breathing time was significantly lower ($P<0.05$) at 5% peak oxygen consumption for both load (4.22 ± 0.26 s) and restricted (4.27 ± 0.21 s) conditions compared to the control condition (5.61 ± 0.55 s). This is not a surprising result, since total breathing time is comprised of both inspiratory and expiratory times. Although the experimental conditions did not influence the rate or depth of breathing at rest or during light exercise, it seems that loading or restricting the upper body affects respiratory timing.

2.4.8.4 Respiratory duty cycle
At rest, the respiratory duty cycle was not different between conditions (0.67 ± 0.01 s for all conditions). At the start of exercise, the duty cycle decreased progressively for all treatment conditions until peak exercise (0.62 ± 0.006 s for control and load conditions, and 0.62 ± 0.007 s for the restricted condition) ($P<0.05$). This is a normal response, and indicates that with increasing exercise intensity, less time is spent during inspiration (Figure 2.19A). However, there were no significant differences between conditions at any workload.

2.4.8.5 Mean inspiratory flow
As expected, mean inspiratory flow increased significantly from rest (0.21 ± 0.01, 0.23 ± 0.01, and 0.22 ± 0.01 L.s$^{-1}$) to peak exercise (2.45 ± 0.11, 2.41 ± 0.09, and 2.40 ± 0.10 L.s$^{-1}$) for control, load, and restricted conditions, respectively. However, there were no differences between the conditions (Figure 2.19B). This is also the anticipated response with increasing
Figure 2.19: Respiratory duty cycle (A) and mean inspiratory flow (B) with respect to exercise intensity during treadmill exercise to exhaustion for control —, load —, and restricted —— conditions. Values are means with standard errors of the means (N=12).
exercise intensity, as a given volume of air is taken into the lungs over a shorter period of time.

2.4.9 Diaphragmatic contractile performance

2.4.9.1 Diaphragmatic excursion

Diaphragmatic excursion appeared to decrease for each condition following exercise compared to baseline. However, this was not significant (Figure 2.20A). Furthermore, diaphragmatic excursion was higher for the experimental conditions compared to control at all time points following exercise. The only exception to this was that the restricted condition was slightly lower (2.235 vs. 2.236 cm) than the control condition 5 minutes following exhaustion. Although these findings were not significant, it is worth considering that external load or restriction of the chest wall may influence the movement of the diaphragm. For instance, in order to displace the same volume of air, the diaphragm may contract further to overcome the restrictive effects of the load and chest strapping, which may limit the movement of the thoracic cage during breathing.

2.4.9.2 Diaphragmatic velocity

There were no observed differences in the speed of diaphragm contraction following exercise, nor was there an affect of the experimental conditions on diaphragmatic velocity (Figure 2.20B). However, it is also worth noting that diaphragmatic velocity was consistently higher following exhaustion for the experimental conditions compared to control. Therefore, it is possible that loading and restricting the thorax may affect inspiratory muscles. Although the changes in diaphragmatic velocity are not significant, the reduced peak values for tidal volume and breathing frequency during the load condition suggest that the experimental conditions influenced breathing mechanics.

2.5 DISCUSSION

The primary aims of this study were to quantify the physiological demands of performing whole-body exercise to voluntary exhaustion, with the addition of a 22 kg external load. Furthermore, this study focussed on the performance of the diaphragm following exhaustive exercise, and if this was influenced by either loading or restricting the chest wall. There were several main findings from this investigation. Firstly, exercise performance was severely reduced by load carriage. Although a predictable outcome, it is worth mentioning as this will form the basis of the discussion which follows. Secondly, loading or restricting the chest wall
Figure 2.20: Diaphragmatic excursion (A) and velocity (B) prior to (Baseline = □) and at 5, 10, and 15 minutes following treadmill exercise to exhaustion for control ■, load ■, and restricted ■ conditions. Values are means with standard errors of the means (N=12).
affected ventilatory function at rest, and during exercise to voluntary exhaustion. Finally, exhaustive exercise with a load or chest wall restriction did not affect the performance of the diaphragm.

2.5.1 Exercise performance during load carriage

Our second hypothesis stated that load carriage, and not chest wall restriction, would significantly reduce exercise tolerance. Since there was a 21% reduction in exercise tolerance for the load condition, our findings were in agreement with this hypothesis. Previous studies have also demonstrated this (Louhevaara et al., 1995; Raven et al., 1977). However, a similar load to that applied in the present study reduced exercise tolerance by 56% (Taylor et al., 2012). During this study, the load was not only distributed to the torso, but also included the head and limbs. An explanation for this reduction in exercise tolerance centres on the relative amount of available oxygen to perform external work. This is important, since oxygen is also consumed to perform internal work.

For example, muscle activity increases as a result of load carriage, and the specific muscles involved are those responsible for posture (Hong et al., 2008), and the lower limbs (Simpson et al., 2011). Due to the acceleration of gravity, it is not surprising that lower limb muscle activity is increased. These muscles act to oppose the weight of the body and any external mass which is placed on it. In addition, placing a load on the upper body causes a change in trunk posture which is dependent on the mass and position of the load (Chow et al., 2010; Cook, 1987; Gregorzcyk et al., 2010; Thomas et al., 1959). Therefore, trunk muscle activity must increase if the person wishes to remain erect. Thus, internal work is performed during load carriage tasks in order to bear the external load and maintain posture.

Furthermore, the increase in postural muscle activity which occurs with load carriage indirectly suggests that there is a proportional increase in the oxygen consumption of these muscles. This is a fair assumption, and there is evidence of a linear relationship between muscle activity and muscle oxygen consumption (Praagman et al., 2003). This supports the notion that, during load carriage, oxygen consumption is divided into that which is required to perform external work (exercise), and that for internal work (load bearing) (Taylor et al., 2012). However, we must prove that each of the subjects in the present study exercised until whole-body exhaustion for this to be justified. If, however, exercise was terminated due to
local muscle fatigue or discomfort, we cannot confirm that load carriage performance is limited by the available oxygen.

Our first hypothesis stated that there would be no differences in peak measures of physiological function. Based on findings from this study, we accept our first hypothesis. In addition, since there were no differences in ratings of perceived exertion at exhaustion between conditions, it is reasonable to suggest that, on average, subjects in this study terminated exercise due to whole-body exhaustion. Furthermore, subjects who participated in this study were highly motivated, well-trained individuals with an average peak oxygen consumption exceeding 60 mL.kg\(^{-1}\).min\(^{-1}\). However, peak heart rate was significantly lower during the load condition. This is surprising and is not consistent with other findings (Louhevaara et al., 1995; Raven et al., 1977; Taylor et al., 2012). Thus, we can only speculate that the reduced peak heart rate may be related to the difference in exercise times. If, however, there were no differences in exercise times between the load and control conditions, it is possible that peak heart rate would not be different between these conditions.

Another interesting observation was that heavier subjects performed better during the load condition compared to their lighter counterparts, which is consistent with previous findings (Frykman & Harman, 1995). This is evident in Figure 2.5, where body mass was significantly correlated with the decrement in performance during the load condition. An explanation for this is that smaller subjects will consume more oxygen to travel at a given speed compared to a heavier subject (Fedak et al., 1974, Taylor et al., 1970). For instance, consider Subject 11, with body mass 84.58 kg, and Subject 13, with body mass 69.06 kg. After travelling a distance of 1 km at approximately 6 km.hr\(^{-1}\), Subject 11 had consumed 155 mL.kg\(^{-1}\) of oxygen, whereas Subject 13 had consumed 169 mL.kg\(^{-1}\). Therefore, since oxygen consumption increases more rapidly with changes in speed for the lighter subject, peak oxygen consumption will be reached sooner. Of course, this will also be dependent on training status. The underlying mechanism for a reduced energetic cost of running for heavier subjects may be related to differences in efficiency, and also the relative contribution of internal work to total work at higher running speeds (Fedak, et al., 1982; Steudel, 1990).

However, this only partly explains why lighter individuals may be disadvantaged, as we have only considered locomotion alone, and not combined with external load. It has been shown that whilst running at a constant speed, humans will consume more energy when carrying a
load, and this is related to the production of force by the muscles, and is a function of the magnitude of the load (Keren et al., 1981; Samanta & Chatterjee, 1981; Soule et al., 1978; Taylor, et al., 1980a). Thus, when the external load is considered, the same relative difference in total mass will exist between the lighter and heavier subjects. Therefore, load carriage requires increased muscle force production to bear the load and maintain posture. Consequently, those with less muscle mass will be disadvantaged as they must carry a larger proportion of their body mass. Thus, lighter subjects must produce a higher relative force to overcome a given load.

In the present study, oxygen consumption was expressed in absolute terms (L.min\(^{-1}\)) and relative to total mass (body mass plus 22 kg weighted vest) (mL.kg\(^{-1}\).min\(^{-1}\)). The latter expression of oxygen consumption to total mass assumes that a linear relationship exists between these two variables. However, it is well established that the relationship between oxygen consumption and body mass is nonlinear. In fact, it has been suggested that oxygen consumption increases as a power function of body mass (Kleiber, 1932; Nevill et al., 1992, Schmidt-Nielsen, 1984). Although well beyond the scope of the current study, this highlights the importance of allometric scaling. For instance, given the nonlinear relationship between oxygen consumption and body mass, linear transformations of these variables (mL.kg\(^{-1}\).min\(^{-1}\)) will bias against heavier individuals, and abnormally high values will be observed for lighter subjects. Therefore, oxygen consumption must be expressed as a power function of body mass. Across a wide range of species, it has been suggested that oxygen consumption should be expressed relative to the 0.75 power of body mass (mL.kg\(^{-0.75}\).min\(^{-1}\)) (Kleiber, 1961; Taylor et al., 1980b). However, within a species this relationship is closer to the 0.67 power of body mass (mL.kg\(^{-0.67}\).min\(^{-1}\)) (Heusner, 1982; Schmidt-Nielsen, 1984).

To illustrate this, oxygen consumption was plotted as a power function of total mass (body mass plus 22 kg weighted vest) (mL.kg\(^{-0.67}\).min\(^{-1}\)) in Figure 2.21. Thus, the influence of body mass and external load at rest, and during incremental exercise to exhaustion has been removed. Unlike Figure 2.8B, oxygen consumption was not lower during the load condition. This transformation allows the comparison of oxygen consumption regardless of body mass, and acknowledges the nonlinear relationship between these variables. Such transformations may be useful to many workplace scenarios where body mass varies greatly within a group of subjects.
Figure 2.21: Relative oxygen consumption to the 0.67 power of body mass with respect to time during rest (0-5 min), walking at 5 km.hr⁻¹ (5-10 min), and incremental treadmill exercise to voluntary exhaustion (10 min onwards) for control ▬, load ▬, and restricted ▬ conditions (N=12).
The classical view regarding limitations to exercise performance centres on oxygen delivery (Hill & Lupton, 1923). For instance, the ability of the cardiovascular system to circulate blood is reduced when there is a greater amount of active muscle mass (Saltin, 1985; Secher et al., 1977). However, depending on a variety of factors such as training status, exercise mode, and motivation, this may vary between individuals. It was not in our interest in conducting this experiment to comment on the influence of exercise mode, or motivation, on performance. However, since we have measured peak oxygen uptake in our subjects, we may compare this with individual performance. Peak oxygen uptake was poorly correlated with the performance decrement during load carriage, as highlighted in Figure 2.10. In addition, peak oxygen uptake was significantly correlated with exercise time during the load condition (Figure 2.22), which suggests that this measure is useful in predicting load carriage performance. This has also been suggested by others, and provides us with a second attribute to assist in predicting load carriage ability (Frykman & Harman, 1995).

The question still remains, is body mass or peak oxygen uptake more important in determining load carriage performance? Consider two individuals, each with identical values for peak oxygen uptake. Based on our findings, and that individuals with similar peak oxygen uptakes may produce different performances (Conley & Krahenbuhl, 1980), the subject with the highest body mass will perform better during load carriage tasks. However, if body mass was identical, peak oxygen uptake will only determine the duration that a load carriage task can be performed, and not the change in performance from an unloaded task. Thus, body mass should be the primary determinant of load carrying ability, which is in agreement with previous findings (Frykman & Harman, 1995). Furthermore, it is actually the lean body mass which is most important in predicting the performance of load carriage tasks as a high percentage of fat tissue is detrimental to performance (Bilzon et al., 2001; Haisman, 1988; Lyons et al., 2005).

2.5.2 Respiratory function during load carriage

During quiet breathing, the diaphragm contracts to increase the volume of the thoracic cavity, therefore causing a pressure differential between the atmosphere and the lungs. As a result, air will flow into the lungs in order to equalise this differential, which is referred to as inspiration. However, the diaphragm is not solely responsible for inspiration during exercise. Accessory muscles are recruited in order to increase the volume of the thorax. These muscles
Figure 2.22: Relationship between peak oxygen consumption and exercise tolerance during incremental exercise to voluntary exhaustion for load condition. Line represents the linear fit ($N=12$, $r^2 = 0.57$, $P<0.05$).

$y = 2.909x + 5.819$
attach directly to the thorax, causing the anterior/posterior dimensions to increase during inspiration (Aliverti, et al., 1997; Grimby et al., 1968; Grimby et al., 1976). Therefore, one may assume that placing an external load, or restricting the thorax, will influence normal breathing mechanics. Confirming our third hypothesis, the present study demonstrated that loading or restricting the chest wall causes a significant reduction in maximum voluntary ventilation (Figure 2.6).

This is most likely due to physically limiting the movement of the chest wall during breathing, which significantly reduces forced vital capacity when devices such as body armour are worn (Camala et al., 1999; Legg, 1988). During exercise, minute ventilation will approach maximum voluntary ventilation. However, peak ventilation will be lower, and the ratio between these values is commonly referred to as the dyspnoeic index, which is approximately 70-90% for healthy individuals (Cotes et al., 2006; Neder et al., 2003). Thus, peak exercise is not a situation which demands maximal ventilation from the respiratory system. Furthermore, arterial oxygen content is seldom reduced during maximal exercise, further suggesting that ventilation does not limit exercise. Only in highly trained endurance athletes, and in certain pathological conditions, are there signs of arterial hypoxemia during exercise (Dempsey et al., 1984; O’Donohue, 1991; Rowell et al., 1964). During this study, the dyspnoeic index was 88% for the control condition, which lies within normative values for healthy individuals. Interestingly, maximum voluntary ventilation was reduced during the experimental conditions, such that values were similar to peak ventilation during exercise (Figure 2.6). Therefore, a ventilatory reserve did not exist when an external load or chest wall restriction was in place, suggesting that ventilation may now be a limiting factor. In fact, the dyspnoeic indices were 101% and 95% for the load and restricted conditions, respectively, which are equivalent to values for patients with restrictive pulmonary disease (Cotes et al., 2006).

Despite there being no differences in peak ventilation, the peak values for tidal volume and breathing frequency for the loaded and restricted conditions were significantly different to the control condition. Thus, in order to achieve the same peak ventilation, respiratory rate increased due to the reduction in tidal volume (Figure 2.13). Similar findings have been reported, suggesting that load carriage, and chest wall restriction, present a limitation to chest wall movement (Li & Hong, 2003; Louhevaara et al., 1985). This is consistent with restrictive pulmonary disease, where a shallow and faster breathing pattern is present, with
significantly lower tidal volumes, and higher breathing frequencies at peak exercise due to reduced lung compliance (Nield et al., 2003; Wilkens et al., 2010). Although expired minute ventilation was not influenced by the experimental conditions, alveolar ventilation may have been reduced due to the change in breathing pattern, which is evident in restrictive pulmonary disease (Wagner et al., 1976). However, we can only speculate as we did not perform this measurement.

In addition, respiratory timing was also affected by the load and restricted conditions. For instance, inspiratory and expiratory time was significantly lower at rest, and during light exercise (Figure 2.18). This is also found in restrictive pulmonary disease, with lower values also observed during peak exercise (Nield et al., 2003; Wilkens et al., 2010). These changes in respiratory rate and timing are most likely caused by a reflex response initiated by golgi tendon organs within the thoracic musculature. For example, the activity of these receptors is enhanced with muscle tension (Hilaire et al., 1983; Houk & Henneman, 1967). Furthermore, the afferent extensions of these fibres project to the brain stem (Cotes et al., 2006). This suggests that increased respiratory muscle tension due to external load or chest wall restriction, may not only cause a reflex response which originates in the spinal cord, but may also influence the central control of breathing.

Our fourth hypothesis stated that diaphragmatic contractile performance would be reduced following exhaustive exercise. Based on our results, we reject this hypothesis. This was surprising, considering that others have reported that respiratory muscle fatigue is present in moderately trained subjects, even without loading or restricting the chest wall (Johnson et al., 1993; Ozkaplan et al., 2005). In contrast, there is evidence that respiratory muscle fatigue does not occur in highly trained individuals such as some of those in the present study (Coast et al., 1990). However, several different methods have been reported in the literature as measures of respiratory muscle performance, which include maximal respiratory pressure, trans-diaphragmatic pressure response to maximal phrenic nerve stimulation, and time to task failure during resistive breathing (Gonzalez & Scheuermann, 2006; Guenette et al., 2010; Perret et al., 1999). Our primary measure of respiratory muscle performance was limited to the diaphragm only, since we examined diaphragm movement using ultrasound. However, since other studies have measured maximal pressures generated during inspiration, this will reflect the performance of all muscles responsible for inspiration, which also includes the accessory muscles during maximal inhalation. Furthermore, the training status of our subjects
may explain why respiratory muscle fatigue was not observed. A methodological limitation to the current study was that we did not assess the reliability of the diaphragm measurements during baseline tests. However, this technique has been shown to be a reliable measure of diaphragm movement (Houston et al., 1992; Kocis et al., 1997).

2.6 CONCLUSION

The decline in performance which occurs during exhaustive treadmill exercise whilst carrying a 22 kg load is largely related to the body mass of the individual. Specifically, heavier subjects will perform better than lighter subjects. Peak oxygen consumption is potentially important in determining the duration that high intensity exercise with load can be sustained. Thus, body mass and oxygen uptake are useful indices in predicting the load carrying ability of young, active males. In addition, minor adjustments in tidal volume, breathing frequency, and respiratory timing occur during rest and peak exercise, and this seems to be related to chest wall restriction, and not external load. These findings indicate that artificially restricting the chest wall produces similar changes in pulmonary function to that which occurs in restrictive pulmonary disease. These adjustments may cause a pulmonary limitation to exercise, which is not normally present in healthy subjects. Furthermore, our findings indicate that diaphragm performance is not affected by exhaustive exercise. However, this should be considered with caution, since several studies have identified respiratory muscle fatigue using different techniques.
2.7 REFERENCES


CHAPTER THREE:  
MAXIMUM ACCEPTABLE WORK DURATION OF LOADED EXERCISE

3.1 INTRODUCTION
Predicting the duration that certain tasks can be performed would be useful in many occupational settings. Within the literature, this has been referred to as the maximum acceptable work duration (Saha et al., 1979; Wu & Wang, 2001; Wu & Wang, 2002). In one particular study, thirty subjects (15 male, 15 female) performed incremental cycle exercise to voluntary exhaustion, and constant load exercise at 60 and 70% of peak work rate (Wu & Wang, 2001). Maximum acceptable work duration was based on measures of heart rate. For instance, this was calculated as the time until the average heart rate was greater than 150 beats.min\(^{-1}\). In addition, acceptable work duration was calculated as the exercise time until absolute heart rate was greater than 180 beats.min\(^{-1}\). Indeed, it is a fair assumption that these methods may produce significantly different measures of work time. However, it is unknown why two measures of acceptable work time were presented in this study. There were three primary outcomes of this study. Firstly, acceptable work durations for high intensity work were identified. Specifically, it was suggested that work at 60 and 70% of the peak work rate should not exceed 19.1 and 6.7 minutes, respectively. Secondly, significant correlations (\(P<0.05\)) were observed for heart rate (\(R^2 = 0.66\)) and oxygen consumption (\(R^2 = 0.76\)) with acceptable work time as the dependent variable. Finally, variations in maximum acceptable work duration were better explained when heart rate and oxygen consumption were combined as predictor variables (\(R^2 = 0.81\)).

In a further study, 12 subjects (6 male, 6 female) performed an incremental cycle test to voluntary exhaustion, and constant load cycle exercise at 20, 30, 40, 50, 60, and 70% of peak work rate, also to voluntary exhaustion (Wu & Wang, 2002). Since, in their previous study, exercise was performed at 60 and 70% of peak work rate (Wu & Wang, 2001), it is reassuring that these recommendations of work time have been extended to include lighter work intensities. However, an alternative method for calculating the maximum acceptable work duration was used. This involved measuring the time taken for absolute heart rate to be 10 beats.min\(^{-1}\) above that observed during the initial hours of exercise. As a result, acceptable work times were not available for the two highest workloads, since heart rate progressively increased from the start of exercise, without reaching a steady state. For workloads of 20 and 50% of peak work rate, acceptable work times were 492 and 72 minutes, respectively. In
addition, heart rate and oxygen consumption were significantly correlated with maximum acceptable work duration \( (P<0.05) \).

A similar method was utilised by Saha et al. (1979) to calculate the maximum acceptable work duration. This is the only study that we are aware of that has determined the acceptable work durations of whole body exercise. Five physically active subjects performed incremental treadmill exercise to determine peak oxygen uptake. In addition, subjects attempted to complete 8 hours of submaximal exercise at 20, 28, 36, 50, 62, and 70% of peak oxygen uptake. Two rest breaks of fifteen minutes, and a 1 hour lunch break were scheduled over the course of the day. To identify an acceptable workload which could be performed for an 8-hour work day, heart rate data were analysed post-exercise. The workload which could be maintained without an apparent increase in heart rate over the course of an 8-hour day was termed the acceptable workload. Accordingly, heart rate remained relatively stable during all exercise intensities up to 36% peak aerobic power. At workloads above this, heart rate continued to rise over the course of the experiment. In addition, all subjects were able to complete the first two workloads (20 and 28% of peak oxygen uptake). However, not all subjects were able to complete the 8 hour task at workloads beyond 36% peak oxygen uptake. Based on this, the authors recommended 35% of peak aerobic power as an acceptable workload for an 8-hour work day.

There are several limitations to the current literature surrounding maximum acceptable work duration. Firstly, two of three studies utilised cycle ergometry as the form of physical work. Although this form of work is appropriate for scientific experiments, it has little relevance to most work situations. Considering that it may not be possible to perform certain tasks in a seated position, treadmill exercise may best represent physical work. Furthermore, even if it is possible to be seated whilst working, such as a delivery driver or forklift operator, those occupations which are physically demanding are not performed in a seated position. In addition, load carriage is a requirement of many occupations such as the military, fire and rescue, and ambulance services. Finally, the published methods for calculating acceptable work time rely on measures of absolute heart rate. This is a poor approach considering that heart rate may vary considerably depending on factors such as age, gender, and training status of individuals (Andrews, 1969; Harms, 2006; Swain et al., 1998). Furthermore, the available literature has not investigated the effects of load carriage on acceptable work duration. Therefore, due to the heightened physiological response associated with load carriage
predictions of acceptable work duration arising from these studies are not suitable for use with tasks involving load carriage.

3.2 AIMS AND HYPOTHESES
The aim of this study was to quantify the physiological demands of submaximal exercise combined with load carriage. In addition, this study provided acceptable work durations based on previously established methods, and suggested the most appropriate method for calculating acceptable work time.

There were four hypotheses relating to this study. First, voluntary exhaustion will occur at workloads above 30% peak oxygen uptake. Second, acceptable work time will be different between each of the experimental conditions. Third, each method for calculating acceptable work duration will produce different results. Fourth, load carriage performance will be correlated with body mass.

3.3 METHODS
3.3.1 Subjects
The same thirteen subjects were recruited from a previous study (Table 2.1). Subjects were asked to refrain from strenuous exercise the day before attending the laboratory and to avoid smoking, caffeine, and alcohol in the 12 hours prior to an experiment. All subjects provided written informed consent to participate and experimental procedures were approved by the Human Research Ethics Committee, University of Wollongong (HE10/400).

3.3.2 Study design and overview
The study had a within-subjects design, with each subject attending the laboratory on five separate occasions. Subjects had participated in a previous study (Chapter 2), therefore were familiar with all procedures for the current study, and had completed a medical screening questionnaire and provided their written, informed consent to participate in the study.

3.3.3 Experimental conditions
Subjects were required to perform submaximal treadmill exercise. The experiment consisted of five different conditions which varied only by intensity: 30, 50, 60, 70, and 80% peak oxygen uptake. These conditions were presented in a balanced order. Military fatigues (long-sleeved shirt and pants) and running shoes were worn for all experiments (combined mass
1.66 kg). In addition, subjects donned a 22 kg weighted vest (MIR Pro Weighted Vest, Mir Vest Inc., CA, USA). This was to simulate the minimum load that Australian soldiers are required to carry. All experiments were performed in a laboratory environment (22°, 35% relative humidity).

The primary researcher was responsible for fitting the vest. To standardise the tension applied by this device, a pressure bio-feedback unit was used (Chattanooga Group Inc., TN, USA) (Figure 2.2). The unit was positioned at the level of the ziphoid process and inflated to 20 mmHg. The weighted vest was then placed on the subject, who was asked to “breathe normally, and indicate with your hand each time you are about to inhale”. The vest was fastened until a pressure of 80-90 mmHg was achieved following a normal exhalation. The pressure was checked on three consecutive breaths to ensure the correct tension was applied. The pressure bio-feedback unit was then deflated and removed.

3.3.4 Experimental protocol
Experiments began with 5 minutes of seated rest, followed by 5 minutes of standing rest, and 5 minutes of walking at 5 km.hr⁻¹ and a gradient of 1%. The treadmill speed was then increased to the desired workload, with the gradient remaining at 1%. Exercise continued until subjects were exhausted, or they had completed 5 km. A distance of 5 km was selected as it represents a basic military training task performed by Australian soldiers. Subjects performed this protocol under five different experimental conditions, with at least 72 hours of recovery between each experiment. The experimental protocol is summarised in Table 3.1.

3.3.5 Calculations
3.3.5.1 Treadmill speed
Peak oxygen uptake during load carriage, as determined in a previous study (Chapter 2), was used to determine the workload for the five treatment conditions. This was performed by calculating the treadmill speed which was associated with each of the five workloads. For example, consider Subject 12 whose peak aerobic power during load carriage was 4.84 L.min⁻¹, and resting oxygen consumption was 0.46 L.min⁻¹. From this, 60% of peak aerobic power was calculated to be 3.09 L.min⁻¹ (((4.84 – 0.46) x 0.6) + 0.46). Due to the linear relationship between oxygen consumption and exercise intensity (Hill & Lupton, 1923; Wyndham et al., 1959), we can calculate the treadmill speed associated with specific oxygen
Table 3.1: Submaximal exercise protocol

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject arrival</td>
<td>Subject dresses in military fatigues and running shoes. Primary researcher fits weighted vest</td>
</tr>
<tr>
<td>0 – 10 min</td>
<td>Resting data collection</td>
</tr>
<tr>
<td>10-15 min</td>
<td>Walking at 5 km.hr⁻¹, 1% grade</td>
</tr>
<tr>
<td>15 min</td>
<td>Speed increased to desired workload, grade maintained at 1%</td>
</tr>
<tr>
<td>Termination</td>
<td>Subject ceases exercise at exhaustion or at the completion of 5 km</td>
</tr>
</tbody>
</table>
consumptions (Figure 3.1). This procedure was performed on an individual basis for all experimental conditions (Table 3.2).

3.3.5.2 Maximum acceptable work duration
These calculations were based on the previously established methods of Wu & Wang (2001, 2002). These authors suggested that fatigue was present beyond specific heart rates, and also was recognised as an elevation of heart rate. Firstly, acceptable work time was defined as the exercise duration from the start of the specified workload (e.g. 60% peak oxygen uptake) until the point at which absolute heart rate was greater than 180 beats.min\(^{-1}\) (Figure 3.2). In addition, maximum acceptable work duration was also calculated in the same manner, however, substituting the absolute heart rate with an average heart rate of 150 beats.min\(^{-1}\) (Figure 3.3). If these values were not reached during exercise, data were extrapolated to obtain the theoretical time.

Furthermore, acceptable work duration was calculated using an additional method which was also based on heart rate. This involved calculating the exercise time until the heart rate was greater than 10 beats.min\(^{-1}\) above the steady state heart rate during the initial hours of work (Wu & Wang, 2002). This was slightly modified, as exercising for several hours is not applicable to the present study. Thus, work time was defined as a heart rate which was 10 beats.min\(^{-1}\) higher than the average heart rate during the first 5 minutes of exercise for each condition (Figure 3.4).

3.3.5.3 Relative oxygen consumption
The average oxygen consumption from the start of the exercise workload until exercise termination was defined as the oxygen consumption during work (\(\dot{V}O_{2\text{work}}\)). Relative oxygen consumption was then calculated using the following equation (Wu & Wang 2001):

\[
\text{Relative oxygen consumption} = \frac{(\dot{V}O_{2\text{work}} - \dot{V}O_{2\text{rest}})}{(\dot{V}O_{2\text{peak}} - \dot{V}O_{2\text{rest}})}
\]
Figure 3.1: Relationship between oxygen consumption and treadmill speed. Linear regression was performed to calculate treadmill speed for the experimental conditions. In this example (Subject 12), speed was calculated to be 10.4 km.hr\(^{-1}\) (\(N=1, r^2=0.94, P<0.05\)). Linear regression equations were rearranged to calculate the treadmill speed for each submaximal workload (\(y = mx + b\), where \(y\) = y axis value, \(m\) = gradient, \(x\) = x axis value, \(b\) = constant).

\[y = 0.3312x - 0.3413\]
Table 3.2: Relationship between oxygen consumption (L.min⁻¹) and treadmill speed (km.hr⁻¹) during incremental exercise to exhaustion with a 22 kg external load. Linear regression equations were rearranged for each subject to calculate the treadmill speed for each submaximal workload.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gradient</th>
<th>Constant</th>
<th>( r^2 )</th>
<th>Calculated treadmill speed (km.hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
<td>-0.26</td>
<td>0.90</td>
<td>5.77</td>
</tr>
<tr>
<td>2</td>
<td>0.30</td>
<td>-0.23</td>
<td>0.92</td>
<td>6.16</td>
</tr>
<tr>
<td>3</td>
<td>0.28</td>
<td>-0.16</td>
<td>0.73</td>
<td>6.02</td>
</tr>
<tr>
<td>4</td>
<td>0.30</td>
<td>-0.45</td>
<td>0.97</td>
<td>6.92</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>-0.46</td>
<td>0.93</td>
<td>6.85</td>
</tr>
<tr>
<td>6</td>
<td>0.31</td>
<td>-0.44</td>
<td>0.95</td>
<td>7.72</td>
</tr>
<tr>
<td>8</td>
<td>0.28</td>
<td>-0.22</td>
<td>0.93</td>
<td>6.29</td>
</tr>
<tr>
<td>10</td>
<td>0.26</td>
<td>0.09</td>
<td>0.94</td>
<td>6.98</td>
</tr>
<tr>
<td>11</td>
<td>0.31</td>
<td>-0.30</td>
<td>0.86</td>
<td>6.06</td>
</tr>
<tr>
<td>12</td>
<td>0.33</td>
<td>-0.34</td>
<td>0.94</td>
<td>6.40</td>
</tr>
<tr>
<td>13</td>
<td>0.30</td>
<td>-0.38</td>
<td>0.93</td>
<td>6.40</td>
</tr>
<tr>
<td>Mean</td>
<td>0.29</td>
<td>-0.29</td>
<td>0.91</td>
<td>6.51</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.02</td>
<td>0.16</td>
<td>0.07</td>
<td>0.56</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.006</td>
<td>0.05</td>
<td>0.02</td>
<td>0.17</td>
</tr>
</tbody>
</table>
**Figure 3.2:** Procedure for calculating maximum acceptable work duration using absolute heart rate (Subject 13). This involved calculating the exercise time until absolute heart rate was greater than 180 beats.min⁻¹. In this example, acceptable work time was calculated to be 26.55 minutes ($N=1$, $r^2=0.74$, $P<0.05$). Linear regression equations were rearranged to calculate the submaximal exercise time for each workload ($y = mx + b$, where $y = y$ axis value, $m =$ gradient, $x = x$ axis value, $b =$ constant).
Figure 3.3: Procedure for calculating maximum acceptable work duration using average heart rate (Subject 13). This involved calculating the exercise time until average heart rate was greater than 150 beats.min\(^{-1}\). In this example, acceptable work time was calculated to be 4.3 min (\(N=1, r^2=0.76, P<0.05\)). Linear regression equations were rearranged to calculate the submaximal exercise time for each workload (\(y = mx + b\), where \(y = y\) axis value, \(m = \) gradient, \(x = x\) axis value, \(b = \) constant).
Figure 3.4: Procedure for calculating maximum acceptable work duration using an elevation of 10 beats.min\(^{-1}\) relative to the average heart rate during the first 5 minutes of exercise (Subject 13). In this example, an average heart rate of 116 beats.min\(^{-1}\) was recorded for this individual subject during the first 5 minutes of exercise during the 30% condition. Therefore, acceptable work time was the exercise time until heart rate reached 127 beats.min\(^{-1}\) (>10 beats.min\(^{-1}\)). This was calculated to be 49 minutes \(N=1\), \(r^2=0.60\), \(P<0.05\). Linear regression equations were rearranged to calculate the submaximal exercise time for each workload \(y = mx + b\), where \(y = y\) axis value, \(m = \) gradient, \(x = x\) axis value, \(b = \) constant).
3.3.5.4 **Relative heart rate**

The average heart rate from the start of the exercise workload until exercise termination was defined as the heart rate during work (HR\textsubscript{work}). Relative heart rate was then calculated using the following equation (Wu & Wang 2001):

\[
\text{Relative heart rate} = \frac{\text{HR}_{\text{work}} - \text{HR}_{\text{rest}}}{\text{HR}_{\text{peak}} - \text{HR}_{\text{rest}}}
\]

3.3.6 **Measurements**

3.3.6.1 **Oxygen consumption**

Subjects breathed through a two-way non-rebreathing valve (Model 2700B, Hans Rudolph Inc., KS, USA) and expired air was directed to a metabolic system (TrueOne 2400 metabolic measurement system, ParvoMedics Inc., UT, USA). Data were averaged for each breath over a 15-second period to determine oxygen consumption, carbon dioxide production, expired minute ventilation, tidal volume, breathing frequency, inspiratory time, and expiratory time. The metabolic system was calibrated with a 3-litre calibration syringe (Model 5530, Hans Rudolph Inc., KS, USA) with known concentrations of oxygen (15.97%), carbon dioxide (4.03%), and nitrogen (80%) prior to each use.

3.3.6.2 **Heart rate**

Heart rate was obtained at 15 second intervals based on R-wave detection during ventricular depolarisation using a heart rate monitor (Model PE3000 and Advantage, Polar Electro Sport Tester, Finland).

3.3.6.3 **Perceived exertion**

Perceived exertion was recorded at 2 min intervals using a 15-point rating of perceived exertion scale (where 6 = very, very light, 20 = very, very hard) (Borg, 1962a, 1962b). Subjects were asked “How hard are you exercising” with reference to the whole body, chest, and legs.

3.3.7 **Statistical analyses**

All data were reported for the first 5 minutes of submaximal exercise, and are means with standard deviations and standard errors of the means. The 95% confidence intervals are given for acceptable work duration as an indication of the upper and lower limits of work. One-way repeated measures analysis of variance was performed across the five experimental
conditions with exercise intensity as the independent variable. Furthermore, two-way repeated measures analysis of variance was performed to explore the interaction between exercise intensity and the two methods for calculating acceptable work time. Bonferroni’s post hoc analysis was performed to locate statistical differences. Statistical significance was accepted if $P<0.05$. In addition, non-linear regression analysis was performed for maximum acceptable work duration, with oxygen consumption and heart rate as the independent variables. Previous studies have demonstrated that the relationship between acceptable work time and physiological variables are explained by an exponential decrease regression model (Wu & Wang, 2001, 2002). Linear regression analysis was also performed to determine correlations between selected variables. The Bland-Altman method (Bland & Altman, 1986) was used to identify the limits of agreement between methods for calculating acceptable work time.

3.4 RESULTS
3.4.1 Baseline data
Subjects 7 and 9 were excluded from the study due to injuries which were not sustained during this study. Baseline and descriptive data for subjects have been reported previously (Tables 2.1 and 2.3).

3.4.2 Exercise tolerance
Oxygen consumption increased with exercise intensity and this was found to be significantly different between exercise conditions ($P<0.05$) (Table 3.3). Thus, subjects exercised at five distinct workloads. Although all subjects were able to complete the required 5 km distance for the lightest exercise intensity, not all subjects were capable of this for the remaining conditions (Table 3.4). Furthermore, since the only variation between the conditions was exercise intensity, then this provides a superficial explanation as to why exercise tolerance is reduced. Therefore, performance in this series of experiments referred to both the distance that subjects covered during each condition and how many trials were completed.

Only 2 subjects were capable of completing the heaviest workload (subjects 4 and 6). To explore this, total distance covered for the 9 subjects who were unable to complete the heaviest workload were correlated with physical characteristics (Figure 3.5). Firstly, body mass was poorly correlated with exercise tolerance, which suggests that an individual’s mass will not influence their performance of high intensity load carriage. However, peak oxygen
**Table 3.3:** Physiological responses to load carriage at 5 exercise intensities (30, 50, 60, 70, and 80% peak oxygen uptake). Values are means for the initial 5 minutes of exercise with standard errors of the means (N=10). Letters in superscript identify where significant differences exist (P<0.05). A different letter indicates a significant difference, whereas like letters indicate no significant difference.

<table>
<thead>
<tr>
<th>Exercise condition (% peak aerobic power)</th>
<th>Variable</th>
<th>30</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen consumption</td>
<td>Absolute (L.min(^{-1}))</td>
<td>1.75 ± 0.09(^a)</td>
<td>2.61 ± 0.08(^b)</td>
<td>2.95 ± 0.12(^c)</td>
<td>3.22 ± 0.12(^d)</td>
<td>3.44 ± 0.12(^e)</td>
</tr>
<tr>
<td></td>
<td>Relative (mL.kg(^{-1}).min(^{-1}))</td>
<td>18.19 ± 0.74(^a)</td>
<td>27.18 ± 0.67(^b)</td>
<td>30.84 ± 0.94(^c)</td>
<td>33.46 ± 0.92(^d)</td>
<td>35.93 ± 0.91(^e)</td>
</tr>
<tr>
<td>Minute ventilation (L.min(^{-1}))</td>
<td></td>
<td>43.34 ± 1.86(^a)</td>
<td>65.61 ± 1.65(^b)</td>
<td>75.49 ± 2.13(^c)</td>
<td>87.32 ± 2.25(^d)</td>
<td>100.60 ± 2.36(^e)</td>
</tr>
<tr>
<td>Tidal volume (L)</td>
<td></td>
<td>1.54 ± 0.10(^a)</td>
<td>1.98 ± 0.12(^b)</td>
<td>2.09 ± 0.10(^b)</td>
<td>2.29 ± 0.12(^c)</td>
<td>2.35 ± 0.12(^c)</td>
</tr>
<tr>
<td>Breathing frequency (breaths.min(^{-1}))</td>
<td></td>
<td>28.83 ± 1.16(^a)</td>
<td>34.11 ± 1.80(^b)</td>
<td>36.77 ± 1.69(^bc)</td>
<td>38.86 ± 2.18(^c)</td>
<td>43.47 ± 2.16(^d)</td>
</tr>
<tr>
<td>Heart rate (beats.min(^{-1}))</td>
<td></td>
<td>120.20 ± 3.07(^a)</td>
<td>148.70 ± 3.95(^b)</td>
<td>157.90 ± 3.48(^c)</td>
<td>165.60 ± 3.47(^cd)</td>
<td>169.10 ± 1.96(^d)</td>
</tr>
<tr>
<td>Inspiratory duration (s)</td>
<td></td>
<td>2.12 ± 0.11(^a)</td>
<td>1.81 ± 0.09(^b)</td>
<td>1.67 ± 0.08(^b)</td>
<td>1.59 ± 0.09(^bc)</td>
<td>1.43 ± 0.07(^c)</td>
</tr>
<tr>
<td>Expiratory duration (s)</td>
<td></td>
<td>1.12 ± 0.06(^a)</td>
<td>0.96 ± 0.05(^b)</td>
<td>0.93 ± 0.05(^bc)</td>
<td>0.88 ± 0.04(^bc)</td>
<td>0.80 ± 0.03(^c)</td>
</tr>
<tr>
<td>Total breath duration (s)</td>
<td></td>
<td>3.24 ± 0.17(^a)</td>
<td>2.77 ± 0.15(^b)</td>
<td>2.60 ± 0.13(^b)</td>
<td>2.47 ± 0.13(^bc)</td>
<td>2.23 ± 0.10(^c)</td>
</tr>
<tr>
<td>Respiratory duty cycle (s)</td>
<td></td>
<td>0.66 ± 0.004(^a)</td>
<td>0.65 ± 0.004(^ab)</td>
<td>0.64 ± 0.006(^ab)</td>
<td>0.64 ± 0.003(^ab)</td>
<td>0.64 ± 0.005(^b)</td>
</tr>
<tr>
<td>Mean inspiratory flow (L.s(^{-1}))</td>
<td></td>
<td>0.73 ± 0.03(^a)</td>
<td>1.10 ± 0.03(^b)</td>
<td>1.27 ± 0.04(^c)</td>
<td>1.46 ± 0.04(^d)</td>
<td>1.69 ± 0.04(^e)</td>
</tr>
</tbody>
</table>
Table 3.4: Distance covered during load carriage at 5 exercise intensities (30, 50, 60, 70, and 80% peak oxygen uptake). Values are the distances covered by individual subjects (m).

<table>
<thead>
<tr>
<th>Subject</th>
<th>30%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>3578</td>
<td>1845</td>
<td>930</td>
<td>984</td>
</tr>
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<td>5000</td>
<td>2171</td>
<td>2019</td>
<td>1414</td>
<td>1407</td>
</tr>
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<td>3</td>
<td>5000</td>
<td>1896</td>
<td>3597</td>
<td>1142</td>
<td>717</td>
</tr>
<tr>
<td>4</td>
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<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
</tr>
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<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>2473</td>
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<td>5000</td>
<td>5000</td>
</tr>
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<td>5000</td>
<td>5000</td>
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<td>5000</td>
<td>5000</td>
<td>3000</td>
</tr>
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<td>11</td>
<td>5000</td>
<td>5000</td>
<td>2815</td>
<td>1738</td>
<td>1074</td>
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<tr>
<td>12</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>4586</td>
<td>1668</td>
</tr>
<tr>
<td>13</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>2212</td>
</tr>
<tr>
<td>Mean</td>
<td>5000</td>
<td>4331</td>
<td>4116</td>
<td>3619</td>
<td>2351</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.00</td>
<td>1214</td>
<td>1303</td>
<td>1848</td>
<td>1484</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.00</td>
<td>366.10</td>
<td>393.00</td>
<td>557.10</td>
<td>447.40</td>
</tr>
</tbody>
</table>
Figure 3.5: Total distance covered in relation to body mass (A), and peak oxygen consumption (B) during 80% condition. Subjects who completed 5 km were excluded ($N=9$). In A, the line represents the linear fit ($r^2=0.002$, $P>0.05$). In B, the line represents the linear fit ($r^2=0.70$, $P<0.05$) ($y = mx + b$, where $y$ = $y$ axis value, $m$ = gradient, $x$ = $x$ axis value, $b$ = constant).
uptake was significantly correlated with exercise tolerance \((P<0.05)\). Therefore, during high intensity submaximal work, peak aerobic power is more important than body mass in predicting load carriage ability. These findings are surprising, as the opposite was shown in the previous chapter in that peak oxygen uptake was poorly correlated with performance \((r^2=0.09)\), and body mass was significantly correlated with performance \((r^2=0.76)\). This is most likely due to the fact that physical characteristics were correlated with distance covered in this study, whereas these variables were correlated with a change in exercise time in the previous chapter.

### 3.4.3 Physiological measures

The observed differences in physiological measures between experimental conditions are expected, considering that subjects performed exercise of varying intensity. For example, oxygen is consumed to perform physical work, and, with increasing work, more oxygen will be consumed. This was reflected by a two-fold increase in oxygen consumption from the lightest to the heaviest workload (Table 3.3). To allow for this, more oxygen must be taken into the body, and consequently delivered to the working skeletal muscles. This was evident, with significant increases in minute ventilation, and heart rate, respectively (Table 3.3).

In addition, physiological responses were examined with reference to distance covered (Figure 3.7). Despite there being a marked difference in these responses between conditions, variables such as oxygen consumption and tidal volume remained relatively constant over the 5 km distance. However, minute ventilation and heart rate continued to increase with the distance travelled, especially during the higher intensity conditions. The increase in minute ventilation was primarily achieved through elevations in breathing frequency, as tidal volume remained relatively stable whilst breathing frequency continued to increase. Furthermore, there were significant differences between conditions for physiological variables at the completion of 5 km (Figure 3.6). However, these should be interpreted with caution as not all subjects were able to complete 5 km for each condition.

### 3.4.4 Perceived exertion

Subjects reported their physical exertion as being more difficult during the heavier exercise workloads (Table 3.5). However, the differences were only significant when comparing the three heaviest workloads (60, 70, and 80% peak oxygen uptake) to the lightest workload
**Figure 3.6:** Physiological responses to treadmill exercise with load at several intensities (% peak oxygen uptake). - 30%, - 50%, - 60%, - 70%, - 80%. Data were averaged at 500 m intervals (0-500 m, 500-1000m etc.). Solid line represents all subjects (N=11). Dashed line indicates that certain subjects had ceased exercise (N≠11). Letters identify significant differences between conditions at completion (P<0.05).
Table 3.5: Perceived exertion following 5 minutes of submaximal exercise for each condition (30, 50, 60, 70, and 80% peak oxygen uptake). Values are means with standard errors of the means. Letters in superscript indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference.

<table>
<thead>
<tr>
<th>Exercise condition (% peak aerobic power)</th>
<th>RPE</th>
<th>30</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole body</td>
<td>8.20 ± 0.63$^{a}$</td>
<td>9.40 ± 0.62$^{ab}$</td>
<td>11.10 ± 0.81$^{bc}$</td>
<td>13.10 ± 0.64$^{cd}$</td>
<td>14.40 ± 0.52$^{d}$</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td>8.10 ± 0.57$^{a}$</td>
<td>9.40 ± 0.56$^{ab}$</td>
<td>11.20 ± 0.79$^{bc}$</td>
<td>13.10 ± 0.64$^{cd}$</td>
<td>14.40 ± 0.52$^{d}$</td>
<td></td>
</tr>
<tr>
<td>Legs</td>
<td>8.10 ± 0.57$^{a}$</td>
<td>10.00 ± 0.76$^{ab}$</td>
<td>11.00 ± 0.79$^{bc}$</td>
<td>13.10 ± 0.64$^{d}$</td>
<td>14.50 ± 0.48$^{d}$</td>
<td></td>
</tr>
</tbody>
</table>
(30% peak oxygen uptake). Although a predictable outcome, this information may be useful in the field, particularly where performing heavier work is beneficial. For example, using the data from Table 3.2, a distance of 5 km will be covered in 46 minutes when working at 30% peak oxygen uptake. However, if work was performed at 50% peak oxygen uptake, then this task would be completed in 32 minutes, and may not be perceived as being more difficult.

3.4.5 Maximum acceptable work duration

Recall there were three methods for calculating acceptable work time. These were the exercise times until a peak heart rate (180 beats.min\(^{-1}\)), average heart rate (150 beats.min\(^{-1}\)), or an elevated heart rate (10 beats.min\(^{-1}\) above the average during the first 5 minutes), were obtained. Using peak heart rate, acceptable work time was consistently lower during high workloads. However, this was only significant when comparing all exercise conditions to the lightest workload (30% peak oxygen uptake) \((P<0.05)\). Lower work times were also obtained at high intensities when average heart rate was the primary measure. Accordingly, significant differences were only observed during the lightest exercise condition \((P<0.05)\). These findings are expected, as heart rate will increase more rapidly during high intensity work. In addition, acceptable work time for the 30% condition was significantly higher than all other conditions \((P<0.05)\) when calculated using a ten beat elevation in heart rate.

When considering all methods for calculating acceptable work time, values obtained using average heart rate, or a ten beat elevation in heart rate, were consistently lower than those obtained using peak heart rate across each of the exercise conditions (Table 3.6). Despite this, these differences were only significant at the lightest intensity \((P<0.05)\). This finding is also predictable, as heart rate increases in a linear fashion with exercise intensity, and is likely to reach these thresholds before a peak value of 180 beats.min\(^{-1}\), particularly during submaximal exercise where a steady state is not present. Therefore, the appropriateness of these measures of work time needs to be considered carefully, since they may produce significantly different results.

To illustrate the differences between the peak heart rate and average heart rate methods for calculating acceptable work time, the 95% limits of agreement were calculated (Bland & Altman, 1986). Respectively, these values were -105.94 – 279.40 min, -0.65 – 47.45 min, -1.25 – 28.74 min, -3.91 – 21.68 min, and 0.24 – 11.29 min for the 30, 50, 60, 70, and 80% conditions (Figure 3.7). Overall, this indicates poor agreement between these two methods.
Table 3.6: Maximum acceptable work duration (min) for each condition. Acceptable work time was calculated using peak heart rate (180\text{peak}), average heart rate (150\text{avg}), and a higher heart rate compared to steady state exercise (+10). * = P<0.05 compared to all other conditions † = P<0.05 compared to all other methods of calculating acceptable work duration for 30% condition only. The upper and lower 95% confidence intervals are displayed below the mean.

<table>
<thead>
<tr>
<th>Subject</th>
<th>30%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>180_{\text{peak}}</td>
<td>150_{\text{avg}}</td>
<td>+10</td>
<td>180_{\text{peak}}</td>
<td>150_{\text{avg}}</td>
</tr>
<tr>
<td>1</td>
<td>266.50</td>
<td>214.27</td>
<td>41.03</td>
<td>20.36</td>
<td>4.79</td>
</tr>
<tr>
<td>2</td>
<td>86.88</td>
<td>9.59</td>
<td>9.59</td>
<td>10.42</td>
<td>2.11</td>
</tr>
<tr>
<td>4</td>
<td>222.74</td>
<td>148.84</td>
<td>45.49</td>
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<td>5</td>
<td>119.48</td>
<td>109.89</td>
<td>15.93</td>
<td>41.71</td>
<td>27.42</td>
</tr>
<tr>
<td>6</td>
<td>98.30</td>
<td>68.33</td>
<td>13.86</td>
<td>31.73</td>
<td>12.44</td>
</tr>
<tr>
<td>8</td>
<td>595.86</td>
<td>244.90</td>
<td>95.03</td>
<td>47.61</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>156.34</td>
<td>105.83</td>
<td>23.41</td>
<td>35.61</td>
<td>3.32</td>
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<td>11</td>
<td>171.59</td>
<td>143.74</td>
<td>34.84</td>
<td>41.66</td>
<td>25.24</td>
</tr>
<tr>
<td>12</td>
<td>141.85</td>
<td>71.92</td>
<td>24.15</td>
<td>19.22</td>
<td>0.00</td>
</tr>
<tr>
<td>13</td>
<td>341.50</td>
<td>216.40</td>
<td>49.06</td>
<td>27.65</td>
<td>5.37</td>
</tr>
<tr>
<td>Mean</td>
<td>220.10†</td>
<td>133.40†</td>
<td>35.24†</td>
<td>34.59</td>
<td>11.19</td>
</tr>
<tr>
<td>Lower 95%</td>
<td>109.96</td>
<td>79.59</td>
<td>17.31</td>
<td>22.43</td>
<td>2.48</td>
</tr>
</tbody>
</table>
Figure 3.7: Bland-Altman plot for assessing agreement between peak heart rate and average heart rate methods for calculating acceptable work time. The percentage above each plot refers to each of the five exercise conditions. The ordinate represents the difference in acceptable work time for the two methods. The abscissa represents the mean acceptable work time for the two methods. The 95% limits of agreement have been given previously (3.4.5 Maximum acceptable work duration).
However, the intervals became narrower with each condition, suggesting that these methods may produce similar results for higher intensity exercise.

Furthermore, acceptable work time was significantly correlated with relative oxygen consumption (Figure 3.8) and relative heart rate (Figure 3.9), with the latter being the strongest predictive variable ($P<0.05$). In addition, when average heart rate was the measure of work time, higher correlations were observed. Since heart rate was the physiological variable which determined acceptable work duration, it is not surprising that this variable was a stronger predictor of work time.

### 3.5 DISCUSSION

The primary aims of this study were to quantify the physiological demands of performing whole-body exercise across a range of intensities, with the addition of a 22 kg external load. In addition, this study focussed on identifying acceptable work durations for whole-body exercise combined with load carriage, based on previously established methods. There were two main findings from this investigation. First, load carrying ability was related to peak oxygen uptake. Second, each of the methods used to calculate work time produced different results.

#### 3.5.1 Exercise performance during load carriage

This experiment required subjects to attempt to complete 5 km on a treadmill at various constant workloads whilst carrying a 22 kg load. Thus, exercise performance in this study was analogous to the distance covered in metres. Voluntary exhaustion occurred at exercise intensities beyond 30% of peak oxygen uptake. Performance was significantly correlated with peak oxygen consumption during the 80% condition (Figure 3.5), similar to previous findings where trained subjects and 5 km running performance were included. This suggests that peak oxygen uptake may give an indication of high intensity running performance (Costill et al., 1976; Fay et al., 1989; Foster et al., 1978). However, such predictions may not be appropriate when load carriage is performed, as we have demonstrated in the previous chapter that load has a significant influence on exercise performance. Nevertheless, there is also evidence that peak oxygen uptake is a good predictor of load carriage performance (Harman & Frykman, 1995).
Figure 3.8: Relationship between maximum acceptable work duration and relative oxygen consumption. In A, work time was calculated using peak heart rate (180 beats.min\(^{-1}\)) \( (N=11, \ R^2=0.67, \ P<0.05) \). In B, work time was calculated using average heart rate (150 beats.min\(^{-1}\)) \( (N=11, \ R^2=0.80, \ P<0.05) \). The lines in each graph represent the non-linear fit.
**Figure 3.9**: Relationship between maximum acceptable work duration and relative heart rate.

In **A**, work time was calculated using peak heart rate (180 beats.min\(^{-1}\)) \((N=11, R^2=0.71, P<0.05)\). In **B**, work time was calculated using average heart rate (150 beats.min\(^{-1}\)) \((N=11, R^2=0.80, P<0.05)\). The lines in each graph represent the non-linear fit.
Traditionally, peak oxygen uptake was accepted as the definitive measure of human performance (Hill & Lupton, 1923). Exercise performance in this study seemed to be related to peak oxygen consumption (Figure 3.5). This supports the use of peak oxygen consumption to predict performance. However, it is now hard to defend this assumption, especially considering that an individual with a lower peak oxygen uptake is capable of a better performance. Although this has been reported in the literature, it was not observed in this study (Conley & Krahenbuhl, 1980; Saltin & Astrand, 1967). Thus, we must consider other physiological measures of human performance.

Running economy has been defined as the steady state oxygen consumption at specific running speeds, and shown to be closely associated with running performance (Conley & Krahenbuhl, 1980; Farrell et al., 1979). For instance, two runners will reach their peak oxygen consumption at different times, given that they have different economies. Thus, if peak oxygen consumption is the limit to exercise, those with superior economies will perform best. As a measure of economy, we calculated the energy cost of running one kilometre and compared this against the distance covered during the 80% condition (Figure 3.10). The cost of running was between 187 and 221 mL.kg\(^{-1}\).km\(^{-1}\), which is expected for humans running at these speeds (Carrier, 1984). However, the cost of running was poorly correlated with distance covered (Figure 3.10), suggesting that the economy of movement is unable to predict performance during high intensity load carriage within the current experiment. With loads up to 30 kg, energy expenditure will rise in proportion to the load carried (Goldman & Iampietro, 1962). Considering that the load utilised in our study was within this range, it is surprising that the cost of running was unable to predict performance using a linear model. Indeed, we have shown that the energy cost of running and body mass are poor predictors of performance during load carriage. Therefore, we reject our fourth hypothesis which stated that load carriage performance will be correlated with body mass. In contrast, peak oxygen consumption provides a good indication of high intensity load carriage performance.

Unlike peak oxygen uptake, the economy of running was unable to explain differences in exercise performance. Although this is not consistent with previous findings, it is likely that peak oxygen uptake was a good indicator of performance due to between-subject variations in our study ($\dot{V}{\text{O}}_{2\text{peak}}$ range = 48.90-72.60 mL.kg\(^{-1}\).min\(^{-1}\)). For example, peak oxygen uptake
Figure 3.10: Distance covered by each subject during loaded treadmill exercise at 80% of peak oxygen uptake with reference to the energy cost of running. Cost of running was calculated during 5 minutes of treadmill exercise at speeds between 8-11 km.hr\(^{-1}\). The line represents the linear fit \((N=9, r^2=0.05, P>0.05)\) \((y = mx + b\), where \(y = y\) axis value, \(m =\) gradient, \(x = x\) axis value, \(b = constant\)).
has been shown to be a poor predictor of performance in a homogenous population, but a
good predictor for individuals of different capabilities (Costill & Winrow, 1970; Pollock,
1977).

3.5.2 Maximum acceptable work duration
Recall that there were three methods of calculating acceptable work time, each being based
on measures of heart rate (see 3.3.5.2 Maximum acceptable work duration). For this measure
to be valid, we must be confident that heart rate is a good representation of physiological
strain. In fact, there is a strong relationship between heart rate and oxygen consumption.
However, this relationship varies depending on a variety of factors, such as exercise mode,
active muscle mass, body temperature, and exercise intensity (Bernard et al., 1997; Brouha et
al., 1963; Vokac et al., 1975). Thus, caution should be taken when using heart rate as a
measure of acceptable work time, as results may vary depending on the task and
environment. The use of absolute heart rate as a measure of work time is a limitation to the
current study. Heart rate may be influenced by several factors such as age, training status, and
gender (Andrews, 1969; Harms, 2006; Swain et al., 1998). For example, a given heart rate
may reflect different relative exercise intensities among a group of subjects. Thus, the utility
of this measure of acceptable work time needs to be considered carefully.

The use of peak and average heart rate to determine acceptable work time was introduced by
Wu & Wang (2001). Logically, these values must represent some physiological threshold for
them to be suggested as end-points. However, we are not aware of any research which has
suggested an absolute value of heart rate as an upper limit for work. In fact, most
recommendations for an acceptable workload are based on values of relative oxygen
consumption (Astrand et al., 1959; Michael et al., 1961; Passmore & Durnin, 1955; Saha et
al., 1979). During exercise with a load, a peak heart rate of 180 beats.min\(^{-1}\) would represent
approximately 92% of peak oxygen uptake for our subjects, based on their relationship during
incremental exercise with load (Figure 3.11), and given a peak oxygen uptake of 45.42
mL.kg\(^{-1}\).min\(^{-1}\) (Table 2.5). It is unlikely that this workload could be sustained. In fact, this
intensity exceeds the maximum recommended workload for an 8 hour day (Michael et al.,
1961; Saha et al., 1979). However, this end-point was recommended for high intensity
exercise, and not work which could be sustained for 8 hours.
Figure 3.11: Relationship between heart rate and oxygen consumption during incremental treadmill exercise with load. The slope, intercept, and coefficient of determination represent means for all subjects. The line represents the linear fit ($N=11$, $r^2=0.91$, $P<0.05$) ($y = mx + b$, where $y = y$ axis value, $m = gradient$, $x = x$ axis value, $b = constant$).
With one exception, we are not familiar with any research which has recommended an average heart rate as the limit to work (Wu & Wang, 2001). In our study, a heart rate of 150 beats.min\(^{-1}\) would reflect approximately 58% of peak oxygen uptake for our subjects, based on their relationship during incremental exercise with load (Figure 3.11), and given a peak oxygen uptake of 45.42 mL.kg\(^{-1}\).min\(^{-1}\) (Table 2.5), which is closer to what has been recommended for prolonged work. Therefore, this measure appears to underestimate the duration that an individual can actually maintain a given workload (Table 3.6). In contrast, an elevation in heart rate seems a logical measure, as it reflects non-steady state conditions. However, this may not be appropriate during high intensity exercise due to the initial rise in heart rate. Thus, suggesting acceptable work durations should only be performed for workloads where a steady state is present.

Our second hypothesis stated that acceptable work time will progressively decrease with exercise intensity. Our findings are in agreement with this hypothesis. In addition, each method for calculating acceptable work duration produced different results, and this seemed to be a function of the exercise intensity. For example, work time could not be calculated for several subjects using average heart rate, at workloads beyond 50% peak oxygen uptake (Table 3.6). This was due to a rapid elevation in heart rate at these intensities, and therefore indicates that this measure is not appropriate for high intensity exercise. Despite this, work time was calculated from peak heart rate for all but one subject (Subject 12), at each workload. Therefore, peak heart rate is a more applicable measure of acceptable work duration for high intensity exercise. However, this measure produced high variation between subjects, with coefficients of variation of 70, 49, 67, 73, and 40% for the lightest to heaviest workload, respectively. This is due to the fact that, at a given workload, there will be individual differences in the heart rate response (Manning & Griggs, 1983; Michael et al., 1961; Saha et al., 1979; Wyndham et al., 1959). Thus, alternative measures of acceptable work time need to be considered.

There was poor agreement between the peak heart rate and average heart rate methods for measuring acceptable work time. We acknowledge that the methods described by Bland & Altman (1986) are applicable when comparing two measurement techniques. That is, a new measurement technique against one that has been established. The present study involved three methods for calculating acceptable work time. Therefore, one method was excluded from this analysis. We sought to identify that established methods for measuring acceptable
work time as presented by Wu & Wang (2001, 2002) are poorly related. This is highlighted by the 95% limits of agreement which were -105.94 – 279.40 min, -0.65 – 47.45 min, -1.25 – 28.74 min, -3.91 – 21.68 min, and 0.24 – 11.29 min for the 30, 50, 60, 70, and 80% conditions, respectively.

There were significant correlations between acceptable work time and physiological variables (Figures 3.8 and 3.9), which is consistent with previous findings (Wu & Wang, 2001; Wu & Wang, 2002). The strength of these predictions seems to be related to both exercise intensity, and the method of calculating work time. For instance, relative heart rate, as opposed to relative oxygen consumption, was the best predictor when exercise below 50% of peak oxygen uptake was performed (Wu & Wang, 2002). However, this was not observed when exercise beyond 50% peak oxygen uptake was performed (Wu & Wang, 2001). In addition, when work time was calculated by an elevation in heart rate, slightly higher correlations were observed compared to using absolute values of heart rate. To explain these observations, we must appreciate that heart rate is influenced by a variety of external factors, such as exercise and environmental temperature (Duncan et al., 1979; Wyndham et al., 1959). The variety of exercise intensities between our study, and others, may explain the differences in predictions of work time. Furthermore, subjects were wearing two layers of clothing (military fatigues and weighted vest) during our study. To allow for convective cooling, it is likely that significant elevations in skin blood flow occurred during exercise, which would also influence heart rate (Edholm et al., 1956; Wyss et al., 1974).

Acceptable work times of 19.1 and 6.7 min have been suggested for intensities of 60% and 70% of peak work rate, respectively (Wu & Wang, 2001). There are several reasons for the differences observed. First, we calculated workloads based on the relationship between treadmill speed and oxygen consumption, and not work rate alone. Second, although we attempted to elicit relative oxygen consumptions between 30-80% of peak values, the actual responses were slightly higher. Furthermore, we anticipated that our work times would be longer than that reported by others, since different exercise modes were utilised (Wu & Wang, 2001). As explained previously, the relationship between heart rate and oxygen uptake will vary depending on the amount of active muscle mass. For instance, heart rate will be higher at a given workload when less muscle mass is utilised (Astrand et al., 1965; Bobbert, 1960; Stenberg et al., 1967). Thus, acceptable work duration will be reduced with cycle ergometry compared to treadmill exercise. However, our work times were only slightly
different to those reported by others, when peak heart rate was the measure of work time (Wu & Wang, 2001). This suggests that there is an elevated physiological strain during load carriage, which is consistent with previous research (Balogun, 1986; Duncan et al., 1979).

3.6 CONCLUSION
We believe that peak heart rate provides the best representation of appropriate exercise duration for well-trained individuals, who are required to perform exercise whilst carrying a 22 kg load, at intensities up to 80% of peak oxygen uptake. Thus, for trained individuals, heavy exercise with a 22 kg load which elicits approximately 80% of the peak oxygen uptake should not exceed 6 minutes, and work requiring approximately 30% may continue for up to 3.5 hours. Peak oxygen uptake is an important determinant of load carriage ability during whole-body exercise between 30-80% of peak oxygen uptake. Considering our previous findings (Chapter 2), both body mass and peak oxygen uptake should be considered where predictions of load carriage performance are sought. Running economy did not explain differences in load carriage performance, which is most likely due to inter-subject variability in peak oxygen uptake. Previously established methods for determining acceptable work duration were based on measures of heart rate. However, considering the between subject variability in acceptable work duration, we recommend that measures of work time should be derived from relative heart rate.
3.7 REFERENCES


CHAPTER FOUR:  
THE EFFECT OF PRIOR ACTIVITY ON REPETITIVE HIGH INTENSITY WORK

4.1 INTRODUCTION
Continuing with our previous example of the firefighter and soldier, repetitive high intensity work is common to these occupations. For example, during one particular task performed by NSW Fire and Rescue personnel, heart rates exceeding 180 beats.min$^{-1}$ were recorded. Firefighters were required to drag a charged hose with a mass of approximately 35 kg through rough terrain for 52 minutes (Sampson et al., 2012). Indeed, this can be classed as high intensity work. Furthermore, soldiers may be required to sprint whilst carrying heavy equipment in order to obtain cover. This may be performed several times and can therefore be defined as repetitive high intensity work. As this is common in the field, a sprint assessment was developed to evaluate the effect of load on infantry soldier sprint performance (Treloar & Billing, 2011). Soldiers were required to perform 6 x 30-metre sprints at 44 second intervals. On average, sprint time was significantly faster with no load compared to a load of 21.6 kg. It has been suggested that both the availability of phosphocreatine, and neuromuscular function, may influence high intensity exercise performance. For instance, phosphocreatine provides energy for muscular contraction during high intensity exercise. However, limited evidence suggests that phosphocreatine stores are depleted when heavy exercise is sustained (Bogdanis et al., 1996; McCartney et al., 1986). In addition, there is conflicting evidence on whether efferent drive from the central nervous system limits exercise performance. Some authors have identified a reduced central nervous system output during exercise (Bigland-Ritchie et al., 1979; Moritani et al., 1986), whilst others have reported a rapid decline in exercise performance with an increase in central drive (Billaut et al., 2006).

Regardless of the exercise mode, humans are unable to achieve the same peak performance during repeated bouts of high intensity exercise (Krustrup et al., 2006; Mendez-Villanueva et al., 2008). Considering the previous examples of the firefighter and soldier, high intensity work is usually coupled with submaximal work. It is known that prior submaximal exercise exceeding 60% of peak oxygen uptake affects the performance of subsequent high intensity work (Capelli et al., 1993; Ferretti et al., 1987; Hitchcock, 1989; Margaria et al., 1971; Sargeant & Dolan, 1987). However, to our knowledge, the effect of prior activity combined with load carriage on subsequent high intensity work is unknown. Therefore, a further aim of
this research is to identify a level of loaded submaximal work which may limit further high intensity exercise performance.

4.2 AIMS AND HYPOTHESES
The aim of this study was to quantify the physical demands of high intensity work which was preceded by loaded submaximal work at varying intensities. Furthermore, this study determined if there was a threshold where prior activity with load affects the performance of subsequent high intensity work.

It was hypothesised that power output would be significantly reduced following prior exercise which was beyond 60% of peak oxygen uptake. In addition, the recovery of sprint performance would be significantly correlated with peak oxygen uptake.

4.3 METHODS
4.3.1 Study overview
This study was designed to follow the experiments performed in the previous chapter. There were 6 exercise conditions, which were performed on separate days with at least 72 hours of recovery. The first condition (control) was performed during the initial familiarisation session, with no prior exercise. The remaining five commenced immediately following the completion of treadmill exercise at 30, 50, 60, 70, and 80% of peak oxygen uptake. Therefore, the subjects were the same as those who participated in the previous study (Chapter 3). Their physical characteristics are displayed in Table 2.1.

4.3.2 Experimental protocol
Subjects performed maximal efforts on a cycle ergometer, following a previous activity. The purpose was to determine if an individuals' ability to perform high intensity work was affected by previous work, as this is common in several occupational settings such as the military and Fire and Rescue services. All experiments were performed in a laboratory environment (22°, 35% relative humidity).

Immediately following the completion of treadmill exercise, the weighted vest was removed, and the subject was positioned in a standing position on a cycle ergometer (Ergomedic 894E Peak Bike, Monark, Sweden), with their feet fastened to the pedals. Thirty seconds following treadmill exercise, subjects performed three 10-second maximal sprints on the cycle
ergometer. The load which was applied was equivalent to 9% of individual body mass, based on previous recommendations (Bar-Or, 1987). This load was applied automatically when a cadence of 70 revolutions per minute was achieved. Sprints were performed in a standing position, and were separated by 50 seconds of recovery with the subject remaining in a standing position on the ergometer (Figure 4.1). The selection of this task was based on unpublished work which demonstrated a close association with 30 metre running performance, which is a task currently being performed within the Australian Army (Treloar & Billing, 2011).

4.3.3 Measurements
Sprint performance was recorded using computer software (Monark Anaerobic Test Software 3.0, Monark, Sweden), and included both raw data and calculated variables:

4.3.3.1 Cadence
Cadence was recorded as raw data every second during the sprints, and was expressed as revolutions per minute (r.min⁻¹).

4.3.3.2 Power output
Power output (W) was recorded as raw data every second during the sprints, and was also expressed relative to body mass (W.kg⁻¹).

4.3.3.3 Peak power output
Peak power output (W) refers to the highest recorded power during each of the 10-second sprints. Since data were recorded at one second intervals, peak power output was calculated using computer software (Monark Anaerobic Test Software 3.0, Monark, Sweden). This value was also expressed relative to body mass (W.kg⁻¹).

4.3.3.4 Mean power output
Power output was recorded on a second-by-second basis during sprints. Therefore, since exercise lasted 10 seconds, mean power output was calculated as the mean of these 10 values. This value was also expressed relative to body mass (W.kg⁻¹).
Figure 4.1: Three 10-second sprints were performed on a cycle ergometer. The control condition occurred on a separate day, with no prior exercise. The experimental conditions involved prior treadmill exercise at 30, 50, 60, 70, or 80% of peak oxygen uptake with a 22 kg load. Each sprint was performed in a standing position as shown above, with 50 seconds of recovery.
4.3.3.5 Performance decrement

Sprint performance decrement was calculated using the following equation (Girard et al., 2011):

\[
\text{Performance decrement (\%)} = \left(1 - \frac{S_1 + S_2 + S_3}{S_b \times N_s}\right) \times 100
\]

\(S_1, S_2, \text{ and } S_3\) refer to the sprint number, \(S_b\) is the highest value recorded from control sprints, and \(N_s\) is the number of sprints. For example, Subject 13 produced peak power outputs of 1066.95, 995.70, and 986.05 W for the first, second, and third sprints, respectively. Control power output was 1145.81 W. These values were substituted into the equation as follows:

\[
\text{Performance decrement (\%)} = \left(1 - \frac{1066.95 + 995.70 + 986.05}{1145.81 \times 3}\right) \times 100
\]

Therefore, the performance decrement with reference to peak power was 7.56%. This calculation was also performed for mean power output.

4.3.3.6 Recovery of power

This was calculated as the power during the second sprint as a percentage of that achieved during the first sprint. Calculations were performed for peak power and mean power.

4.3.4 Statistical analyses

All data were reported as means with standard deviations and standard errors of the means. Two-way analysis of variance across the six conditions was conducted, with exercise condition and sprint as the independent variables. One-way analysis of variance compared exercise conditions independent of sprint. Where subjects were divided into two groups, the Student’s \(t\) test compared the means. Bonferroni’s post hoc analysis was performed to locate statistical differences, and statistical significance was accepted if \(P<0.05\). Linear regression analysis was performed to determine correlations between selected variables.
Table 4.1: Sprint performance during control sprints, and following each exercise condition (30, 50, 60, 70, and 80% of peak oxygen uptake). Values represent the means and standard errors of the means for each of the three sprints ($N=11$).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>30</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence (r.min$^{-1}$)</td>
<td></td>
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</tr>
<tr>
<td>1. 129.67 ± 1.31</td>
<td>1. 128.31 ± 1.21</td>
<td>1. 130.40 ± 1.50</td>
<td>1. 131.60 ± 1.39</td>
<td>1. 127.27 ± 1.69</td>
<td>1. 123.84 ± 1.40</td>
<td></td>
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<tr>
<td>2. 123.90 ± 1.21</td>
<td>2. 123.00 ± 1.21</td>
<td>2. 123.73 ± 1.29</td>
<td>2. 123.58 ± 1.28</td>
<td>2. 119.90 ± 1.54</td>
<td>2. 117.58 ± 1.40</td>
<td></td>
</tr>
<tr>
<td>3. 118.98 ± 1.32</td>
<td>3. 117.52 ± 1.18</td>
<td>3. 117.38 ± 1.32</td>
<td>3. 116.86 ± 1.33</td>
<td>3. 114.08 ± 1.56</td>
<td>3. 112.62 ± 1.44</td>
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<tr>
<td>Peak power (W)</td>
<td></td>
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<tr>
<td>1. 1112.40 ± 47.33</td>
<td>1. 1081.00 ± 33.97</td>
<td>1. 1109.00 ± 36.57</td>
<td>1. 1131.80 ± 38.21</td>
<td>1. 1087.90 ± 45.89</td>
<td>1. 1066.90 ± 41.77</td>
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<tr>
<td>2. 1046.30 ± 39.23</td>
<td>2. 1048.40 ± 39.38</td>
<td>2. 1046.10 ± 41.69</td>
<td>2. 1046.20 ± 31.73</td>
<td>2. 1016.20 ± 47.31</td>
<td>2. 984.76 ± 36.28</td>
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<tr>
<td>3. 1012.00 ± 38.52</td>
<td>3. 994.48 ± 29.26</td>
<td>3. 1003.80 ± 37.82</td>
<td>3. 993.10 ± 43.83</td>
<td>3. 961.04 ± 47.39</td>
<td>3. 925.79 ± 37.51</td>
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<tr>
<td>Peak power (W.kg$^{-1}$)</td>
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<tr>
<td>1. 14.89 ± 0.56</td>
<td>1. 14.38 ± 0.35</td>
<td>1. 14.81 ± 0.48</td>
<td>1. 15.30 ± 0.59</td>
<td>1. 14.54 ± 0.65</td>
<td>1. 14.29 ± 0.51</td>
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<tr>
<td>2. 14.00 ± 0.44</td>
<td>2. 13.93 ± 0.39</td>
<td>2. 13.94 ± 0.48</td>
<td>2. 14.13 ± 0.46</td>
<td>2. 13.57 ± 0.64</td>
<td>2. 13.20 ± 0.47</td>
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<tr>
<td>3. 13.55 ± 0.42</td>
<td>3. 13.23 ± 0.30</td>
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<td>3. 13.38 ± 0.51</td>
<td>3. 12.82 ± 0.60</td>
<td>3. 12.42 ± 0.50</td>
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<td>Mean power (W)</td>
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<tr>
<td>1. 889.03 ± 32.50</td>
<td>1. 875.86 ± 27.34</td>
<td>1. 894.11 ± 26.74</td>
<td>1. 895.51 ± 23.24</td>
<td>1. 861.11 ± 32.91</td>
<td>1. 824.18 ± 31.87</td>
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<tr>
<td>2. 833.47 ± 30.39</td>
<td>2. 834.21 ± 25.71</td>
<td>2. 839.75 ± 28.68</td>
<td>2. 830.19 ± 26.20</td>
<td>2. 806.41 ± 33.20</td>
<td>2. 785.19 ± 33.91</td>
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<tr>
<td>3. 797.61 ± 29.65</td>
<td>3. 784.50 ± 23.76</td>
<td>3. 788.09 ± 32.46</td>
<td>3. 779.29 ± 29.13</td>
<td>3. 761.80 ± 35.31</td>
<td>3. 746.09 ± 32.86</td>
<td></td>
</tr>
<tr>
<td>Mean power (W.kg$^{-1}$)</td>
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<tr>
<td>1. 11.88 ± 0.35</td>
<td>1. 11.67 ± 0.28</td>
<td>1. 12.11 ± 0.34</td>
<td>1. 12.01 ± 0.27</td>
<td>1. 11.53 ± 0.40</td>
<td>1. 10.98 ± 0.33</td>
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<td>2. 11.14 ± 0.33</td>
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<td>2. 11.36 ± 0.33</td>
<td>2. 11.06 ± 0.30</td>
<td>2. 10.79 ± 0.40</td>
<td>2. 10.47 ± 0.35</td>
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<tr>
<td>3. 10.67 ± 0.34</td>
<td>3. 10.46 ± 0.25</td>
<td>3. 10.65 ± 0.38</td>
<td>3. 10.39 ± 0.34</td>
<td>3. 10.19 ± 0.43</td>
<td>3. 9.96 ± 0.40</td>
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</tbody>
</table>
4.4 RESULTS

4.4.1 Sprint performance
Cadence and power output were used as indices of sprint performance. Values obtained during each sprint, and within each exercise condition, are displayed in Table 4.1.

4.4.1.1 Cadence
Consistent with a normal response to maximal cycling, cadence reached peak values after approximately 5 seconds, and then progressively declined (Figure 4.2). There was no significant interaction between exercise condition and sprint (Figure 4.3). However, there was a significant main effect for exercise condition \((P<0.05)\), where cadence was lower following the highest workloads compared to control and several other exercise conditions (Figure 4.4A). This suggests that fatigue was greater following the 70% and 80% conditions. As expected, there was also a significant main effect for sprint \((P<0.05)\). On average, higher cadences were achieved during the first sprint (Figure 4.4B), indicating that a period of 50 seconds was insufficient to allow full recovery between sprints.

4.4.1.2 Power output
Accordingly, power output decreased over time, with the highest values obtained within the first 3 seconds of each sprint (Figure 4.5). Since power output is influenced by cadence, it was not surprising that there were also significant main effects for exercise condition and sprint \((P<0.05)\). Specifically, mean power output was reduced by 3.6% and 6.5% following exercise at 70% and 80% of peak oxygen uptake, respectively (Figure 4.6A). Compared to the initial sprint, mean power was reduced by 6% and 11.2% for the second and third sprints, respectively (Figure 4.6B). It is likely that this decrease in power was due to previous high intensity fatiguing exercise, with limited recovery following treadmill exercise, and between sprints. However, there was no significant interaction between exercise condition and sprint (Figure 4.7). Furthermore, peak power output was not influenced by exercise condition and sprint (Figure 4.8), nor was there a significant main effect for exercise condition (Figure 4.9). However, a higher peak power output was achieved during the first sprint compared to the second and third sprints \((P<0.05)\) (Figure 4.10).

Mean power output was also expressed relative to body mass. There was no significant interaction between the independent variables with reference to mean power (Figure 4.11). However, lower values were observed following the higher intensity conditions, and there
Figure 4.2: Cadence during 3 x 10-second maximal sprints on a cycle ergometer. Sprints were performed during control measurements —, and 30 seconds following treadmill exercise at 30 —, 50 —, 60 —, 70 —, and 80% — of peak oxygen uptake. Means are plotted at one second intervals (N=11).
Figure 4.3: Cadence measured at control, and following loaded treadmill exercise at 30, 50, 60, 70, or 80% of peak oxygen uptake. Lines represent the first —, second —, and third — sprints on a cycle ergometer. Values are means with standard errors of the means ($N=11$, $P>0.05$).
Figure 4.4: Cadence with reference to exercise condition (A), and sprint (B). Letters in lower case indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference. Values are means of all sprints (A), or conditions (B), with standard errors of the means ($N=11$).
Figure 4.5: Power output during 3 x 10-second maximal sprints on a cycle ergometer. Sprints were performed during control measurements (—), and 30 seconds following treadmill exercise at 30, 50, 60, 70, and 80% of peak oxygen uptake. Means are plotted at one second intervals (N=11).
Figure 4.6: Mean power output with reference to exercise condition (A), and sprint (B). Letters in lower case indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference. Values are means of all sprints (A), or conditions (B), with standard errors of the means ($N=11$).
Figure 4.7: Mean power output for control, and following loaded treadmill exercise at 30, 50, 60, 70, or 80% of peak oxygen uptake. Lines represent the first, second, and third sprints on a cycle ergometer. Values are means with standard errors of the means (N=11, P>0.05).
Figure 4.8: Peak power (A) and relative peak power (B) for control, and following loaded treadmill exercise at 30, 50, 60, 70, or 80% of peak oxygen uptake. Lines represent the first, second, and third sprints on a cycle ergometer. Values are means with standard errors of the means ($N=11$, $P>0.05$).
Figure 4.9: Absolute (A), and relative (B) peak power output with reference to exercise condition. Values are means of all sprints with standard errors of the means ($N=11$, $P>0.05$).
Figure 4.10: Absolute (A) and relative (B) peak power output independent of exercise condition during the first, second, and third sprints. Letters in lower case indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference. Values are means of all conditions with standard errors of the means.
Figure 4.11: Relative mean power output at control, and following loaded treadmill exercise at 30, 50, 60, 70, or 80% of peak oxygen uptake. Lines represent the first —, second —, and third — sprints on a cycle ergometer. Values are means with standard errors of the means ($N=11$, $P>0.05$).
was a decrease with each sprint (Figure 4.12). These findings suggest that sprint performance is reduced when it is preceded by whole-body exercise with a load, and this will be influenced by the intensity of previous work. Furthermore, performance seems to progressively decline with each sprint, which may be related to insufficient recovery between sprints.

4.4.1.3 Performance decrement
The performance decrement was the change in sprint performance, and therefore was an indication of fatigue. Values relating to cadence, peak power output, and mean power output are displayed in Table 4.2. It appeared that performance declined with increasing intensity of previous activity as demonstrated by higher values. Despite this, the only significant difference was between the 50 and 80% exercise conditions for mean power. Therefore, the same peak power was achieved, however subjects were unable to maintain this following high intensity work. Furthermore, since mean power was reduced, it is likely that subjects experienced a greater level of fatigue following the 80% condition. Assuming that subjects were exposed to relatively high power outputs on the treadmill during this condition, it is likely that the level of phosphocreatine within the muscle was reduced, which may explain the reduced performance on the cycle ergometer.

4.4.1.4 Individual differences in sprint performance
Approximately 50% of subjects were capable of completing the 70% exercise condition. Therefore, it was appropriate to compare the performances of these individuals with those who exercised until exhaustion, as it may provide an insight as to why some were better performers than others. Six subjects were capable of completing the 70% condition (Group 1), and the remaining five subjects became exhausted before completing 5 km (Group 2). Performances for these groups are displayed in Tables 4.3 and 4.4. There were no significant differences between groups for any of the performance measures. Despite this, Group 2 displayed lower values for all measures of sprint performance. This suggests that performing exhaustive work may affect the performance of subsequent high intensity exercise.

The recovery of peak power was 94.49 ± 2.03, 96.97 ± 1.88, 94.51 ± 2.82, 92.80 ± 2.21, 93.38 ± 1.67, and 92.55 ± 1.91% for control, and the 30, 50, 60, 70, and 80% exercise conditions, respectively. There were no significant differences compared to control, or between conditions for the recovery of peak power. These values confirm that peak power is
Figure 4.12: Relative mean power output with reference to exercise condition (A), and sprint (B). Letters in lower case indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference. Values are means of all sprints (A), or conditions (B), with standard errors of the means ($N=11$).
Table 4.2: Indices of fatigue during control sprints, and following each exercise condition (30, 50, 60, 70, and 80% of peak oxygen uptake). Values for power decrement are means and standard errors of the means, and were calculated using all three sprints (N=11). * = P<0.05 vs. 50%.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>30</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence decrement (%)</td>
<td>5.47 ± 0.90</td>
<td>6.31 ± 1.56</td>
<td>5.63 ± 1.81</td>
<td>5.41 ± 2.16</td>
<td>8.09 ± 3.21</td>
<td>10.04 ± 2.17</td>
</tr>
<tr>
<td>Peak power decrement (%)</td>
<td>6.59 ± 1.14</td>
<td>7.56 ± 2.43</td>
<td>6.51 ± 2.69</td>
<td>5.84 ± 3.40</td>
<td>8.93 ± 4.32</td>
<td>11.58 ± 3.43</td>
</tr>
<tr>
<td>Mean power decrement (%)</td>
<td>6.48 ± 1.17</td>
<td>7.13 ± 2.03</td>
<td>6.20 ± 2.21</td>
<td>6.60 ± 2.54</td>
<td>9.36 ± 3.60</td>
<td>12.37 ± 2.57 *</td>
</tr>
</tbody>
</table>
Table 4.3: Subjects were divided into those who were able to complete 5 km during the 70% condition (Group 1), and those who were not (Group 2). No significant differences were observed between groups for any variable ($P>0.05$). Values are means of all sprints for control condition.

<table>
<thead>
<tr>
<th>Group 1 (N=6)</th>
<th>Cadence (r.min$^{-1}$)</th>
<th>Peak power (W)</th>
<th>Peak power (W.kg$^{-1}$)</th>
<th>Mean power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4</td>
<td>119.53</td>
<td>841.59</td>
<td>12.75</td>
<td>713.31</td>
</tr>
<tr>
<td>S5</td>
<td>125.87</td>
<td>1120.76</td>
<td>14.37</td>
<td>871.73</td>
</tr>
<tr>
<td>S6</td>
<td>131.07</td>
<td>1181.27</td>
<td>14.58</td>
<td>961.17</td>
</tr>
<tr>
<td>S8</td>
<td>119.23</td>
<td>1103.23</td>
<td>13.13</td>
<td>928.92</td>
</tr>
<tr>
<td>S10</td>
<td>139.63</td>
<td>1216.17</td>
<td>16.89</td>
<td>864.18</td>
</tr>
<tr>
<td>S13</td>
<td>136.13</td>
<td>1086.77</td>
<td>15.53</td>
<td>875.87</td>
</tr>
<tr>
<td>Mean</td>
<td>128.60</td>
<td>1092</td>
<td>14.54</td>
<td>869.20</td>
</tr>
<tr>
<td>S.D.</td>
<td>8.51</td>
<td>132.00</td>
<td>1.53</td>
<td>85.33</td>
</tr>
<tr>
<td>S.E.M</td>
<td>3.47</td>
<td>53.87</td>
<td>0.62</td>
<td>34.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group 2 (N=5)</th>
<th>Cadence (r.min$^{-1}$)</th>
<th>Peak power (W)</th>
<th>Peak power (W.kg$^{-1}$)</th>
<th>Mean power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>111.67</td>
<td>839.36</td>
<td>12.91</td>
<td>654.05</td>
</tr>
<tr>
<td>S2</td>
<td>128.23</td>
<td>1146.44</td>
<td>15.29</td>
<td>884.15</td>
</tr>
<tr>
<td>S3</td>
<td>114.50</td>
<td>977.78</td>
<td>12.53</td>
<td>795.14</td>
</tr>
<tr>
<td>S11</td>
<td>118.17</td>
<td>1099.20</td>
<td>14.09</td>
<td>914.09</td>
</tr>
<tr>
<td>S12</td>
<td>122.00</td>
<td>1129.95</td>
<td>13.55</td>
<td>777.80</td>
</tr>
<tr>
<td>Mean</td>
<td>118.90</td>
<td>1039</td>
<td>13.67</td>
<td>805.00</td>
</tr>
<tr>
<td>S.D.</td>
<td>6.50</td>
<td>129.50</td>
<td>1.08</td>
<td>102.20</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>2.91</td>
<td>57.90</td>
<td>0.48</td>
<td>45.71</td>
</tr>
<tr>
<td>Difference to Group 3 (%)</td>
<td>-7.54</td>
<td>-4.85</td>
<td>-5.98</td>
<td>-7.39</td>
</tr>
</tbody>
</table>
Table 4.4: Subjects were divided into those who were able to complete 5 km during the 70% condition (Group 1), and those who were not (Group 2). No significant differences were observed between groups for any variable ($P>0.05$). Values are means of all sprints for 70% exercise condition.

<table>
<thead>
<tr>
<th>Group 1 (N=6)</th>
<th>Cadence (r.min$^{-1}$)</th>
<th>Peak power (W)</th>
<th>Peak power (W.kg$^{-1}$)</th>
<th>Mean power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4</td>
<td>130.67</td>
<td>996.52</td>
<td>15.10</td>
<td>794.54</td>
</tr>
<tr>
<td>S5</td>
<td>97.30</td>
<td>873.91</td>
<td>10.92</td>
<td>675.99</td>
</tr>
<tr>
<td>S6</td>
<td>138.90</td>
<td>1309.16</td>
<td>16.36</td>
<td>1014.60</td>
</tr>
<tr>
<td>S8</td>
<td>110.37</td>
<td>995.64</td>
<td>11.58</td>
<td>863.69</td>
</tr>
<tr>
<td>S10</td>
<td>134.47</td>
<td>1220.61</td>
<td>16.95</td>
<td>927.65</td>
</tr>
<tr>
<td>S13</td>
<td>126.93</td>
<td>956.95</td>
<td>13.67</td>
<td>820.85</td>
</tr>
<tr>
<td>Mean</td>
<td>123.1</td>
<td>1059</td>
<td>14.10</td>
<td>849.60</td>
</tr>
<tr>
<td>S.D.</td>
<td>15.99</td>
<td>168.10</td>
<td>2.49</td>
<td>116.20</td>
</tr>
<tr>
<td>S.E.M</td>
<td>6.53</td>
<td>68.63</td>
<td>1.02</td>
<td>47.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group 2 (N=5)</th>
<th>Cadence (r.min$^{-1}$)</th>
<th>Peak power (W)</th>
<th>Peak power (W.kg$^{-1}$)</th>
<th>Mean power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>115.00</td>
<td>888.88</td>
<td>13.47</td>
<td>666.43</td>
</tr>
<tr>
<td>S2</td>
<td>102.53</td>
<td>803.17</td>
<td>10.71</td>
<td>685.00</td>
</tr>
<tr>
<td>S3</td>
<td>119.13</td>
<td>1037.15</td>
<td>13.30</td>
<td>828.02</td>
</tr>
<tr>
<td>S11</td>
<td>121.50</td>
<td>1022.62</td>
<td>13.82</td>
<td>852.35</td>
</tr>
<tr>
<td>S12</td>
<td>127.80</td>
<td>1134.41</td>
<td>14.18</td>
<td>778.36</td>
</tr>
<tr>
<td>Mean</td>
<td>117.20</td>
<td>977.20</td>
<td>13.09</td>
<td>762.00</td>
</tr>
<tr>
<td>S.D.</td>
<td>9.42</td>
<td>130.80</td>
<td>1.38</td>
<td>83.44</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>4.21</td>
<td>58.51</td>
<td>0.62</td>
<td>37.32</td>
</tr>
<tr>
<td>Difference to Group 3 (%)</td>
<td>-4.79</td>
<td>-7.72</td>
<td>-7.16</td>
<td>-10.31</td>
</tr>
</tbody>
</table>
reduced during repetitive sprinting, and suggest that prior activity does not influence the magnitude of this decline. In addition, there were significant correlations between the recovery of peak power and peak oxygen uptake (Figure 4.13). However, these were only statistically significant for control sprints and the 30% exercise condition \((P<0.05)\). Similar to peak power, the recovery of mean power was not different between conditions, nor was there a difference compared to control. Respectively, values were 94.00 ± 2.12, 95.37 ± 1.26, 93.96 ± 1.61, 92.21 ± 1.82, 93.74 ± 1.91, and 95.54 ± 2.82% for control up to the 80% exercise condition. Peak oxygen uptake was also significantly correlated with mean power recovery. However, this was only observed for the control condition (Figure 4.13). The findings relating to peak power recovery and mean power recovery, suggest that peak oxygen uptake is important in the recovery period between repetitive high intensity work. This may be related to the contribution of the aerobic energy system during periods of recovery. Furthermore, aerobic metabolism may be increased during the work periods of repetitive exercise. However, we can only suggest this since oxygen consumption was not measured during the sprints.

4.5 DISCUSSION
The aim of this study was to quantify the physical demands of repetitive high intensity exercise, which was preceded by load carriage across a variety of intensities. In addition, the purpose of this experiment was to determine if load carriage affects the performance of subsequent high intensity exercise. There were several findings from this study relating to exercise performance. Firstly, there was no significant interaction between exercise condition and sprint, with regards to measures of performance. Secondly, sprint performance declined following load carriage, and this seemed to be a function of the intensity of previous work, and the repetitive nature of subsequent exercise.

It was our intention to determine the effect of a load carriage task on the performance of high intensity running, as these reflect common tasks performed within the military. For example, load carriage is performed during a pack march, and if soldiers come under attack in the field, they may sprint to obtain cover. Due to the unpredictable nature of this occupation, soldiers may be required to perform high intensity work following a previous task. Therefore, we combined these two activities in this study. However, for this experiment to be valid, we must demonstrate that high intensity sprinting on a cycle ergometer is a good representation of running performance. Cycle ergometry was the preferred exercise mode as it would allow the
Figure 4.13: Relationship between power recovery during repetitive sprinting, and peak oxygen consumption. Significant correlations were observed for peak power for control ($N=11$, $r^2=0.42$, $P<0.05$), and the 30% condition ($N=11$, $r^2=0.54$, $P<0.05$). There was a significant correlation for mean power during control only ($N=11$, $r^2=0.52$, $P<0.05$).
experiments to be conducted in a controlled laboratory environment. Thus, we performed a pilot study which compared the results of 3 x 10-second sprints on a cycle ergometer and 10 x 20-metre sprints in the field. As previously mentioned, sprints on the ergometer were separated by 50 seconds. In contrast, sprints in the field were separated by 20 seconds. There was a correlation between the performances of these exercise modes (Table 4.5), suggesting that running performance may be predicted by high intensity sprints on a cycle ergometer. This is consistent with previous research (Baker et al., 1993; Bar-Or & In-Bar, 1978).

4.5.1 Sprint performance
The decline in power output with time, and between subsequent bouts of exercise is an expected response, and is consistent with previous findings (Ball et al., 1999; Bogdanis et al., 1996; McCartney et al., 1986; Sargeant & Dolan, 1987). The physiological mechanisms underlying this reduction in performance have long been debated, with a variety of factors suggested as being responsible. Consequently, the focus of this discussion will centre on two commonly reported limitations to high intensity, short duration exercise. These relate to energy supply, and neuromuscular factors.

4.5.1.1 Energy supply
It is now widely accepted that the energy supply for short-duration, high intensity exercise is derived from immediate sources of adenosine triphosphate (Hultman et al., 1967; Karlsson et al., 1971; Karlsson & Saltin, 1970). These sources are depleted quickly, allowing maximal exercise for only a few seconds. Thus, for exercise to be sustained, adenosine triphosphate must be resynthesised. This may occur in several different ways, and is made possible by phosphocreatine (Hultman et al., 1967). The result is that high intensity muscular work may continue for up to approximately 10 seconds. This also represents the point at which phosphocreatine stores are depleted (Jacobs et al., 1983; Jones et al., 1985). The decrease in power output during high intensity exercise occurs in parallel with a reduction in available phosphocreatine (Bogdanis et al., 1996; McCartney et al., 1986). Furthermore, other factors such as inorganic phosphate seem to play a role in skeletal muscle fatigue. For instance, there is evidence that inorganic phosphate interferes with cross-bridge function and reduces myofibrillar calcium sensitivity (Millar & Homsher, 1990; Takagi et al., 2004). However, there are many factors which may contribute to muscular fatigue (Allen et al., 2008), and these are beyond the scope of this discussion.
**Table 4.5:** Correlations between performance measures during 10 x 20-metre running sprints with 20 seconds of recovery (Run), 3 x 10-second sprints on a cycle ergometer with 50 seconds of recovery (3x10), and a 30-second sprint on a cycle ergometer (WAnT). Values are coefficients of determination ($r^2$), and were all significant ($P<0.05$).

<table>
<thead>
<tr>
<th>Exercise mode</th>
<th>Total power (W.kg$^{-1}$) vs. total sprint time (sec)</th>
<th>Mean power (W.kg$^{-1}$) vs. mean sprint time (sec)</th>
<th>Peak power (W.kg$^{-1}$) vs. fastest sprint time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run vs. WAnT</td>
<td>0.85</td>
<td>0.85</td>
<td>0.77</td>
</tr>
<tr>
<td>Run vs. 3x10</td>
<td>0.87</td>
<td>0.87</td>
<td>0.84</td>
</tr>
<tr>
<td>WAnT vs. 3x10</td>
<td>0.94</td>
<td>0.94</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Although biochemical analyses were not performed in the present study, we can assume with confidence that the decrease in power output which was observed, was due to rapidly declining levels of phosphocreatine. Furthermore, repetitive high intensity work places further demand on this energy system, considering that the ability to reproduce the same performance is dependent on the recovery period. For instance, even with recovery periods of up to 4 minutes, phosphocreatine levels will only recover to approximately 80% of resting values (Bogdanis et al., 1996). Indeed, there were modest periods of work in the current study. However, exercise was maximal, and recovery was limited to only 50 seconds. It is unlikely that this would have been adequate to restore phosphocreatine to pre-exercise levels.

Although immediate sources of adenosine triphosphate and phosphocreatine supply energy for single bouts of short duration, high intensity work, there is an increasing contribution of aerobic metabolism when this work is prolonged, and repetitive. Accordingly, this occurs in conjunction with a reduction in anaerobic metabolism, such as glycolysis and glycogenolysis (Bogdanis et al., 1996, Spriet et al., 1989). Furthermore, oxygen consumption is significantly increased during the recovery period following high intensity work, suggesting that aerobic fitness may be important during this period. In addition, high intensity, intermittent exercise has been recommended as a training regime to increase aerobic fitness (Rodas et al., 2000). This may be beneficial where reduced training volumes are sought without compromising training adaptations. Due to the nature of our exercise protocol, we are confident that elevations in oxygen consumption during recovery periods, and with subsequent bouts of exercise, would have occurred.

It is logical that high aerobic fitness would be desirable when this form of work must be performed. For instance, there is evidence that the recovery of peak power during repetitive sprinting is associated with measures of endurance performance (Bogdanis et al., 1996). This was observed in the present study, with regards to the recovery of mean power during control sprints (Figure 4.13), and is in agreement with our second hypothesis which stated that the recovery of sprint performance will be correlated with peak oxygen uptake. Similar results were observed for the recovery of peak power, with significant correlations during control and the 30% exercise condition (Figure 4.13). Thus, a high peak oxygen uptake may enhance the recovery of brief tasks which are physically demanding, and repetitive in nature. This will allow for subsequent bouts of exercise with minimal variation in performance. However, this
should be interpreted with caution, as in some cases, less than 50% of the variation in recovery could be explained by peak oxygen uptake (Figure 4.13). To our surprise, peak oxygen uptake was unable to explain differences in the recovery of power when a prior task was performed, at least during exercise beyond 30% of peak oxygen uptake. Therefore, there is some underlying mechanism whereby previous activity interferes with the performance of subsequent work.

During the present study, previous activity affected the performance of subsequent high intensity work. Furthermore, the reductions in power appeared to be more severe when the previous activity was beyond 60% of peak oxygen uptake. These results are consistent with our first hypothesis, and with previous findings (Capelli et al., 1993; Ferretti et al., 1987; Hitchcock, 1989; Margaria et al., 1971; Sargeant & Dolan, 1987). Indeed, it is likely that the reduction in sprint performance is related to phosphocreatine availability. It has been shown that previous exercise reduces phosphocreatine stores, and the degree of depletion is related to the intensity of prior activity (Hultman et al., 1967; Karlsson et al., 1971; Knuttgen & Saltin, 1972). Such high external work rates during the present study would have demanded a high rate of energy production. For instance, the external work rate exceeded 2 kJ.min\(^{-1}\) during the 80% condition, whereas values for the 30% condition were half of this (Figure 4.14). In addition, it is not only the intensity of previous activity which will influence sprint performance. As the duration of exercise increases, so does the decrement in sprint performance (Sargeant & Dolan, 1987). From an applied perspective, our findings relating to prior exercise intensity and sprint performance may assist in providing occupational recommendations. For example, in occupations where repetitive high intensity work is common, limiting previous activity to less than 60% of peak oxygen consumption will ensure that sprint performance is maintained. Indeed, there are tasks within the military and Fire and Rescue services which are physically demanding, repetitive, and are performed following a prior task.

4.5.1.2 Neuromuscular factors

In addition to the above mechanisms concerning energy supply, there is also evidence that the central nervous system may be involved in limiting exercise. For instance, during maximal muscle contractions, force progressively declines and this occurs in conjunction with decreased motor unit recruitment (Bigland-Ritchie et al., 1979; Moritani et al., 1986).
Figure 4.14: External work with reference to exercise condition. Letters in lower case indicate significant differences ($P<0.05$). A different letter indicates a significant difference, whereas like letters indicate no significant difference. Values are means of all sprints with standard errors of the means ($N=11$).
Furthermore, this reduced neuromuscular activity has also been shown to occur during, and following submaximal exercise (Nicol et al., 1991; St Clair Gibson et al., 2001). These findings suggest that fatigue is not caused by a peripheral limitation within the skeletal muscle, but occurs as a result of a central control mechanism. This has been referred to as the “central governor” model of fatigue, and suggests that higher centres within the brain are responsible for coordinating pacing strategies for exercise (St Clair Gibson & Noakes, 2004). The arguments in favour of this mechanism suggest that pacing strategies are set by the central nervous system, such that an appropriate exercise intensity can be maintained without compromising homeostasis (St Clair Gibson & Noakes, 2004). Indeed, there is further evidence in support of the central governor theory. For example, when subjects were requested to perform maximal sprints, submaximal values of perceived exertion were recorded (Kay et al., 2001). This is suggestive of a subconscious pacing strategy, and may ensure that the subject can perform subsequent activity if required. Even when exhausted, subjects in the present study did not report maximal values for perceived exertion (Table 3.9). Thus, since subjects were anticipating further work, a pacing strategy may have been in place.

However, this theory is heavily criticised, and results from other studies are not in agreement with the central governor model. In one particular study, repetitive sprinting lasting 6 seconds on a cycle ergometer was performed, with 30 seconds of recovery (Billaut et al., 2006). This work to rest ratio was similar to the present study. An increase in motor unit recruitment with a concurrent decrease in performance was demonstrated, which has been observed previously (Nummela et al., 1992). Thus, efferent drive from the central nervous system is increasing, ruling out centrally-mediated fatigue. In contrast, others have reported a reduction in central nervous system drive during repetitive sprinting (Racinais et al., 2007). A very similar protocol was utilised, with 10 repeat sprints, 30 seconds of recovery, and each sprint lasting 6 seconds.

Furthermore, it is well appreciated that lactate concentration within the muscle increase significantly during high intensity exercise (Karlsson et al., 1971; Karlsson & Saltin, 1970; Knuttgen & Saltin, 1972). As a result, the concentration of hydrogen ions may influence the binding potential of calcium to troponin (Blanchard & Solaro, 1984; Fuchs et al., 1970). Furthermore, others have suggested that the pH affects the affinity of the sarcoplasmic reticulum for calcium (Nakamaru & Schwartz, 1972). Indeed, muscle contraction is
dependent on calcium, so these effects will certainly influence exercise performance. In addition to direct effects on the muscle, metabolic products of muscle contraction stimulate group III and IV afferents within the muscle (Rotto and Kaufman, 1988). This may place an inhibitory effect on the efferent signal, therefore compromising muscle contraction.

4.6 CONCLUSION
In accordance with the literature, we are confident that sprint performance was reduced due to declining levels of phosphocreatine. In addition, it seems that sprint performance is not affected when the intensity of prior activity does not exceed 60% of peak oxygen uptake. In contrast, the ability to perform repetitive maximal work is significantly reduced when the intensity of previous activity exceeds 60% of peak oxygen uptake. Although the performance decrements were not significantly affected, there was a two-fold increase following exercise at 80% of peak oxygen uptake compared to the 30% exercise condition. In addition, since our findings are similar to those when prior exercise did not involve load carriage, we conclude that load carriage does not affect the performance of subsequent high intensity exercise.

It was not our intention to measure muscle electrical activity or products of metabolism in the present study. Therefore, we can only speculate that high intensity exercise performance was affected by the aforementioned mechanisms. Based on our findings, there are two recommendations. Firstly, when repetitive high intensity work follows load carriage, the intensity of load carriage should not exceed 60% of peak oxygen consumption. Secondly, due to the relationship between the recovery of power and peak oxygen uptake, the latter may assist in the recovery of repetitive maximal work, so long as no prior exercise is performed which exceeds 30% of peak oxygen uptake.
4.7 REFERENCES


