DETERMINATION OF A TOTAL BODY MODEL OF EFFICIENCY APPLIED TO A ROWING MOVEMENT IN HUMANS

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ABSTRACT

Efficiency represents the ratio of work done to energy expended. In human movement, it is desirable to maximise the work done or minimise the energy expenditure. Whilst research has examined the efficiency of human movement for the lower and upper body, there is a paucity of research which considers the efficiency of a total body movement. Rowing is a movement which encompasses all parts of the body to generate locomotion and is a useful modality to measure total body efficiency. It was the aim of this research to develop a total body model of efficiency and explore how skill level of participants and assumptions of the modelling process affected the efficiency estimates

Three studies were used to develop and evaluate the efficiency model. Firstly, the efficiency of ten healthy males was established using rowing, cycling and arm cranking. The model included internal work from motion capture and efficiency estimates were comparable to published literature, indicating the suitability of the model to estimate efficiency. Secondly, the model was developed to include a multi-segmented trunk and twelve novice and twelve skilled participants were assessed for efficiency. Whilst the efficiency estimates were similar to published results, novice participants were assessed as more efficient. Issues such as the unique physiology of trained rowers and a lack of energy transfers in the model were considered contributing factors. Finally the model was redeveloped to account for energy transfers, where skilled participants had higher efficiency at large workloads.

This work presents a novel model for estimating efficiency during a rowing motion. The specific inclusion of energy transfers expands previous knowledge of internal work and efficiency, demonstrating a need to include energy transfers in the assessment of efficiency of a total body action.

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I would like to dedicate this work to my dad, whose unique philosophy still is with me today.

Most of all, to Mel, Connor and Aidan. You are my 0,0,0.

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CHAPTER 1: INTRODUCTION

Sport performance, physical activity and activities of daily living all require muscular force in order to achieve a specific outcome. The muscular activity required has an energetic cost for the work done, and it is often desirable to improve movement efficiency; that is to minimise the cost of a task or to achieve more work for the same energetic cost (Zelik and Kuo, 2012). Mechanical efficiency is the ratio of work accomplished for the amount of energy expended (Equation 1.1, Winter, 2005).

$$Efficiency = \frac{workdone}{energyexpenditure} \tag{1.1}$$

Efficiency can be used to evaluate how well movements are carried out and assess the effect of changes to movement patterns, for example performing more work or greater speed (de Groot *et al.*, 2002). Improvements in technique or physical fitness will potentially enhance efficiency and improve performance (Cavanagh and Kram, 1985b; Purkiss and Robertson, 2003). For example, a small change in efficiency (≈1%) during a modelled 40km cycling time trial caused a large change (≈60seconds) in performance (Moseley and Jeukendrup, 2001).

Assessment of efficiency requires the measurement of energy expenditure and work done. Energy expenditure is commonly assessed via indirect calorimetry and the energy cost for a given work load is derived (Robergs *et al.*, 2010). Quantifying metabolic energy expenditure provides information about the performance of the physical activity (Bechard *et al.*, 2009). Whilst energy expenditure is reasonably straightforward to assess, work done is more complex. Work done is considered as the sum of external work; that is, the work done by the centre of mass on the environment, and internal work, the movement of the limbs relative to the centre of mass (Saibene and Minetti, 2003). Total work has been assessed via force plates, but this approach is limited to activities with ground contact (Zastsiorsky, 2000). Alternative measures of work have included ergometers (Ettema and Loras, 2009) and the use of 3D motion capture (Saibene and Minetti, 2003). Energy expenditure has been used as an indicator of movement skill and coordination (Lay *et al*., 2002), but Purkiss and Robertson (2003) suggested internal work is the main biomechanical discriminator of performance, indicating the importance of assessing this quantity. It is unclear whether biomechanics alter energy cost or energy cost alters biomechanics (Kram, 2011).

Whilst there is general agreement that efficiency is as represented in equation 1.1, what specifically constitutes work done and energy expenditure has been viewed in different ways and resulted in varied calculations of efficiency such as gross, net, work and delta efficiency (Cavanagh and Kram, 1985a). Some of these approaches have received criticism for not considering the mechanical basis of internal work (Kram, 2011), ignoring the possibility of energy transfer (Caldwell and Forrester, 1992) or inappropriate energy estimations (Ettema and Loras, 2009). Modifications have been made to energy expenditure including subtracting resting energy expenditure (net efficiency) and energy expenditure during an unloaded action (work efficiency), as well as delta efficiency (Gasser and Brooks, 1975; Stainsby *et al*., 1980). Furthermore, it is suggested that many calculations of internal work do not allow for transfer of energy within or between segments, questioning the biomechanical and physiological specificity of the calculation (Caldwell and Forrester, 1992; Martindale and Robertson, 1984). This assumes that all work has a metabolic cost, which erroneously influences the data (Williams and Cavanagh, 1985).

Efficiency has been most extensively studied during leg-only activities such as cycling and running (Bijker *et al*., 2001; Sidossis *et al*., 1992), or arm-only activity such as arm cranking (Goosey-Tolfrey and Sindall, 2007). There has been less research considering the body working as a total body, such as rowing (Fukunaga *et al*., 1986) or cross country skiing (Nakai and Ito, 2011). Gross and net efficiency have been suggested to increase with respect to exercise (Cavanagh and Kram, 1985a) or to be and inverted 'u' shaped (Zelik and Kuo, 2012), although there is little consensus. There is equivocal research indicating no change in efficiency with increased skill levels (Moseley *et al*., 2004) or increase due to training (Hopker *et al* ., 2009). However, there is a paucity of studies that have considered these issues using a total body action.

Rowing is considered an activity that incorporates the total body (trunk, upper and lower limbs) in a coordinated action (Shephard, 1998; Soper and Hume, 2004). Commonly, an on-water rowing competition occurs over 2000m, where participants could be rowing with a single oar (sweep rowing) in a crew of 2, 4 or 8, or 2 oars (sculling) individually, or in a crew of 2 or 4 (Soper and Hume, 2004). High level performance requires appropriate physiological conditioning to generate the required force output for the duration of the event, as well as, effective technique to transfer the efforts of the rower to propulsion of the boat (Baudouin and Hawkins, 2002).

The force applied to oar by the rower is developed during a cyclical rowing technique, which has periods of high intensity activity (i.e. the drive phase) interspersed by relatively low levels of activity (i.e. the recovery), repeated throughout the event (Soper and Hume, 2004). The effort made by the rower has to overcome the resistant drag of the boat, whilst attempting to maximise the lift mechanics of the oar (Baudouin and Hawkins, 2002). The efficiency of rowing will be determined by the rower, the oar, the water and the boat (Nozaki *et al*., 1993). Each of these points represents a potential loss of efficiency, similar to the description of the efficiency cascade described by Minetti (2004) for swimming. To examine the efficiency of rowing is a complex task due to the many aspects which contribute to performance. Previous research has simplified the process by focussing upon specific elements of total rowing performance.

For logistical reasons, rowers commonly train on rowing ergometers, which simulates the rowing stroke on dry-land. It has been suggested that rowing ergometery can mirror the physiological demands of rowing, but that the technique differs, particularly in terms of the upper limbs and the trunk (Lamb, 1989; Shephard, 1998; Soper and Hume, 2004). Despite these limitations in terms of technique, the use of ergometry is popular within laboratory settings as the environment can be controlled and procedures such as motion capture and electromyography can be applied to gain further understanding of the mechanics of the rowing stroke (Sforza *et al*., 2012; Cerne *et al*., 2013; Ng *et al*., 2013). Application to on-water rowing performance from the results of ergometer based inquiry will have implicit limitations, as issues such as water density and drag (Baudouin and Hawkins, 2002), the interaction of the oar and water (Caplan and Gardner, 2007) and the effective application of effort by the rower (i.e. transmission efficiency, Minetti, 2004), would need to be considered. However the use of an ergometer allows for the simplification of the complete on-water rowing action, providing qualification of actions and subsequent changes of the rower (i.e. the participant) and is the approach used within this thesis.

The overreaching aim of this thesis was to develop a total body model of efficiency to examine a rowing action. Rowing motion requires extension and flexion of the legs, trunk and arms in sequenced action (Shiang and Tsai, 1998). As such, a large muscle mass is active and there are several physiological challenges, particularly in sending enough blood to the work muscles, which is indicative a high physiological demand on the body (Volianitis and Secher, 2009; Kram, 2011) and reflects the demands of whole body movement. To achieve the overarching aims of the programme, the following research objectives were undertaken:

1. Develop an initial total body model of efficiency that incorporated internal work, external work and energy expenditure and test the model by
   (a) examining efficiency for established actions such as cycling and arm-cranking as well as rowing; and
   (b) examining efficiency at different exercise intensities

2. Apply the model to healthy novice and skilled rowers, across increasing exercise intensities

3. Refine the model to account for factors that may influence the calculation of efficiency in a total body model for rowing such as energy transfer

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The ratio of mechanical work and energy required is known as mechanical efficiency Winter, 1979). There is evidence to suggest that humans instinctively attempt to minimise the energetic cost of an activity, maximising efficiency (Zelik and Kuo, 2012). In the run-walk transition, it is demonstrated that an individual's choice to walk or run is influenced by the lowest energy cost (Hreljac *et al.*, 2007). This questions whether the mechanical activity dictates the energy cost or whether the energy cost dictates the mechanical activity. Put another way, does technique alter energy cost or does energy cost alter technique (Kram, 2011)?

A greater knowledge of how metabolic energy and muscle activity are linked will increase understanding of executing movement patterns (Umberger and Rubenson, 2011). It is not possible to measure the energetic cost and muscular output of a single muscle in vivo, hence human movement is commonly considered as a total system (Kram, 2011). Whilst changes due to increasing exercise intensity are identifiable at the total body level, it is difficult to link to a specific muscle (Umberger and Rubenson, 2011; Kram, 2011). Furthermore, only the work done on an object or body can be measured with a great degree of certainty, as it is impossible to determine the role of a single muscle in the work done by the body, to move an external load (Bartlett and Bussey, 2011). However, the net forces used to achieve the result can be estimated using inverse dynamics.

This literature review will consider both the numerator and denominator of the efficiency equation, the role of muscle, energy expenditure, how it changes with activity and how to measure it. The Chapter will then progress to consider mechanical work, both internal and external, and how to quantify work. Finally, the review will consider efficiency generally, i.e. the definition used in previous literature and the results and gaps identified from previous studies.

2.2 Mechanical work, energy and power

2.2.1 Introduction

Classically, work is defined as the distance through which a force is applied or as the measure of energy flow from one body to another (Winter, 2005). Mechanical energy is the ability to do work (i.e. cause motion) at a given instant of time. Work is the energy flow from one body to another. Both of these are measured in joules. Power is the rate of energy flow (i.e. work) and is measured in joules per second (Winter, 2005).

Human movement is achieved through the work done by muscles, against external resistance. The magnitude of work must be equal to or greater than the energy of the object (Winter, 2005). In moving the object the body performs external work against the external resistance (mass of object, fluids, etc.) and internal work must be expended to move individual body segments. Hence, total work done is the sum of external and internal work done.

In muscle, chemical energy is converted to mechanical energy, which is transferred to heat and work, in line with the first and second laws of thermodynamics (Robertson, 2014). Entropy is the energy which is transferred into forms that cannot be used to do work (i.e. heat) hence minimising entropy should lead to performance enhancement. There are implications for work done, as this may signify poor technique, injury or pathology.

The work-energy relationship suggested that changes in muscular force alter the energy in the system (Robertson, 2014). If the muscle exerts more force during an action, *ceteris paribus*, then more work is done and there is a change (increase) in energy (Zatsiorsky, 2002). During muscular activity, if the muscle force is greater than the load, movement occurs and the muscle performs positive work. If the muscular force is less than the load then the muscle will elongate, despite efforts to shorten, this is negative work. It is more difficult to measure negative work than positive work, hence a number of models of efficiency have used an absolute change in work done approach, rather than attempt to calculate a net result (Winter, 1979).

To assess efficiency, appropriate measures of work are required; however, this is not straight forward, as work can be considered internal work or external work and there is disagreement in the literature on what constitutes total work (Zatsiorsky, 1998). By calculating the mechanical work done, greater insight into movement patterns can be obtained as this would potentially explain why and how a movement occurred (Purkiss and Robertson, 2003). This would enhance the understanding of the work to cost ratio. Actions and impairments of a segment of the body could be assessed and modified to reduce the total work done through training and rehabilitation (Detrembleur *et al*., 2003).

2.2.2 Work Done

Mechanical energy at a given point in time is sum of potential (PE), translational (TKE) and rotational energy (RKE) which are determined by position, velocity and mass (Zatsiorsky, 2002). To assess the work done it is necessary to obtain measures of PE, TKE and RKE of the body (internal work) and include any relevant external resistance (external work) such as power output on an ergometer or fluid resistance.

The work of a muscle is used to overcome external resistance (external work) and to move the body segments (internal work). As work done is the product of force and distance, it implies that in order for work to be done there must be displacement, hence isometric muscle actions do not produce work, although they do have an associated energetic cost (Zatsiorsky, 2002). Additionally, if a muscle was passively extended, for example by gravity, then no work is done by the muscle. This highlights the difficulty in assessing work done that includes isometric, eccentric or passive muscular actions (Zatsiorsky 2002; Winter, 2005). Although controversial, mechanical work (total work) is commonly partitioned into external work and internal work. These will now be considered.

2.2.3 External work

External work is an estimation of the mechanical work to raise and accelerate the body centre of mass (CoM), and is the total of the changes in potential and kinetic energy of the body CoM (Saibene and Minetti, 2003; Nardello *et al*., 2011). External work is also considered as work done to objects outside of the body, such as lifting a weight and working against an ergometer (Zatsiorsky, 2002).

The absolute change of energy is considered as external positive work (Willems *et al*., 1995) as an external force is necessary to increase the mechanical energy of body centre of mass, relative to the surrounding environment. To measure external work, the potential energy and the kinetic energy of the body centre of mass is required (Nardello *et al*., 2011) and calculated over a given time period. This results in the movement of the body centre of mass relative to the environment (Thys *et al*., 1996).

The accurate measure of external work is major challenge in assessing efficiency (Ettema and Loras, 2009). External work is regarded as a reliable measure of work done by muscle in activities such as level walking. However due to the storage and reuse of elastic energy in the tendons, the change in energy during activities such as running and downhill walking is not due to the work done by muscles but elastic energy and gravity, respectively (Sabine and Minetti, 2003). Also the roles of positive and negative external work need to be considered. Winter (2005) considered positive work of a muscle as work done during a concentric action, increasing the energy level, whereas negative work of a muscle as work done during an eccentric action opposing movement, decreasing the energy level. Total external work of the centre of mass is the sum of positive and negative external work (Minetti *et al*., 1993).

External work has been calculated from force plate data for walking and crutch gait (Thys *et al*., 1996) and participants with cerebral palsy (van den Hecke *et al*., 2007), based on the methods of Cavagna (1975). If force plate data are unavailable, external work can be calculated from motion capture data by determining the CoM location for each segment and calculating the position of the total body CoM (Saibene and Minetti, 2003) as previous reported in horses (Minetti *et al*., 1999) and older adults (Mian *et al*., 2006). External work has been indicated to be a useful tool for assessing the interventions of 1 to 4 year olds with gait irregularities (Schepens and Detrembluer, 2009). Greater levels of absolute external work have been reported in obese participants compared to non-obese participants during walking (Browning *et al*., 2009). However, in relative terms, there was no significant difference between obese and non-obese participants and Browning *et al*. (2009) concluded that external work was not responsible for the increased metabolic cost of walking. Studies that have only quantified external work may miss the mechanisms that influence an increase in metabolic cost.

Much of the literature has examined the external work of walking, which has a clear displacement relative to the environment (Willems, *et al.*, 1995). In situations where an ergometer, such as a treadmill, stationary cycle or rowing machine is used, no appreciable displacement occurs and as such measuring external work needs to be approached from a different perspective. A number of papers have considered external work to be the power output from an ergometer such as cycling (Widrick *et al.*, 1992). The use of ergometers, particularly cycle ergometers, has been recommended as one of the more effective options, due to high reliability, explaining the popularity of this methodology (Ettema and Loras, 2009). In activities such as walking and cycling there are reciprocal movements of the limbs (i.e. as one arm is raised the other is lowered) hence this does not affect the trajectory of the body centre of mass (Nardello *et al.*, 2011). This would not be true for activities that are symmetrical in nature such as ergometer rowing (Hofmijster *et al.*, 2009). In absence of force plates, ergometer power output or work done is an acceptable alternative for assessing external work (Ettema and Loras, 2009). External work, particularly when considered as ergometer power output, can be analogous to walking, running, cycling or rowing velocity. In sport, the aim would often be to maximise the velocity, hence the higher the external work the more beneficial the action would be.

2.2.4 Internal work

Internal work represents the work associated with movements of the limbs relative to the centre of mass and is the sum of the increases in energy of the body segments relative to the body COM (Saibene and Minetti, 2003). Internal work is calculated from the movement of the body segments and an appropriate inertial data set (Nardello *et al.*, 2011). The mass of each segment is commonly derived from standard tables (i.e. Winter, 1990; de Leva 1996). The energy of a segment is calculated from the potential energy, translational kinetic energy and rotational kinetic energy of the segment's centre of mass relative to the body centre of mass (equation 2.1).

$$E_{seg} = mgh + \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{2.1}$$

Where, m= mass of segment, g= acceleration due to gravity, h= height, v=linear velocity of CoM, I=moment of inertia and ω= angular velocity.

The energy of the body at a point in time would be calculated by summing the values for potential and kinetic energy for each segment included in the body. The internal work done would then be calculated from the change in segment energy over the time period of interest (Caldwell and Forrester, 1992).

Measuring internal work is methodologically more challenging than measuring of external work. From equation 2.1, the change of position and velocity of the centre of mass throughout the motion, needs to be measured. In absence of force plate measurements the use of motion capture technology has been advocated (Nardello *et al.*, 2011). This may suggest threats to ecological validity as it would be laboratory based and often requires the use of an ergometer, but does allow for the control of the data collection. Additionally, an appropriate data set for distributions of segmental mass and rotational characteristics are required (Nardello *et al.*, 2011).

Regardless of the method, it is only possible to measure some of the internal work at any point in time as isometric actions, co-contractions and frictional losses cannot be quantified (Schepens *et al.*, 2004). Furthermore, the issues of energy transfer within and between segments can influence the calculations and are often ignored (Frost *et al.*, 2002). If an ergometer is used, then the potential energy is accounted for within the work done to the ergometer and should not be calculated from motion analysis (Ettema and Loras, 2009). For a multi-link system such as the human body, Konig Theorem states that the total kinetic energy is calculated from two sources: the kinetic energy of the body centre of mass and the kinetic energy of the body segments, relative to the position of the centre of mass (Minetti *et al.*, 2000; Zatsiorsky, 2002). These sources are considered as external work and internal work respectively, and form the basis of calculating total work done (Cavagna and Kaneko, 1977).

There are limited studies that report values of internal work for total body actions. This can be further limited as studies will tend to report the kinetic energy only. Bechard *et al*., (2009) examined the total kinetic energy (translational and rotational) of 28 elite Olympic rowers. Five on-water strokes were video captured (60FPS) at both a low (18-22) and fast (32-40) strokes per minute. The joint landmarks were manually digitised by a single analyst and the anthropometric data were based on de Leva (1996). The peak kinetic energy was 35.3± 17.8 J and 74.3±36.7 J for low and high stroke rate during the drive phase respectively, which gives some indication of the peak internal work during a total body action during a rowing action.

Slawinski *et al*. (2010) examined the segmental kinetic energy of eight elite sprinters executing a sprint start, using a 16 segment body model, 4 x 10 metre sprint starts within a three-dimensional (3D) motion capture volume. The translational and rotation kinetic energy for each segment was calculated using the segmental inertial data set of Dumas *et al*., (2007). The maximum kinetic energy for each segment was; Thigh=91.4 J, Shank=69.1 J, foot = 25.3 J, upper arm=23.3 J, forearm=32.2 J, hand=22.2 J and trunk=258.3 J. Although a different and more explosive movement pattern, compared to rowing, it gives indications of the range of segmental kinetic energy.

Many studies that purport to measure efficiency do not include measures of internal work, instead looking at the ratio of external work to energy expenditure (Goosey-Tolfrey and Sindall, 2007, Lucia *et al*., 2004). Studies that have included internal work often assume that there is no energy transfer either within or between segments. There are a limited number of studies that have considered energy transfers when determining internal work (Caldwell and Forrester, 1992; Martindale and Robertson, 1984). Appropriate quantification of internal work would give information of mechanical differences between performers (Purkiss and Robertson, 2003), developing insight to suggest modifications to movement performance (Cavanagh and Kram, 1985b).

2.2.4.1 Use of motion capture to determine internal work

Three-dimensional motion analysis is considered one of the most appropriate methods of recording where the bones of the body are in space and time (Cappozzo *et al*., 2005). Methods such as electromagnetic tracking systems are wired and can restrict movement, suggesting their use is less suitable (Elliot and Alderson, 2007). Most three-dimensional motion analysis systems track the position of reflective markers, which are placed on the body of the subject, as they move through time and space. The accuracy of the three-dimensional motion analysis systems has been assessed (Ehara *et al*., 1995; Richards, 1999). These studies generally show that the ability to measure the position of a marker in time and space is very accurate (<1mm) providing they are correctly calibrated and used (McGinley *et al*., 2009).

The data on position and time can be used to calculate the position of joint centres and derive further information such as displacements, velocities, accelerations and angles of segments. Minimising errors is a requirement for accurate data and understanding the movement pattern. The use of marker-based three-dimensional motion analysis has been extensively carried out for the lower-body, particularly gait analysis (Rau *et al*., 2000). Many researchers have taken the approaches used in the lower body and used these as the basis for methods and processes to understand the motion of the upper-body (Hill *et al*., 2008). Commonly, the marker set is linked to the manufacturer of the motion capture system. In the absence of force plates, or during actions without ground contact, motion capture is a suitable method to determine internal work done (Aissaoui *et al*., 1996; Saibene and Minetti, 2003). Limitations to marker based protocols can include marker occlusion. Specifically, in actions such as rowing where there is a large degree of trunk flexion and extension, whilst in a sitting position, the anterior pelvic markers can be occluded. Protocols including placing additional markers on the hips (McCelland *et al*., 2010) and the use of a pointer (Cappozzo *et al*., 2005) have been successfully used to limit such issues.

2.2.5 Positive and negative work

A challenge to assessing the work done is that a number of sources of work are very difficult to account for. Positive work is considered synonymous with concentric muscle actions, whereas negative work is considered synonymous with eccentric muscle actions (Winter, 2005). Positive work would increase the energy of a system or segments, where as negative work would decrease the energy of a system or segment (Zatsiorsky, 2002). In activities such as walking, the reciprocal arm and leg are often assumed to cancel out any changes in work done (Willems *et al.*, 1995). DeVita *et al*.,

(2007) suggested that positive work can be considered to be generating mechanical energy whilst negative work was the dissipation of mechanical energy. If the change in segmental energy is calculated from the positional data of a segment, there is no definitive way of knowing if muscles are working concentrically or eccentrically.

Positive work is considered to have a greater energetic cost than negative work, hence some studies have attempted to compensate for this by adjusting for energy expenditure 3:1, for positive and negative work respectively (Frost *et al*., 2002). Additionally assumptions of the same cost for positive and negative work have been made (Winter, 1979), it has been ignored (Martin *et al*., 1993) or mitigated from adjustment due to the nature of the movement (Martindale and Robertson, 1984).

2.2.6 Total work done

The total work done is considered the sum of external and internal work (Minetti, 1993; Willems *et al*., 1995; Thys *et al*., 1996). Total work is the net work done by all the muscles acting upon the system (Zatsiorsky and Gregor, 2000). Co-contractions, isometric actions and absorption of energy in joints and muscle are not accounted for, hence the actual work done may be higher than estimated (Winter, 2005). It is difficult to account for losses of work due to such forces as friction and degradation of energy to heat (Zatsiorsky and Gregor, 2000). As this is not the actual muscle work, it is recommended that this is termed 'apparent work' (Zatsiorsky and Gregor, 2000).

Total work done being the sum of internal and external work, has been criticised by Zatsiorsky (1997) based on the work of Aleshinsky (1986), who suggested that whilst the energy of a system can be represented as the sum of internal and external energy, the analogy to work of a system being the sum of internal and external work is not mechanically sound. In response, Thys *et al*. (1997) indicated that the premise was theoretical but contained assumptions that were unrealistic. They also suggested that the approach derived acceptable results. Zatsiorsky suggested that Thys *et al*'s. (1996) method could not be considered accurate as there is no gold standard to compare against, and questioned their assertion that the results were acceptable by examining an unusual 'comfortable' gait argument where the joint work was of greater magnitude than the general centre of mass. This suggested that there is a difference between the work performed by the body and the work done on the body. Thys *et al*. (1996) countered by suggesting that work of the joints is the sum of internal and external work. They suggested that the issues of energy transfer between segments, co-contractions, the role of stored elastic energy and multi-articular muscle were of greater interest especially as they were common to all approaches. van Ingen Schenau (1998) raised concerns on the use of only using positive work as the mechanical power output as this ignores the contribution of elastic sources to the mechanical work output. van Ingen Schenau (1998) suggested that the negative work done should be included in the denominator of the efficiency equation. It is suggested that there are other sources that are not being considered such as the role of elastic energy as well as the use of positive work only (van Ingen Schenau, 1998; Zatsiorsky, 1998).

Furthermore, Kautz and Neptune (2002) have argued that internal and external work are not independent quantities. By examining cycling they argued that the decreases in energy are not solely due to the negative work of the leg muscles, due to energy being transferred to the cranks.

2.2.7 Summary of Mechanical work

The importance of internal work is highlighted when this can be quantified and compared between individuals or other variables. For a given work rate (e.g. 100w) energy expenditure can tell if one individual requires more or less energy than another individual. Whilst this may be useful and influenced by an number of issues, it does not really address why there are differences. By measuring internal work, the segmental differences between individuals can be compared and this may elucidate the cause of additional internal work and hence so called inefficiencies. There is debate on the independence of internal and external work, and what constitutes total work. To develop the understanding of mechanical work within this thesis, total work will be considered as the sum of internal and external work, and these will be considered independent. These assumptions will be explored as the thesis progresses.

2.3 Mechanical energy transfer and work done

2.3.1 Introduction

The quantification of internal work is suggested as a tool to evaluate the proficiency of a movement (Caldwell and Forrester, 1992), to quantify the mechanical work done, to assess the metabolic cost and to estimate the efficiency of the movement (Norman *et al*., 1985), as a metric to assess technique and examine skill differences (Norman and Komi, 1987; Purkiss and Roberstson, 2003), to determine the contributions of body segments to the motion and estimate the degree of energy transfer within and between segments (Norman and Komi, 1987). In order to achieve this, accurate measures of all elements of efficiency are needed, specifically internal work. Accurate measures of internal work done must include all potential and kinetic energy components, all energy transfers within and between segments and account for positive and negative work by muscle (Winter, 1979, Willems *et al*., 1995).

There are a number of approaches to quantifying internal work based on the assumptions made in the calculations (Caldwell and Forrester, 1992). A key debate in the literature is the existence and function of energy transfer within the body. If energy transfer is not accounted for, then the assumption is that all new work is done by muscle and is supported by an increased metabolic cost, thus affecting efficiency calculations. However it is argued that energy transfer can occur through pendulum, whip or tendon methods without increasing the metabolic cost (Caldwell and Forrester, 1992). Whilst most authors agree that transfer occurs and that not including it is unrepresentative of physiological and biomechanical reality, there is disagreement on the degree of transfers (Williams and Cavanagh, 1985; Frost *et al*., 1997). Furthermore, transfer of energy is suggested to be an important component in skilled performance and has been shown to improve performance (Norman *et al*., 1985; Lees *et al*., 2004). The quantification of energy transferred could be an important factor of performance. Due to the methodology, there are relatively few studies that have quantified internal work and energy transfer for total body movements accounting for the essential components as outlined by Winter (1979). There is a dearth of studies that have used these types of internal work measures to examine efficiency. These studies and approaches will be detailed below.

2.3.2 Measures of internal work done

Studies where the motion of the body's centre of mass was used as a measure of work done have been criticised as that approach ignored the internal work of limb movement, underestimating the work done (Williams, 1985). This is commonplace in studies that have used force plate as a single source of work done (Cavagna, 1977). Ettema and Loras (2009) have indicated that using an ergometer is appropriate as a source of external work. Minetti (1993) indicated that ergometer output included potential energy components of work hence only translation and rotational kinetic energy are collected as internal work, as per Konig Theorem, to avoid double counting potential energy. It has been suggested that the external work, and by extension potential energy, can be underestimated from ergometers (Ettema and Loras, 2009).

The evolution of cine film and video analysis (Widrick *et al.*, 1992), force plates (Willems *et al.*, 1995) and 3D motion capture (Saibene and Minetti, 2009) have allowed for the quantification of internal work by calculating the displacement and velocities of the segmental centres of mass, deriving estimates for internal work that can be summed to external work as total mechanical work. It is argued that work done calculated from the net moments of force at each joint is a more accurate method than changes in mechanical energy, but these methods require force measurement, (i.e. force plate) and are not appropriate where there is no ground contact such as rowing (Robertson, 2014). In order to determine internal work, the instantaneous value of potential, translational kinetic and rotational kinetic energy is required, necessitating a protocol that uses force plates or motion capture with body segment parameter (BSP) data. Protocols that use external work from ergometers as potential energy, do not allow the instantaneous measures required, hence the more complicated methodology (Ettama and Loras, 2009). Force plates are useful in activities that have ground contact and have been used for running and walking. Protocols that have used cycling or total body models such as cross-country skiing (Norman *et al.*, 1985; Norman and Komi 1987) or rowing (Martindale and Robertson, 1984) have used motion capture protocols.

2.3.3 Internal work and energy transfer

A number of studies that quantified internal work have not accounted for energy transfer within their calculations, assuming all work done has a metabolic cost (Caldwell and Forrester, 1992). Without accounting for energy transfers, the total work done and efficiency estimations are overestimated. The ability of an individual to transfer energy between segments may be used as an indicator of the quality of technique, suggesting that changes (specifically increases) in segmental energy not being supported by new metabolic energy are a cost saving mechanism of good technique (Norman and Komi, 1987). This indicated that part of an 'efficient' technique is one that transfers energy in order to have a low metabolic cost (Norman and Komi, 1987).

The following section will review the three methods of calculating internal work that include the different assumptions of energy transfer from the literature and will use the nomenclature and equations of Caldwell and Forrester (1992). The methods essentially use the same source data but differ as to when summations of energies occur and the degree of energy transfer they permit.

2.3.4 Work done assuming no energy transfers (Wn)

The absolute change in potential energy (PE), translational kinetic energy (TKE) and rotational kinetic energy (RKE) are calculated separately for each segment from start to finish of the motion of interest. The absolute changes in PE, TKE and RKE are summed for each segment and all segments of interest are then summed together. This typically derives the largest value for internal work of the three methods.

The segments within this method are considered independent from each other, not allowing energy transfer other than by muscular work, and the method is likely to overestimate work done (Caldwell and Forrester, 1992). This method has been commonly termed 'pseudowork' as it is not considered a realistic biomechanical or physiological representation of human motion (Williams and Cavanagh, 1983; Norman *et al.*, 1985). It has been suggested that work done assuming no energy transfer (Wn) should not be used for activities such as running (Williams and Cavanagh, 1983). However, its utility is that it forms the baseline for the evaluation of energy transfer and is therefore commonly calculated (Norman and Komi, 1987).

2.3.5 Work done assuming transfers within segments (Ww)

At each time period during the action, the PE, TKE and RKE are summed and the change in segmental energy (SE) is calculated over the time period for all segments of interest. The absolute change in each segment is calculated and summed with the absolute change of all segments. The instantaneous energy of a segment (PE+TKE+RKE) is calculated and the change over the time period of interest is summed. The change in all segments of interest is summed.

Segment energy is calculated from the instantaneous values of PE, TKE and RKE and allows for exchanges of PE, TKE and RKE within the segment without contribution from muscular activity. There is little debate about this method in the literature, seemingly gaining agreement from authors about what it represents, its limitations and how it is calculated. However, it is not used for estimating efficiency nor is work done assuming transfers within segments (Ww) reported as 'internal work' as the assumptions overestimate the muscular cost of the activity (Williams and Cavanagh, 1983). However, Ww is important in estimating the transfer of energy (Norman and Komi, 1987).

2.3.6 Work done assuming transfers within and between segments (Wwb)

At each time period during the action, the PE, TKE and RKE of a segment are summed. The sum of the total energy of all segments of interest forms the instantaneous total body energy. The absolute change in total body energy across the motion of interest (time) is then calculated.

The calculation of internal work with transfers between all segments was proposed by Winter (1979). There is little disagreement on the theoretical basis of work done assuming transfers within and between segments (Wwb) as there does not appear to be dissenting argument that energy does not transfer both within and between segments, with most research in this area considering Wwb as internal work in preference to Wn or Wwb. There is, however, disagreement as to whether transfer to all segments should be allowed or whether it should be restricted to contiguous segments, which make physiological and mechanical sense (Frost *et al.*, 1997; Frost *et al.*, 2002). Williams and Cavanagh (1983) highlighted the issue of an unlikely transfer between the left foot and right forearm, however this was during gait analysis and is quite different to a total body closed kinetic chain activity such as rowing. This will be explored later.

All methods of internal work start with the same kinematic data but differ in their method of calculation as to when summing and changes are calculated. These different procedures can produce very different estimates of internal work, where Wn produces the largest estimate of internal work and Wwb the smallest, as shown later, and can influence efficiency estimates (Williams and Cavanagh, 1983).

2.3.7 Studies that have included energy transfer in calculation of internal work

Work done assuming no energy transfers (Wn) has been quantified larger than Wwb for walking and running (Caldwell and Forrester, 1992) in a single participant (68 J vs 37 J, 260 J vs 100 J Wn vs Wwb, walking and running respectively). Although not explicitly reported in rowing, Martindale and Robertson (1984) stated the calculated values for Wn were larger than Wwb, specifically Wwb approximated 26 % of the Wn value. Norman *et al*., (1985) reported Wn=1269 J, Ww=998 J, Wwb=383 J for expert skiers and Wn=898 J, Ww=761 J, Wwb=286 J for novice skiers.

In its original conception, Winter (1979) allowed transfers between all segments, regardless of their location to the primary muscles responsible for the action. This received some criticism as to the validity of transfer between non-contiguous segments. Frost *et al*. (1997) used an approach only allowing transfer to adjacent segments of the same limb but not between trunk and limb. Results indicated Wn was greater than Wwb (e.g. 3.95 and 2.14 $W.kg^{-1}$ at 1.34 $m.s^{-1}$ and 11.85 and 8.07 $W.kg^{-1}$ at 2.46 $m.s^{-1}$ for 10-12 year olds). Unfortunately no data were presented comparing the all segment vs restricted segment transfer.

A comparison of five energy transfer methods, examining mechanical work during forefoot and heel strike during running, showed different values per method of calculation (Slavin *et al.,* 1993). Two additional methods of transfer between segments, transfer within and between adjacent segments (WwbAS) and within and between the same limb and trunk (WwbLT) were calculated in addition to Wn, Ww and Wwb (all segments). Within the three Wwb models, WwbAS showed the highest level of work (763 J and 776 J at heel strike and forefoot strike, respectively at ‘fast’ speed), where as WwbLT (54 J and 555 J at heel strike and forefoot strike, respectively at ‘fast’ speed) and Wwb (450 J and 484 J at heel strike and forefoot strike, respectively at ‘fast’ speed) were similar and interchanged positions between conditions.

Whilst there may be an argument for considering the extent of energy transfers between segments, especially non-contiguous segments (i.e. left hand-right foot) there is argument provided that these assumptions might be limited. Winter and Robertson (1978) demonstrated that some of the energy generated at the ankle was transferred to the thigh and trunk during walking. Wells (1988) further demonstrated transfers to non-contiguous segments, when considering bi-articular muscles. Furthermore, it was demonstrated that vertical jump performance improved due to the use of an arm action, where energy generated at the shoulders was transferred to the rest of the body (Lees *et al*., 2004). However, Lees *et al*. (2004) were unable to explain how this energy was used. Although in a vertical direction, a jump is not dissimilar in movement pattern to the drive phase of a rowing action. Lees *et al*. (2004) highlighted the role that the trunk must play in transferring the energy from the arms to the legs.

The assumptions of transfer between non-contiguous segments has argued against transfers between all segments but these studies are limited to running and walking (Williams and Cavanagh, 1983, Slavin *et al*., 1993; Frost *et al*., 1997; Frost *et al*., 2002). However, other research has demonstrated transfer to non-contiguous segments (Winter and Robertson, 1978; Wells, 1988; Lees *et al*., 2004). If a limited model of transfer were used, then it would only be possible to compare to other such models. By using an unrestricted, all-segment transfer method, no assumptions are made and comparison to more research is possible. Specifically, the model used in Martindale and Robertson (1984) used Wwb. Based on the above Wwb without restriction will be adopted as the model for transfer within and between segments. The method of calculation affects the values of mechanical work done. However, it is common to calculated Wn, Wb and Wwb as they can be used to quantify the energy transfer within a motion.

2.3.8 Quantifying energy transfers

With all sources of internal work included, it is possible to estimate the amount of energy transferred within and between segments. A larger energy transfer is considered an indicator of efficient/effective technique as mechanical work is being done without the need for additional metabolic energy (Norman *et al*., 1985; Norman and Komi 1987). In order to estimate the energy transfer, different methodologies have been adopted but that have a common basis; that is, internal work is calculated with no transfers, calculated allowing transfers within a segment and calculated assuming transfers within and between segments (Winter, 1979; Williams, 1983; Norman *et al*., 1985; Norman and Komi 1987; Caldwell and Forrester, 1992; Willems *et al*., 1995). Using these three measures it is possible to calculate the transfer within and between segments, (Winter, 1979; Norman *et al*., 1985; Norman and Komi, 1987).

To quantify the energy transfer within a model, Norman *et al*. (1985) used the commonly calculated levels of mechanical work Wn, Ww and Wwb. These are used to estimate the transfer within (Tw), between (Tb) and total transfer (Twb) and are commonly reported as a percentage of Wn.

$$Tw=Wn-Ww \tag{2.2}$$

$$Tb=Ww-Wwb \tag{2.3}$$

$$Twb=Tw+Tb \tag{2.4}$$

Where Tw = transfer within segments, Tb = transfer between segments and Twb = total transfer within and between, Wn = work done assuming no transfer, Ww = work done assuming energy transfer within segments, Wwb = work done assuming energy transfer within and between segments.

Martindale and Robertson (1984) reported transfer approximating Tw=13 %, Tb=25 % and Twb=38 % at low intensity and 12 %, Tb=20 % and Twb=32 % at high intensity for 4 rowers. Norman *et al*., (1985) reported Tw approximating 26 %, Tb=49 % and Twb=70 % compared to Tw=15 %, Tb=52 % and Twb = 68 % for expert and novice skiers. Using two inclines Norman and Komi (1987) reported transfer approximating Tw=23 %, Tb=49 % and Twb=72 % for level and Tw=18 %, Tb=48 % and Twb=66 % for a 9 % gradient for elite skiers in the top 10 of a world championship race. They further reported transfer approximating Tw=23 %, Tb=49 % and Twb=72 % for level and Tw=20 %, Tb=43 % and Twb=63 % for a 9 % gradient for elite skiers in places 30-60 of a world championship race. This indicated that differences in performance may have been attributable to the level of transfer and this indicated that skill level may be evaluated by the ability to transfer energy, as this would have a lower metabolic cost.

2.3.9 Positive and negative work

Whether work done is considered positive or negative can have an impact on the metabolic cost of the activity. In its simplest form positive work increases the energy levels and can be analogous to a concentric muscle action whereas negative work decreases the energy levels and can be considered similar to eccentric muscle actions (Willems *et al*., 1995). In gait, where the contralateral limbs (if assumed to be symmetrical) cancel out any changes in work done (Willems *et al*., 1995), it is suggested that the cost of the concentric actions is three times more than the eccentric actions (Frost *et al*., 2002). Difficulties in assessing positive and negative work have been avoided by assuming that the cost is the same (Winter, 1979) or not including this issue (Martin *et al*., 1993). Robertson and Winter (1980) suggested that the magnitude and type of transfer was dependent on segment velocity, type of contraction and changes in joint angles. Furthermore, this requires quantification of joint powers, which is complex unless using a force plate. When considering the drive phase of a rowing action, Martindale and Robertson (1984) indicated that concentric muscle actions would be the main contributor and hence negative work would be minimised. They did not include the assessment of positive and negative work within their study.

2.3.10 Total Work

Total work done is considered as the sum of internal and external work. The method described above calculated only internal work so it is necessary to calculate external work in order to form total work. External work is the energy change due to the movement of the centre of mass. In gait studies this is often assessed using data from a force plate. Caldwell and Forrester (1992) suggested that if wind and slippage of the foot are negligible then external work can be ignored for gait studies. Willems *et al*. (1995) indicated that the equal but opposite displacements of the segments during gait does not change the potential energy of the centre of mass of the whole body, but indicated that this may underestimate the work done by active muscle against gravity. Martindale and Robertson (1984) calculated the change in energy of the centre of mass between the start and finish position of the rowing cycle and this was added to the values for internal work. Any intermediate values would cancel out (Robertson, 2014). By inclusion of external work total work can be ascertained.

2.3.11 Energy transfer and calculations of efficiency

There is little research that has attempted to calculate efficiency using the Wwb model of internal work. Willems *et al*. (1995) reported net muscular efficiency of positive work for a range of walking and running speeds accounting from transfer within the lower body. Their efficiency range, interpreted from a graph, was approximately 17 % to 60 %, commenting that this was much higher than the maximum muscular efficiency of 25 %, but argued that their values were enhanced by elastic energy. Frost *et al*. (2002) reported net efficiency range of 40 % to 75 % for 30 children walking and running. Both of these studies examined walking and running but did use internal work that assumed transfers within and between segments, but limited to the lower body. The higher values of efficiency were seen in the running trials, where the displacement of the whole body centre of mass was greater than walking, causing a greater increase in potential energy. Williams and Cavanagh (1983) indicated a range of net efficiency from 35-92 dependant on the assumptions of the calculation model used, concurring with the findings above.

There does not appear to be any data for total body models that have incorporated energy transfer within a total body model. Norman and Komi (1987) collected Wwb and applied the reported metabolic cost for a similar cohort during cross-country skiing to estimate efficiency at 38 %. This is considerably higher than the efficiencies reported by Sandbakk *et al*. (2012) of up to 20 %. However, Sandbakk *et al*. (2012) did not account for energy transfers. There does not appear to be data for the efficiency of rowing using internal work accounting for energy transfers.

2.4 Body segment parameters

2.4.1 Introduction

In order to calculate the kinetics of human motion and inverse dynamics, body segment parameter (BSP) data (segment mass, CoM location and moment of inertia) is required (Cheng *et al.*, 2000; Zatsiorsky, 2002; Rao *et al.*, 2003). To estimate the amount of internal work done, the energy of a segment (between potential energy, transitional kinetic energy and rotational kinetic energy) is measured and converted to work. To calculate the three different energies of a segment the displacement, time, mass, position of centre of mass and moment of inertia is required. Body segment parameters (BSP) data for living participants are estimations hence the minimisation of errors is required. Estimations of error have been made (Pearsall and Costigan, 1999; Durkin and Dowling, 2003; Rao *et al.*, 2006; Damavandi *et al.*, 2009). These studies suggest the need for the most accurate and appropriate BSP estimation. As body mass and moment of inertia approximate the third and fifth power of height respectively, small errors can indicate large changes in BSP (Zatsiorsky, 2002). A number of methods have been used to establish BSP. This section will address the use of data obtained from cadaveric and in vivo populations, the cohort the sample is drawn from, and how the body has been segmented. The broadest distinctions between obtaining BSP are direct measurements from cadavers and indirect methods such as *in vivo* and modelling approaches.

2.4.2 Cadaveric methods

Cadaveric studies whilst direct and to an extent accurate, are dependent upon the dissection protocol and how the body fluids are accounted for (Reid and Jensen, 1990). The data of Dempster (1955) have been widely used but the study used a low number of subjects (n=8), that were all Caucasian, male, older (52-83 years at the time of publication), raising questions of the applicability to other populations (Bartlett and Bussey, 2011). Questions have also been raised as to the storage of the cadavers and there have been suggestions that the cadavers were emaciated to some degree and experienced fluid loss (Reid and Jensen, 1990). The cadavers were born in the late 1800s or early 1900s, when life expectancy, health and dietary condition were very different to current standards. This questions the applicability to contemporary individuals, especially sports participants. The main criticisms of cadaveric studies are that they have low numbers, tend to look at elderly Caucasian male samples and have some differences in the dissection protocols (Reid and Jensen, 1990; Pearsall and Reid, 1996). Dempster's data along with Clauser *et al*. (1969) and Hinrichs (1984) have been developed into regression equations allowing this to be applied to current cohorts. Dempster's data are routinely used as a comparator to other methodologies and has been shown to give reasonably accurate predictions (Winter, 2005). However these regressions need to be carefully considered and matched to the cohort sample.

2.4.3 *In vivo* estimations

Due to the restrictions of not being able to directly measure BSP's in living cohorts, various different approaches have been used, and these have become more common place with technological advances. One of the most widely acknowledged approaches was the gamma-ray scanning approach of Zatsiorsky and Seluyanov (1983) which measured 100 young Caucasian males. Later research added 15 females to this work. This has to be noted for having one of the largest samples of data that reported segment masses, positions of centres of mass and moment of inertia in three dimensions. The disadvantage of this method is the exposure of the participants to radiation, as well as the cost and availability of the equipment. These data have been widely cited due to the cohort containing 'young' samples and having a considerably large number of participants making it more applicable for extrapolating to other groups such as sports people. However, as its segments were divided by bony landmarks it has rarely been used for biomechanical analysis. These data were reworked to have segment division based on joint centres (de Leva, 1996) and this data has been used more widely. Computerised Tomography (CT) scanning has been used by Erdmann (1997) and Pearsall *et al*. (1996). While showing data that are considered to be accurate and reliable, it also has the disadvantages of exposure to radiation, cost and time of scanning in processing (Durkin, 2008). Magnetic Resonance Imaging (MRI) scanning has been used by Cheng *et al*. (2000) to determine BSPs. Whilst an MRI does not emit radiation, the availability, cost and time of scan and processing inhibit the use of this approach. The use of dual X-ray absorptiometry (DEXA) has been used (Durkin and Dowling, 2003; Wicke *et al*., 2008). Whilst being much quicker than other scanning technologies and more widely available, the DEXA only scans in the frontal plane. Whilst the use of regression equations is easier to use than scanning technologies and mathematical models, it does present a lower degree of accuracy (Nigg, 2007).

Dumas *et al*. (2007) suggested that many of the regression equations developed are linear in nature, which are more expedient to use as they rely upon total body mass and segment length. Dumas *et al*. (2007) suggested that non-linear regression equations, such as Zatsiorsky and Seluyanov (1983) and Yeadon and Morlock (1989), are preferred to linear regression, as they are more individualised being based on a greater number of subject specific measurements (Zatsiorsky, 2002). Standard errors of 21 % of linear regression and 13 % for non-linear regression of the arm of a single subject were reported (Yeadon and Morlock, 1989). There is some suggestion that models should be based on geometric models as this reduces the errors (Pavol *et al*., 2002). The accuracy is further increased if density can be non-uniform (Nigg, 2007). This has to be tempered against the time and difficulty of obtaining the measurements needed for such geometric models (Pavol *et al*., 2002)

2.4.4 Cohort

Predictive equations are only valid on the population on which they were developed. Cheng *et al*., (2000) obtained BSP data for Chinese adults as this was not previously available. For instance, the data of Dempster has been used in many studies such as Minetti (1998) and Nelson and Widule (1983). Dempster's data were derived from eight, Caucasian males aged 52-83, which means some of the participants were born in the nineteenth century, where lifestyles, health, nutrition and training knowledge was limited by today's standards, yet the data set has still been used. Data such as Zatsiorsky and Seluyanov (1983) and Durkin *et al*., (2002) used young subjects and hence may be a more appropriate database to model predictions upon. However, neither Zatsiorsky and Seluyanov (1983) nor Durkin *et al*., (2002) reported the specific ages of the populations.

2.4.5 The Trunk

It is important within the context of this work to consider how the trunk has been divided into sections, as this will influence the design of the spine model. In reviewing current spine models that are used in 3D motion analysis, few, if any spinal models have been created considering the BSPs. This is due to the interest in angles of the spine not the motion of the segment. Previous research has used simple models of the trunk segment, often considering the head and trunk as a single, rigid, uniformly dense segment (Caplan and Gardner, 2007). Particularly in gait studies, the trunk has been considered a single segment, from the hip joint to the shoulder or head (Richards, 2008) although this is considered oversimplification (Erdmann 1997). Plagenhoef *et al.* (1983) described the trunk as being very large and mobile and, as such, complex to deal with, as parts of the trunk can move relative to each other and thus cannot be considered as rigid (Zatsiorsky, 2002). The density of the trunk is not constant. Fully inflated lungs reduce the density of the upper trunk, and this will change through the breathing cycle (Wicke *et al*., 2008).

The segmentation of the trunk is an important issue. Clear segmentation is also difficult, as muscles from more distal segments cross the trunk (Zatsiorsky, 2002). Whilst researchers tend to agree that C7 is the most superior point of the whole trunk and of the upper trunk or thorax segment (Plagenhoef *et al*., 1983; de Leva, 1996; Pavol *et al*., 2002; Holt *et al*., 2003; Fowler *et al*., 2006), there is little consensus beyond this. Some studies have considered the trunk as one section (Cheng *et al*., 2000), divided the trunk into three parts, upper, middle and lower or Thorax, abdomen and pelvis (Plagenhoef *et al*., 1983; Erdmann, 1997; Wicke *et al*., 2009), where others have used 5 sections (Pavol *et al*., 1992). The division of the trunk segments appears to be arbitrary and lacks justification for the segmentation. de Leva (1996) gives data for the whole trunk, the upper part of the trunk and the lower part of the trunk, which correspond to markers used in common motion analysis models (Plug-in-Gait, Vicon).

When developing a model, considering the simplest approach for the action of interest is suggested (Nigg and Herzog, 2007). Hence, the trunk needs to be divided into segment parts that account for the movement of the spine during the rowing action (Erdmann, 1997). Due to the motion of the spine during the rowing action, the trunk can be considered to have a minimum of 4 segments hence a trunk model should reflect this (Kleshnev, 2010). Holt *et al*. (2003) investigated the spinal angle of prolonged rowing on an ergometer. The spine angle was examined using a Flock of Birds device with receivers placed on the T12/L1 and L5/S1 junctions of the spine and 10 cm proximal to the epicondyle of the femur. Whilst this paper was examining spinal angles, it indicated important segmentation in the lower trunk, specific to the rowing action. It is important to match this to an appropriate trunk model for BSPs.

2.4.6 Summary

Due to the time and cost of *in vivo* estimations, standard tables are commonly used to estimate BSP (Plagenhoef *et al.,* 1983; Winter, 2005). Specifically, the tables of Plagenhoef *et al.* (1983) and Winter (2005) are often used but have their origins in the work of Dempster (1955). Within the differences in the source population and any application to modern-day athletes, the use of these data should be applied with caution. Zatsiorsky and Seluyanov's (1983) data incorporated a more modern population, from a sport college, hence, is likely to have a greater number of active individuals, as well as a much larger sample size. However these data were segmented by landmarks making it difficult to apply with modern 3D motion capture data which focuses around joint centres. As the focus of this thesis looks at a rowing motion, where spinal movement is occurring, a BSP data set that accounts for the variation in density of the trunk and segmentation of sections needs to be utilised. de Leva's (1996) reworking of Zatsiorsky and Seluyanov (1983) data resolved most of these issues and is suggested as the most appropriate data set for this thesis.

2.5 Energy Expenditure

2.5.1 Introduction

Energy expenditure is a representation of the physiological cost of a given activity. For muscle to produce mechanical work there is a metabolic cost (Umberger and Martin, 2007). Energy expenditure can be measured directly on an isolated muscle fibre, whereas measurement of a whole muscle or system can only be measured indirectly (Jones *et al*., 2004). In vivo performance must be measured as the metabolic process of the whole body, most commonly from indirect calorimetry (Kram, 2011). Indirect calorimetry has been widely used to assess the energetic cost of activity, but it has to be evaluated with care. The energy expenditure is the value of all the metabolic processed in the body. This includes the cost of any activity, but also includes basal metabolism, digestion, temperature regulation, etc. (McArdle *et al*., 2010). Within a testing protocol it is possible to make some quantification of basal or resting metabolism and the additional energy due to activity or exercise.

2.5.2 Basal/resting energy consumption

At rest, basal metabolic rate (BMR) usually ranges from 3.3 to 6.0 J dependent on factors such as body mass, fat free mass, age and gender (McArdle *et al*., 2010). More commonly, a resting metabolic rate (RMR) is measured due to methodological simplicity, and this is suggested to be slightly greater than BMR (McArdle *et al.*, 2010). These measures are simple to do and allow some degree of quantification and classification of energy expenditure. There is uncertainty whether BMR or RMR remains the same level during exercise (Ettema and Loras, 2009). This has led to different approaches to the denominator of the efficiency equation.

2.5.3 Measuring energy expenditure

Energy expenditure is commonly assessed via indirect calorimetry, measuring the expired volume of oxygen and r-value (ratio of volume of carbon dioxide to volume of oxygen). The R-value is associated with a given energy expenditure (from standard tables such as Peronnet and Massicotte, 1991), for the amount of oxygen consumed, to estimate the energy expenditure for a given work load (Robergs *et al*., 2010). Indirect calorimetry has been suggested to give accurate measurements (Ainslie *et al*., 2003) and has been used in laboratory-based (Hofmijster *et al*., 2009) and field-based protocols (Nakai and Ito, 2011). There are a number of assumptions of this approach. It is assumed that all participants are in a physiological steady-state when data are collected. This would be seen by a relatively unchanging heart rate and oxygen consumption rate (Robergs *et al*., 2010). Indirect calorimetry is sensitive to the metabolic effects of prior activity and digestion. It is recommended that all participants are post-absorptive and have not exercised prior to this form of testing (Ainslie *et al*., 2003). However as the participant needs to be in steady state, only a net change over a period of time can be assessed, and perhaps more importantly does not give any indication as to the reason for the change (van de Walle *et al*., 2012).

As exercise intensity increases, the demand for energy increases. This is usually met by the aerobic sources of adenosine triphosphate (APT) generation in the body, as there is a large supply of energy (lipid and carbohydrate) and there are no negative by-products (Scott *et al*., 2008). However the aerobic pathways are limited to the rate that they can produce energy. If the energy demand is greater than the possible aerobic supply, the extra energy is supplemented using anaerobic metabolism (Scott *et* *al*., 2008). Whilst it is relatively simple to assess the contributions and changes to energy supply from indirect calorimetry, quantifying the contribution of anaerobic energy is less simple. Indirect calorimetry has a shortcoming in that exercising intensities need to be sub-maximal, due to heavy exercise load causing the R-value to rise above 1.0, where increasing energy expenditure cannot be measured. Hence, this approach is suitable for submaximal endurance activities where the r-value is less than 1.0 (Robergs *et al*., 2010). If exercise intensity increases beyond an R-value of 1.0 there is a need to quantify the additional energy expenditure, provided by anaerobic metabolism (Scott *et al*., 2008; Robergs *et al*., 2010).

Anaerobic energy expenditure has been estimated from blood lactate values at the end of a work rate (McArdle *et al.*, 2010). However, as blood lactate can underestimate muscle lactate, there is a transit time issue, especially in multiple stage testing and issues of availability, storage and analysis of blood lactate it is not without issue. Accumulated oxygen deficit (AOD) is the difference between the measured oxygen uptake and the estimated total energy demand (Russell *et al*., 2000). The estimated total energy demand is based on the regression equations of Medbo *et al*., (1988), suggested to be appropriate to assess anaerobic energy expenditure (Maciejewski *et al*., 2013). A number of studies have questioned the validity of the method (Bangsbo, 1998, Gastin 2001, Noordhof *et al.*, 2010; Pettitt and Clark, 2013). There are a number of practical difficulties, in as much as athletes or participants have to complete several tests, over several days with multiple stages. Ten submaximal stages were reported as necessary to establish validity (Nordhoff *et al.*, 2010). With no agreed procedure on measured accumulated oxygen deficit (MAOD), Craig *et al.*(1985) questioned whether MAOD is an appropriate approach. Using fixed energy equivalent for the volume of oxygen consumed is a consistent, simple methodology and is considered as an appropriate alternative to the other methodologies (Nakai and Ito, 2011; Scott *et al.*, 2008). Hettinga *et al*. (2007), van Drongelen *et al.* (2009) and Sandbakk *et al*., (2012) used the maximal R-value when R>1.0, acknowledging a possible underestimation of energy expenditure, but with no additional protocol.

2.5.4 Total body physiology

Using the total body (upper limbs, lower limbs and trunk) poses a number of challenges to the supporting physiology. Most sports and activities are primarily completed by the legs (i.e. walking, running and cycling) or by the arms (i.e. arm cranking, wheelchair propulsion). VO_2 is related to the active muscle mass, thus VO_2max for arm cranking was reported to be approximately 70 % of the VO_2max achieved during cycling in untrained participants. Arm-trained participants achieved 90 % of VO_2max of legs (Secher and Volianitis, 2006) or possibly exceeded VO_2max of legs in swimmers and rowers (Volianitis, *et al*., 2004). During maximal arm cranking using seven rowers and eight 'fit' male participants, rowers' VO_2max was ~45 % larger, suggesting arm training increased blood flow to the arms during exercise (Volianitis *et al*., 2004). Higher VO_2max values were seen in rowers compared to untrained participants, due to higher arm blood flow, linked to greater muscle mass due to training and higher O_2 extraction.

When the arms and legs are simultaneously used for locomotion, the VO_2max is similar to leg values for untrained participants. However, there is an approximate 10 % increase in VO_2max compared to leg values for trained participants (Secher and Volianitis, 2006). Using nine well trained cross country skiers it was demonstrated that the oxygen consumption was lower and blood lactate levels were higher in the arms than the legs (Stoggl *et al.,* 2013). As there is not a large rise in VO_2max for legs and arms compared to legs only, a central limitation to VO_2max is suggested, i.e. cardiac output (Secher and Volianitis, 2004). The highest reported VO_2max values have been attributed to cross-country skiers, which is considered a total body activity, as there is a large contribution from the arms to motion (McArdle *et al*., 2010). The second highest VO_2max is attributed to runners, where there is little contribution from the upper body. Rowing is usually high on such a list, but the different movement pattern, the seated position and the larger than average size of rowers make comparisons difficult (Shephard, 1998).

The rowing action recruits most of the major muscle groups in the upper and lower body (Secher, 1993). As such a large proportion of muscle mass is recruited, the blood flow to working muscles can be compromised, particularly at higher workloads (Roberts *et al*., 2005). Changes of 10-20 % in blood flow to the legs and arms have been reported when leg exercise is added to arms and vice versa (Volianitis and Secher, 2002; Secher and Volianitis, 2006). Combining arm and leg exercise allows an increase in VO_2max above leg-only exercise. Training additionally allows for an increase in VO_2max. However, this is limited by the cardiac output of the heart (Secher and Volianitis, 2006).

A link between ventilation and movement patterns in rowing has been reported (Bateman *et al*., 2006). Trained rowers have ‘entrained’ their breathing to coincide with certain phases of the rowing stroke (Siegmund *et al*., 1999). It is suggested that training and experience is linked to entrainment as international rowers showed smaller variation in entrainment than novices (Bateman *et al*., 2006). The body position at the catch and finish of drive is suggested to impair the expiratory volume (VE) and VO_2 at high intensity rowing (Yoshiga and Higuchi, 2003). Conversely, the drive phase assists ventilation (Siegmund *et al*., 1999) and rowing can cause a hyperventilation where breathing frequency is elevated and tidal volume reduced (Szal and Schoene, 1989).

Rowing places a challenge on the physiology of the body as it requires the arms, legs and trunk to be active and cardiac output to support all the exercising muscles. It is also suggested that the mechanics of the stroke can influence the breathing patterns (entrainment). It is suggested that the responses to rowing will vary between the trained and untrained as higher VO_2 can be achieved by arm-trained individuals. The interaction of these issues caused Volianitis and Secher (2009) to describe rowing as the ultimate challenge to the human body.

2.6 Biomechanical Determination of energy consumption

2.6.1 Introduction

Energy cost increases as a function of speed of travel, as muscle fibres have to develop force quicker (Kram, 2011). Hence, the cost of activity will depend upon the active muscle mass recruited and the rate of developing force within the muscles (Kram, 2011). However, when running speed increases, the average force produced by a muscle does not change (Kram and Taylor, 1990). This suggests that an increase in energy cost with faster locomotion is due to the muscle having to produce more force rather than producing more work (Kram and Dawson, 1998). Contrary to the increased cost associated with increased velocity, red kangaroos have been shown to have the same metabolic energy cost whether they hop at 2 $m.s^{-1}$ or 6 $m.s.^{-1}$ (Kram and Dawson, 1998). The role of their long tendons facilitates this and the research suggested the locomotive muscles are not performing any greater work at increased speeds.

It is suggested that stored energy reduces the need for active work but not active force (Dean and Kuo, 2011). Active force is applying the load to a tendon, thus the cost of locomotion includes muscle force production as well as cost of work (Dean and Kuo, 2011). This cost is thought to increase with muscle force production but decrease with an increasing duration of contraction (Dean and Kuo, 2011). It is suggested that the production of mechanical work in a muscle is up to 20-30 % efficient (Smith *et al.*, 2005; Doke and Kuo, 2007). However, in instances where force is produced but no work is done (isometric actions, co-contractions), the cost of producing that force is more difficult to estimate (Doke and Kuo, 2007) as more force requires more metabolic energy.

It has been demonstrated that the intermittent stimulation of muscle in cyclical action, such as walking, running, cycling and rowing, requires greater ATP than continuously stimulated muscle (Doke and Kuo, 2007). This cost rises when the stimulations are short and with respect to the forces required (Doke and Kuo, 2007). As the metabolic cost of the action is the mechanical work done plus the cost of force production, it becomes difficult to estimate such cost unless the production of work is controlled (Doke and Kuo, 2007), such as controlling the power output of an ergometer. In an experiment examining bouncing activity of nine healthy adults, energy expenditure was greatest at high and low frequencies (bounce rates), suggesting efficiency was an inverted U-shape. The increase in metabolic cost was not explained solely by the increase in work done, suggesting that the cost of producing force is relatively high.

Efficiency started to increase as the frequency of bouncing increased, suggesting that there was greater contribution from the tendon. This allowed the peak value of efficiency to approximate 45 % (Dean and Kuo, 2011). Whilst the efficiency of muscle is suggested to be approximately 20-30 % (Smith *et al.*, 2005), this value is for an isolated muscle fibre. It is feasible that the efficiency of a musculo-tendonous unit, *in vivo*, could be more efficient when the elasticity of the muscle fibres and particularly the tendon are considered (Neptune *et al.,* 2009). If there are tendonous contributions to work which are not considered, then a metabolic cost could be erroneously applied to this work done, affecting the efficiency estimations. This suggests that there is not a straight forward relationship between work done and metabolic cost as factors such as stored elastic energy can do work for no cost. Without a model of efficiency to make some account for this, the efficiency estimates are likely to be incorrect.

2.6.2 Summary

Measuring the energetic cost of an activity is difficult to isolate and as such whole body measurements are often used (Kram, 2011). When considering efficiency, often a value of 25 % is given as a maximum, despite some studies showing higher efficiencies. It is suggested that the 25 % limit is for muscle, but that this needs to be modified to consider the roles that tendons play, where it has been shown that their properties can cause a rise in the efficiency of human activity to approximately 40 % (Dean and Kuo, 2011). How the muscle is functioning and the movement pattern will influence the metabolic cost and the amount of energy transferred.

2.7 The role of musculotendonous unit

2.7.1 The function of muscle

Muscle is the source of all forces for voluntary movement and plays an important part in the efficiency of movement (Herzog, 2007). Muscle is both the generator of force (work) and a consumer of energy. Muscle generates force to produce movement and is the main contributor to motion (Herzog, 2007). The production of muscular force is dependent upon the type of muscular action, the velocity of the action, the load to be moved and the goal of the task. Force production has an energetic cost and this will vary upon the factors mentioned previously as well as the muscle fibre type (Coyle *et al.*, 1992). Additionally, muscle can produce heat and support the skeleton (Tricoli, 2011).

2.7.2 Types of muscle action

Isometric actions involves muscle remaining at a constant length, with no associated external movement, although energy is being expended. A concentric action is an active shortening of muscle, whereas lengthening of the muscle despite efforts to shorten, is referred to as an eccentric action (Herzog, 2007). Both concentric and eccentric muscle actions have different energetic costs for the work done, where concentric actions are metabolically more costly (Kautz and Neptune, 2002). However, it is unusual to have a purely concentric or eccentric muscle action, especially in cyclical movement as a concentric muscle action is preceded by an eccentric muscle action (Komi and Nicol, 2000). Hence, in most cyclical locomotive activities there is a stretch-shortening cycle of muscle occurring and some work is being provided by stored elastic energy (Komi and Nicol, 2000).

2.7.3 Length-tension relationship

The length-tension (L-T) relationship describes the parabolic change in maximal force production as the length of the muscle changes (Herzog, 2007). Within the body, this relates to the angle of the joint that the muscle crosses, so maximal force will occur at a specific joint angle and reduce either side of this angle. The position (joint angle) of a muscle partly determines how much force it can produce, hence good technique is linked to lower energy expenditure by the muscle functioning at the most force-producing length with a minimum energy cost.

2.7.4 Force-velocity relationship

The force-velocity (F-V) relationship describes how the velocity of shortening influences the forces produced by a muscle based upon the sarcomere being at optimal length (Herzog, 2007). During concentric actions, muscle force decreases as shortening velocity increases up to a critical velocity where force production equals zero. During an eccentric action, force increases as velocity increases to a critical point where force becomes constant. The F-V relationship is further complicated with the inclusion of elastic energy stored in the tendons (Herzog, 2007). This allows the muscle, *in situ*, to exceed velocity of shortening that is seen from just muscular contraction.

2.7.5 Excitation-coupling mechanism

The excitation-coupling (E-C) mechanism within muscle is the source where metabolic energy is converted in to force output or work (Jones *et al*., 2004; Smith *et al.*, 2005). The greater the rate of cross-bridge action, the greater the ATP used to support this process, hence the greater the force production and greater energy is required. There is an increasing energy cost for higher force outputs as cross-bridge activation is one of the main consumers of ATP (Smith *et al.*, 2005). The Fenn effect states that the rate of work and heat produced is proportional to the cross-bridge turnover. Efficiency of muscle shortening will vary with the velocity of shortening and between slow and fast fibre types. The maximum efficiency during shortening is a similar value in both slow and fast twitch fibres, but the velocity at which that peak is achieved is markedly different (Jones *et al.*, 2004). Within a multi-link system, such as total body movement, each muscle will consume energy and produce force at different levels. It is suggested the efficiency of E-C coupling is approximately 40 % (van Ingen Schenau et al., 1997).

2.7.6 Efficiency of muscular actions

Efficiency is the measurement of the working muscles in a system (Winter, 2005). However, muscle action has its own efficiency and gives some theoretical limit to the overall efficiency that can be achieved by the human body (Smith *et al*., 2005). Muscle converts metabolic energy into heat and work (Smith *et al.*, 2005). Muscular (concentric) action has a net efficiency of approximately 20-40 %, *in vitro*, with mammalian muscle being closer to 20 % (Smith *et al.*, 2005). This suggested the limit to efficiency as being close to these figures, dependent on the task. The type of muscle action can affect the mechanochemical efficiency, where concentric actions were approximately 15 % and eccentric actions approximately 35 % efficient during sub-maximal torque production conditions (Ryschon *et al*., 1997). However, all muscles do not have a single value for efficiency as this will vary with the force and velocity of muscular action (Umberger and Martin, 2007). This suggests that the net efficiency of muscular contraction will be the sum of all active muscles being used for a given action. Much of the understanding of muscle efficiency comes from studies using isolated muscle fibres. Whether the same limits are found *in vivo* needs to be considered as contributions from elastic energy or other calculation errors have been suggested to change this range of efficiency (Neptune *et al*., 2009). Humans are considered a multi-linked segment system of levers and actuators (Zatsiorsky, 2002). The lever system can have an effect on the force output of a muscle. The efficiency of walking is suggested to be between -125% and +25% dependent upon the gradient (i.e. downhill to uphill; Minetti *et al*., 1993).

The work done by a muscle is less than the work done by the contractile units due to losses of work because of such forces as friction and degradation of energy to heat (Zatsiorsky and Gregor, 2000). Muscular action, therefore, has its own efficiency, even before a human system is considered. It is not possible to measure the forces being exerted by individual muscles, so the work done is estimated based on the external forces acting on the body and the movements carried out. As this is not the actual muscle work, Zatsiorsky and Gregor (2000) recommended that this is termed 'apparent work'. When combined in a linked body system, movement occurs due to the net work done by all the muscles acting upon the system (Zatskiorsy and Gregor, 2000).

2.7.7 Muscular efficiency vs mechanical efficiency

Much of the criticisms of efficiency studies have suggested that the proffered values for efficiency were representative of muscle efficiency rather than mechanical efficiency (Ettema and Loras, 2009). Much of the understanding of muscle efficiency comes from studies using isolated muscle fibres. Whether the same limits are found in *vivo* needs to be considered as contributions from elastic energy or other calculation errors have been suggested to change this range of efficiency (Neptune *et al*., 2009). It is unlikely that the efficiency of performance of an activity could be compared to that of a single muscle, a muscle group or the active muscles in a task (Neptune *et al*., 2009). This 'overall' value will account for muscle activity, entropy, transfer of energy and loss of energy through other mechanical pathways. Therefore the efficiency of an action is most likely to be a measure of the efficiency of the performance and should be carefully considered before being discussed as muscular efficiency. Hence, within this thesis the term efficiency will refer to mechanical efficiency and it will not attempt to link it to muscular efficiency.

2.7.8 Summary of musculotendonous unit

A muscle's main role is to produce force. The magnitude of the force will be task dependent and influenced by the type of action, position of the limbs and the velocity of the action. The influence of stored elastic energy within the tendon is currently not fully understood, but is recognised as a mechanism that enhances function. However, the magnitude of the elastic contribution is difficult to quantify. Co-contractions of muscles, stored elastic energy and transfer of energy within and between body segments are very difficult to assess and, they will not only affect the force and power produced by a musculoskeletal unit, but also the energy cost of that activity. Additionally, isometric actions may not contribute directly to work done, but may have a considerable influence on energy cost/consumption. The complex interaction of all of the factors reviewed in this section produce mechanical work and movement which has an energetic cost.

2.8 Estimating efficiency

2.8.1 Introduction

With an appropriate measure of mechanical work done and energy expenditure the estimation of efficiency is possible. However, throughout the literature the term 'efficiency' is used and often means different things to different authors depending on their field of research (Cavanagh and Kram, 1985a). This section will consider these terms and derive definitions for this work. This includes modifications to both the numerator and denominator of Equation 1.1.

'Muscular efficiency' has been considered the ratio of mechanical work to the metabolic energy used (Stainsby *et al.*, 1980). The use of the term muscular is somewhat challenging as this value may be accounting for more than muscular activity (i.e. tendon activity and energy costs that include basal metabolism). This definition is commonly known as gross efficiency and measures the work done usually by the whole body against the total energy cost of the activity (Cavanagh and Kram, 1985a). As gross efficiency is a measure of the whole body, it is difficult to suggest that it is synonymous with muscular efficiency (Sandbakk *et al.,* 2012). Cavanagh and Kram (1985a) suggested there are difficulties with terminology and how terms are used interchangeably, such as muscle and muscular efficiency, as well as gross and overall efficiency. Given that some of the total energy expended will be BMR/RMR, the use of the term muscular efficiency is largely inaccurate and the term gross efficiency is preferred. However, the idea of work divided by energy expenditure has been considered over simplistic and hence definitions have been revised by subsequent researchers (Gasser and Brooks, 1975; Stainsby *et al.,* 1980). Within gross efficiency there is the cost of BMR/RMR included and the cost of moving the body parts.

2.8.2 Gross, net, work and delta efficiency

The use of total energy cost (gross efficiency) has been considered as too simplistic to assess efficiency as it accounts for metabolic work of non-contributing parts of the body including resting metabolic energy (Gasser and Brooks, 1975; Stainsby *et al.,* 1980). Modifications including subtracting resting energy expenditure (net efficiency) and energy expenditure during an unloaded action (work efficiency) as well as delta efficiency (change in work done divided by change in energy expenditure) have been suggested (Gasser and Brooks, 1975; Stainsby *et al.,* 1980). The work of Gaesser and Brooks (1975) and Stainsby *et al.* (1980) generated four types of efficiency: gross, net, work and delta. These differences are based on the denominator used. These are:

$$Gross\ efficiency = \frac{External\ work\ accomplished}{Energy\ Expenditure} \tag{2.5}$$

$$Net\ efficiency = \frac{External\ work\ accomplished}{Energy\ Expenditure - resting\ energy\ expenditure} \tag{2.6}$$

$$Work\ efficiency = \frac{External\ work\ accomplished}{Energy\ Expenditure - energy\ expenditure\ in\ unloaded\ conditions} \tag{2.7}$$

$$Delta\ efficiency = \frac{increment\ in\ external\ work}{increment\ in\ energy\ expenditure} \tag{2.8}$$

The four efficiencies outlined above are suggested to measure different aspects of performance. That is, they either include or exclude oxygen consumption for unmeasured work such as resting metabolism, or energy used by muscle stabilising the body (Hintzy and Tordy, 2004). This has lead to efficiency research not having a consistent denominator across studies which makes comparisons difficult. Work efficiency is rarely used within the literature. Most efficiency research has used gross or net efficiency with occasional reference to delta efficiency, especially in cycling research.

2.8.2.1 Gross efficiency

Gross efficiency is the most simple and commonly used model of efficiency. It examines the external work done, commonly from an ergometer and used energy expenditure from expired gas analysis. In cycling, gross efficiency was shown to have high levels of repeatability (Moseley and Jeukendrup, 2001). Noordhof *et al*. (2010) examined gross efficiency during cycling which was not considered to vary significantly between and within days in 18 healthy physically active males, suggesting that it is a consistent measure. Furthermore, gross efficiency was not affected by stroke rate in 17 well trained female rowers (Hofmijster *et al*., 2009). Gross efficiency has been argued to be too simplistic, in particular the denominator has received criticism (Gaesser and Brooks, 1975; Stainsby *et al*., 1980). It is argued that by using gross efficiency the energy cost of the work done includes the resting metabolic rate (i.e. the energy cost is all the metabolic processes occurring not just due to the work being performed). Proposed modification to the denominator has been made in order to account for the resting metabolic rate and the movement of the limbs. Stainsby *et al*. (1980) suggested that the modifications to the denominator would only be valid if the denominator remained at the same value despite increases in work or exercise rate. Gross efficiency will increase with work rate and hence can be erroneous if used to research changes due to exercise intensity (Ettema and Loras, 2009). However gross efficiency was used to examine change in work rate by Hofmijster *et al*. (2009) but did not show any change as the stroke rate of elite female rowers increased. Sidiossi *et al*. (1992) suggested that gross efficiency should not be used with unskilled performers as technique is an important function of efficiency.

2.8.2.2 Net Efficiency

Net efficiency has been examined in running and walking (Cavagna and Kaneko, 1977), swing through gait with elbow crutches (Thys *et al*., 1996) and roller skiing (Nakai and Ito., 2011). Net efficiency subtracts the resting metabolic cost from the exercising metabolic cost. If all factors remained the same, the net efficiency would report a higher value than gross efficiency. This is not an actual increase in efficiency but a change due to the method of calculation. The assumption within this approach is that the resting metabolic rate remains constant with respect to changes in work intensity or duration (Ettema and Loras, 2009). Net efficiency is suggested to reflect energy above resting metabolic energy, which is expended to complete the desired activity, suggesting the efficiency of the active muscle (Ettema and Loras, 2009). However, in a multi-segmented, multi-muscled system it is difficult to suggest a single efficiency of muscular action. Net efficiency assumes that the resting value is consistent throughout all workloads and is isolated from the process of doing work, although the independence of resting and exercising metabolism is questioned (Ettema and Loras, 2009). Previous research has not differentiated between basal metabolic rate and resting energy expenditure in determining net efficiency. Unlike gross efficiency, net efficiency does not increase due to an increased workload, suggesting that it is a more appropriate method to assess efficiency. Nakai and Ito (2011) showed a parabolic nature with respect to intensity for net efficiency in roller skiing. Although widely used, the issue of the constant baseline prompted Cavanagh and Kram (1985a) to describe net efficiency as conceptually flawed.

2.8.2.3 Work Efficiency

Work efficiency is often defined in relation to cycling. It subtracts the energy used in cycling against zero resistance, assessing the cost of moving the legs, but not against any resistance. This value is subtracted from the total energy expenditure and is suggested to represent the energy cost of moving the load on the cycle only (Cavanagh and Kram, 1985a). Applying this procedure to activities other than cycling becomes challenging as there may not be a fixed movement pattern to replicate unloaded (Ettema and Loras, 2009). As work efficiency has the same baseline assumptions as net efficiency, and is difficult to apply to non-cycling protocols, it has been described as being seriously flawed by Cavanagh and Kram (1985a).

2.8.2.4 Delta efficiency

Gaesser and Brooks (1975) evaluated the baseline corrections and the effect of speed and work rate on efficiency during cycling. They concluded that as gross, net and work efficiency did not represent the changes in pedal rate, work rate and calorific output, delta efficiency is the most appropriate method of calculating efficiency. Delta efficiency does not require a measure of resting metabolic rate and is thought to be less sensitive to changes in energy cost due to changes in work rate. However, criticism of delta efficiency is based on the assumption that the increasing contributions from muscles will all occur with the same efficiency (Ettema and Loras, 2009). This implies that when measuring muscular efficiency, efficiency is independent of work rate. Studies such as Bijker *et al*. (2001, 2002) reported efficiencies for running around 50 %. This is considered to be so high as to be erroneous. Hence, Ettema and Loras (2009) consider that delta efficiency is not a true measure of efficiency. Whilst delta efficiency is used in some cycling research it is rarely used elsewhere and so along with work efficiency will not be considered as a metric in this thesis.

The type of efficiency used in the literature appears to be fairly arbitrary. Gross efficiency is commonly used, increases with work rate, is consistent within and between days (Noordhof *et al*., 2010) but could be misleading if used to research changes due to exercise intensity (Ettema and Loras, 2009). Although gross efficiency is criticised for a curved work rate-efficiency curve, it does not have the assumptions of net, work or delta efficiency. Net efficiency has been examined in running and walking (Cavagna and Kaneko, 1977), swing through gait with elbow crutches (Thys *et al*., 1996) and roller skiing (Nakai and Ito, 2011). However, net efficiency assumes that the resting value is consistent throughout all workloads and is isolated from the process of doing work. There is evidence to suggest there is a change in resting energy value as exercise intensity changes (Ettema and Loras, 2009). Delta efficiency is calculated in some cycling studies but is generally less used than gross or net efficiency. Work efficiency is rarely reported within the literature. Changes to the denominator make comparisons difficult as different measures have been used for the same activity (Cavanagh and Kram, 1985a). Work done (the numerator) has often been considered as just the external work done. This is the work performed to overcome an external resistance and it can be accurately measured (Kautz and Neptune, 2002). This is commonly derived from the power output on an ergometer such as a cycle (Ettema and Loras, 2009) or an arm crank (Smith *et al*., 2007). It can also be derived from strain gauges and has been used to assess on-water rowing (Fukunaga *et al*., 1986). Not only will the exclusion of internal work influence the efficiency values, it will not give any quantification of the movement, therefore not offering any explanation of efficiency (Cavanagh and Kram, 1985a). Total work done, as the sum of external and internal work, has been criticised as there is an assumption that these are two independent energy flows (Kautz and Neptune, 2002), however, it is still commonly used.

Although there is no agreement on which form of efficiency is most appropriate, both net and gross are commonly reported in the literature and remain the most used forms of efficiency. In summary, the method for assessing energy expenditure is well established but how that is used (i.e. as gross or net efficiency) is yet to reach a conclusion, but within mechanical efficiency studies (as opposed to physiologically oriented studies) net is more commonly seen (van Ingen Schenau, 1998). Although not universal in method, it is often possible to report both gross and net efficiency.

2.9 Results of efficiency studies

During uphill and downhill walking through a –25 to +25 % gradient, Johnson *et al*., (2002) reported a range of gross efficiency from -59 % to 29 % as the gradient varied. Bijker *et al*. (2001) examined the delta efficiency of running using both inclination of a treadmill and horizontal impeding forces. The level of delta efficiency was approximately 44 %. Sidossis *et al*. (1992) collected gross and delta efficiency of 15 competitive cyclists and suggested a gross efficiency of 21 % and a delta efficiency of 20-24 %. They concluded that gross efficiency should not be used with unskilled performer as technique is an important function of efficiency. Marsh *et al*. (2000) examined the effects of cadence and experience on cycling efficiency and found no differences in terms of delta efficiency. Bijker *et al*. (2001) suggested that cycling has a delta efficiency of approximately 25 %.

Moseley and Jeukendrup (2001) suggested that delta efficiency had an advantage in that it was not susceptible to changes in metabolic rates as exercise intensity increases to support homeostasis. They also commented upon the assumption of net efficiency and work efficiency; that is, the presumption that the resting metabolic cost remained the same through all intensities of exercise. They examined the reproducibility of gross and delta efficiency during cycling activity. Their results suggested that gross efficiency had high levels of repeatability. However, delta efficiency had greater levels of variability but considered its theoretical advantages to be outweighed by the lower levels of reproducibility.

The above are examples of efficiency calculated using the lower-body. In contrast, the efficiency of upper-body activity has received less attention. de Groot *et al*. (2005) examined the gross efficiency of tetraplegic and paraplegic wheelchair users. Gross efficiency increased over a three-month period as practice occurred in all groups. Hintzy and Tordi (2004) examined 18 healthy males who completed three wheelchair ergometer tests at 40, 55 and 70% of VO_{2max}. Efficiency increased with intensity, except for work efficiency. Goosey-Tolfrey and Sindall (2007) examined synchronous and asynchronous arm-cranking at three intensities. Synchronous crank was found to be more efficiency but all intensities and modes were around 14-18 % efficient. Janssen *et al*. (2001) assessed the efficiency of hand cycling on a motorised treadmill to be approximately 10 %. Efficiency values for the upper body tend to be smaller than the lower body mainly due to the size of the active muscle mass (Secher and Volianitis, 2006).

Data from efficiency studies have tended to examine either the upper or lower body. Very few studies have examined the role of the total body and the corresponding efficiency. Actions that require the simultaneous use of upper and lower body are methodologically more complex to analyse, especially when the role of the trunk as the link segment is considered. However, the rowing stroke is a total body action that involves the upper and lower body, making it a useful modality for assessing total body efficiency.

SUMMARY

In sport, the advancement in physical fitness, technique and psychology are great. Less attention has been given to biomechanical concepts such as internal work done and efficiency, due to the complexity of determining these quantities. Determining the mechanical energy (or work done) for motion has been described by Zatsiorsky (2002) as an unsolved problem within biomechanics. Limited research has examined the efficiency in the lower body during walking (Johnson *et al.,* 2002; Detrembleur *et al.*, 2003; Schepens *et al.*, 2004), running (Cavagna and Kaneko, 1977; Kryolainen *et al.*, 1995; Bijker *et al*., 2001) and cycling (Sidossis *et al*., 1992; Marsh *et al*., 2000; Bijker *et al*., 2001; Moseley and Jeukendrup, 2001). The upper body has received some attention particularly considering wheelchair propulsion (de Groot *et al.*, 2002; Hintzy and Tordi, 2004) and arm cranking (Goosey-Tolfrey and Sindall, 2007). However, few studies have examined the work done by the upper and lower body simultaneously. Furthermore most of the studies reported here have only examined external work within the measure of efficiency and this need to be addressed to enhance the understanding of a total body model.

2.10 Work done and calculating efficiency

The calculations of efficiency used within the literature have not been consistent. One of the earliest approaches was that of Winter (1979). The calculations followed three stages. Firstly, summing the potential, translational kinetic and rotational kinetic energy of each segment. Secondly, determining the total energy of all segments at each point in time and thirdly, adding the absolute changes in total energy across time. This approach uses absolute changes and, therefore, minimises the impact of positive and negative work in the calculations. By using an absolute change model, the negative work is removed, suggesting that any energy loss is converted into heat. This ignores the possibility of the negative work being converted into external work, which Ettema and Loras (2009) suggested is an unjustified simplification. This approach has been used in cycling (Widrick, 1992), walking (Willems *et al*., 1995) and roller skiing (Nakai and Ito, 2011). Currently there does not appear to be a study that uses ergometers such as an arm crank which has included measures of internal work.

2.10.1 Calculating Efficiency

External work and internal work are summed to provide total work done, which is divided by the energy expenditure calculated for the task. This would commonly be net energy expenditure, gross energy expenditure or occasionally work energy expenditure. Assumptions have to be made about the role of transfer of energy between body segments (Nardello *et al*. 2011), the role of stored elastic energy (van Ingen Schenau, 1998) and issues such as co-contractions or isometric actions. Once the internal kinetic energy has been calculated, with assumptions of energy transfer accounted for, the segmental energy can be summed (Nardello *et al*., 2011). However, how these are summed together are not without issues as Zatsiorsky (2002) explained that some models sum the relative changes, whereas others sum the absolute changes. The earlier mentioned reciprocal movement of the limbs in activities such as walking are generally brought about by internal, muscular forces. Thus any work done to move the segments relative to the body's centre of mass is considered internal work (Nardello *et al*., 2011).

2.11 Factors affecting efficiency

There is no clear consensus within the literature on factors that can affect efficiency. From a conceptual point of view, based on equation 1.1, it is the interaction between the technique and fitness of the individual. Either factor, or both could be examined and raises questions on whether efficiency can be enhanced. Research which has considered changes in efficiency has mainly focused on cycling and to a lesser extent, cross-country skiing. Whilst it may be expected that novices and trained individuals would display differences in efficiency, there is a body of evidence to suggest that that there is no significant difference in terms of cycling efficiency and experience. Elite cyclist and novices have similar efficiencies (Marsh and Martin, 1993; Nickleberry and Brooks, 1996; Marsh *et al*., 2000; Moseley *et al*., 2004). However, due to these studies being cross sectional in design, they do not examine what training does to efficiency (Hopker, 2012). Conversely, differences in efficiency of 1.2 % have been reported between elite and professional cyclists (Lucia *et al*., 1998) and 1.4 % between training and untrained cyclists (Hopker *et al*., 2007).

2.11.1 Effects of training

Changes in gross efficiency have been associated with endurance-based training. It has been suggested that these changes are within the oxidative capacity of type 1 muscle fibres (Coyle *et al*., 1992; Coyle, 2005) hence, a lesser energy cost for the same workload. Similarly changes in gross efficiency have been reported after six weeks of high intensity, sport-specific training (Hopker *et al.*, 2010). Gross efficiency of cyclists has been shown to increase during one season (Hopker *et al*., 2009) and over multiple seasons (Santalla *et al.*, 2009). Hopker *et al*. (2009) examined changes in gross efficiency of 14 endurance trained cyclists across a single season. Gross efficiency increase by 1 % during the cycling season and declined by 1% during the off-season (Hopker *et al.,* 2009). Santalla *et al.* (2009) suggested that the use of delta efficiency could be a more appropriate method for assessing the changes in muscle efficiency. They postulated that training may alter both physiological and mechanical responses including recruitment patterns in muscle. Annual testing of 12 male 'world-class' cyclists over a five year period showed increased delta efficiency 23.61 % (±2.78) to 29.97 % (±3.7) despite no significant increase in VO_2max. This increase in delta efficiency is linked to changes in the muscle. Positive correlations between both delta and gross efficiency and type 1 aerobic muscle fibres have been reported (Coyle *et al*., 1992). They suggest the muscle plasticity (adaptive potential) can be linked to the improvement in efficiency. Additionally Gore *et al*. (2007) described increases in efficiency due to mitochondrial efficiency as a result of hypoxic training. Furthermore muscle recruitment has been postulated as a mechanism of improvement in delta efficiency (Hansen and Sjogaard, 2007). The changes in efficiency are hypothesised to be as a result of the volume and intensity of training. Within cycling efficiency is considered as a key determinant of endurance cycling performance. Hence, how training effects changes in (metabolic) efficiency is important (Hopker *et al*., 2010). As these studies have used well trained athletes, it is likely that their VO_2 is developed to near maximum and that to develop further in order to improve efficiency would require a large increase in the training stimulus, which would be impractical. This suggests that a more effective method may be to examine the work done concepts and focus on technique.

2.11.2 Technique

Changes in technique have been linked to changes in efficiency (Camara *et al*., 2012). Hintzy *et al*. (2005) examined the changes in cycling efficiency of nine sedentary female participants. After six weeks of endurance training (18 sessions of 45 minutes) significant improvements in gross and net efficiency were observed. A minor (but significant) change was found in work efficiency, which was speculated to be due to technique (skill) improvement affecting the zero loaded condition. A significant reduction in the VO_2 of unloaded cycling was reported, suggesting training improved motor control and reduced energy expenditure to perform the unloaded cycling. Hopker *et al*. (2010) showed an increase in gross efficiency after six weeks high intensity training, although the reason for these changes were not clear. The delta efficiency of twelve professional cyclists showed a ≈ 3 % improvement (ΔDE ≈ 15 %) despite no significant change in VO_2max over a five year period, suggesting the trainability of efficiency.

There appears to be evidence to suggest that efficiency is fixed and conversely that it is adaptable. This is influenced via fitness and technique. As most of these studies have used cycling as the mode of exercise, it has to be recognised that this is a simple, controlled action that only uses the lower body, suggesting less scope for the affects of technique using a total body action. However, within these studies internal work has not been included.

2.12 Total body models of efficiency

The body is often considered as a lower or upper body as this is easier to model. There are a number of activities that use the lower and upper body simultaneously, for example rock climbing, cross-country skiing, shot-putting and rowing. By quantifying the mechanical work done and efficiency of such actions a greater understanding of the movement of the total body can be achieved. There is a paucity of studies that have attempted to quantify efficiency of a total body action. There are limited modalities where the total body is being used to contribute to locomotion, with the two most common examples being cross-country skiing and rowing. Frequently these two activities are examined using ergometers within laboratories, but have also been investigated in the field.

By considering the efficiency of the total body there are a number of complexities that need addressing. There needs to be a method to establish external work, internal work and energy expenditure for the upper and lower body. Due to these methodological challenges, very few studies have examined total body efficiency. Ettema and Loras (2009) suggested that an attempt to define muscular efficiency in whole body movements was 'fruitless'. As suggested earlier, Neptune *et al*. (2009) indicated that it is unlikely that efficiency of a movement could be considered to represent the efficiency of a muscle. This again brings issues of the different types of efficiency (Minetti, 2004) and as such when considering human movement, then perhaps performance efficiency is a more appropriate descriptor. However, if trying to measure and improve the efficiency of the movement rather than the efficiency of the muscle, then there is still value in this approach.

During cross-country skiing, gross efficiency was demonstrated to increase with respect to exercise intensity (Sandbakk *et al*., 2012). Seven elite male participants were tested over three intensities (low moderate and high) at two inclines (2 % and 8 %) and gross efficiency ranged from 10 to 16 %. Gross efficiency of total body exercise does not appear to be affected by cadence (Leirdal *et al*., 2013). Eight male, national-level cross-country skiers completed three trials at four different speeds. Each speed used a freely chosen cadence and 10 % higher and 10 % lower cadences. No differences were seen as a result of cadence and it was suggested that the body is self-optimising in reference to energy cost. Gross efficiency was reported between 14 and 16 % (Leirdal *et al*., 2013). Skill level has been positively associated with gross efficiency where higher-ranked skiers have higher gross efficiency than lower-ranked skiers (Ainegren *et al*., 2013; Sandbakk *et al*., 2013).

Within cross country-skiing gross efficiency has been estimated between 10 % and 17 % (Sandbakk *et al*., 2012; Sandbakk *et al*., 2013), which is lower than that reported for cycling (Ettema and Loras, 2009). It is suggested that cycling is supporting a greater percentage of body weight compared to cross-country skiing, hence the differences in reported gross efficiency (Leirdal *et al*., 2013). Although wheel chair propulsion is weight bearing the reported gross efficiency range of 2-10 % is much lower than cross-country skiing, but is likely to differ due to the active muscle mass and power output of muscle (Leirdal *et al*., 2013).

A total body model of efficiency has been developed for analysis of roller skiing (Nakia and Ito, 2011). Eight cross-country skiers completed four minute trials roller skiing at five different speeds, with a 6minute rest between conditions. Kinematic data were collected using a two-dimensional video camera (60 Hz). An 18 segment model (three segments per limb, a head, trunk, skis and poles) was used. The efficiency model was based on Winter (1979) and included energy transfer within and between segments. Energy expenditure was estimated from expired gas analysis, however, using a fixed value of 1L of oxygen =20.93 kJ, irrespective of intensity. Net efficiency for individual participants increased with respect to speed and ranged from 17.7 % to 52.1 %. Mean net efficiency values increased with speed to a peak of 37.3 %. Nakia and Ito (2011) reported values that were greater than the proposed efficiency of muscle, questioning the results. They also used the approach of Winter (1979) to calculate the internal work. This included the potential energy changes for each segment, contrary to the Konig theorem (i.e. counting potential energy twice).

Although there are limited studies on total body efficiency, there is an indication in changes in efficiency due to intensity. Nakai and Ito (2011) showed a parabolic relationship between net efficiency and exercise intensity, although results should be interpreted cautiously as efficiency values are larger than other reported studies. Sandbakk *et al*. (2012) reported increasing efficiency of cross-country skiers. However the study only used two intensities so it is not possible to extrapolate to the shape of the relationship between efficiency and exercise intensity.

There are a number of issues unique to a total body model. One of these is the role of the trunk. The trunk is the link in the kinetic chain between the upper and lower body, and as such has responsibility for transferring forces and energy between the lower and upper body, particularly in rowing (Pollock *et al*., 2009).

2.13 Efficiency of rowing

This thesis will use rowing as the total body movement to examine efficiency. This will be based around ergometer rowing as this eliminates the logistical challenges of conducting the research on water. The rowing stroke is a cyclical movement of two phases. Firstly, the drive phase starts at the catch (Figure 2.1a) where a forceful extension of the body occurs, moving the ergometer handle over the feet, until the legs are almost straight, the trunk has moved posteriorly and arms are bent, with the handle against the sternum. Secondly, the recovery phase is the period from the end of the drive back to the start of the drive (figure 2.1c). This is a relatively passive motion that can be achieved with minimal muscular force (Shephard, 1998).

Figure 2.1a The start of the drive phase of ergometer rowing (From ‘The perfect stroke’ British Rowing.)

Figure 2.1b The middle of the drive phase of ergometer rowing (From ‘The perfect stroke’ British Rowing.)

Figure 2.1c The finish of the drive phase of ergometer rowing (From ‘The perfect stroke’ British Rowing.)

The rowing ergometer has been demonstrated to produce similar physiological responses as on-water rowing and is considered a suitable method for assessing VO_2 and energy expenditure (Shephard, 1998). Whilst there are some differences in the rowing stroke between on-water and ergometry, the ergometer is accepted as the most appropriate dryland method to assess technique (Lamb, 1989; Soper and Hume, 2004). Drag factor is usually set between 120 and 140 [1.2-1.4 $Nm.s^{-2}$] (Ingham *et al.*, 2002; Neville *et al.*, 2010; Volger *et al.*, 2010) although most commonly at 130 [1.3 Nm.s^{-2}](Benson *et al.*, 2010; Gallagher *et al.*, 2010; Longman *et al.*, 2011).

Within rowing the power output of the rower is produced by the coordinated efforts of the segments of the body (Attenborough *et al.*, 2012). Hence, lower coordination will lead to less power being developed and a less effective stroke (Turpin *et al.*, 2011). A number of studies have involved rowing, either on-water or using a rowing ergometer. The focus of the research is varied, often looking at stroke technique (Soper and Hume, 2004), force output (Kleshnev, 2010) and injury mechanisms (McGregor *et al.*, 2004). It is generally agreed that greater force is related to superior performance (Shephard, 1998; Soper and Hume, 2004). However, only examining the force output does not indicate where or how the force was produced nor the level of coordination and skill in developing the action. Having a measure of internal work would give some indication to the movement pattern (Purkiss and Robertson, 2003). Important biomechanical parameters of rowing include the stroke length, duration and ratio of drive to recovery, the magnitude and duration of force on the stretchers and handle, the power of the stroke, the motion of the handle, the trunk inclination and the load on the joints (Soper and Hume, 2004).

The consistency of stoke has been examined between skilled and unskilled populations. Although there are differences it is generally shown that both skilled and unskilled can row with consistent movement patterns. Using 5 elite, 5 junior and 5 non-rowers, differences within the technique and consistency of the stroke were observed between the groups (Cerne *et al.*, 2013). Stroke duration of the drive phase approximated 0.83 seconds for all intensities. The novice participants decreased stroke duration (drive time) in response to increased intensity from 1.41 to 0.89 seconds. Overall considered elite rowers showed high consistency and non-rowers showed acceptable consistency (Cerne *et al.*, 2013). Using ten adolescent males and ten females, Ng *et al.* (2013) showed high reliability (ICC range 0.94-0.9) for stroke duration. Kleshnev (2005) reported drive times of 1.21 seconds and 0.97 seconds for 20 and 32 strokes per minute respectively. Kleshnev (2005) reported the stroke lengths of 1.44 and 1.41 m at stroke rates of 20 and 32 strokes per minute, respectively for five female trained rowers. Stroke lengths of approximately 1.6 m were reported for elite rowers and 0.98-1.17 m in novice rowers using ergometer (Cerne *et al.*, 2013). It is suggested that skilled and novice participants can perform ergometer rowing with similar kinematics (Hase *et al.*, 2004). Untrained and trained participants were reported to have consistent kinematics during increasing ergometer intensities, which showed little change with increases in power output (Turpin *et al.*, 2011). Additionally, lower variation in handle and stretcher forces for skilled participants compared to novices have been reported (Hase *et al.*, 2004). In summary, novice participants appear to be able to row consistently using ergometers, suggesting that ergometer rowing can be used with unskilled performers and achieve a consistent movement pattern.

There is a paucity of rowing efficiency research. Previous studies have used different methodologies, and often have used low numbers of participants. Nelson and Widule (1983) reported on-water efficiency values for 18 skilled and unskilled female college rowers of 87 % and ≈75 %, respectively. These results are much higher than other results presented in the literature. Efficiency was calculated using what was described as biomechanical efficiency being the ratio of actual trunk and knee angular velocity to possible trunk and knee angular velocity. Fukunaga *et al.* (1986) examined the efficiency of static rowing in a motorised tank of moving water at a speed of 3 $m.s^{-1}$, by examining the force produced, via strain gauges on the oars, and the metabolic cost of rowing. They examined gross, net, work and delta efficiency, and suggested that efficiency ranged between 15 and 28 %. This demonstrated the potential to assess all forms of efficiency and how they would vary. Nozaki *et al.* (1993) examined the efficiency of two scullers using an on-water protocol. They measured work done by the forces recorded by strain gauges on the oars and metabolic cost via a portable expired air analysis system. They found that efficiency rose from 20 % at a boat speed of 2 $m.s^{-1}$ to 24 % at 4 $m.s^{-1}$. On-water assessment has used different methodologies and needs to be interpreted with care as rowing efficiency is derived from the rower, the boat and the oar-water interaction, thus measuring a more complex system than ergometer rowing. Affeld *et al.*, (1993) considered the above, as rowing efficiency, where ergometer rowing is considered rower efficiency.

Ergometer based studies consider efficiency less frequently than on water studies. Mohri and Yamamoto (1985) reported the rowing efficiency for four national and twenty-four unskilled female rowers using a sweep ergometer. Net efficiency of 11.4 % and 10.6 % for skilled and novice, respectively, were reported as statistically different. However, internal work was not accounted for. Both Martindale and Robertson (1984) and Bechard *et al*., (2009) did account for internal work during rowing, but did not make estimates of efficiency. Hofmijster *et al*. (2009) examined the gross efficiency of 17 competitive female rowers. Efficiency was estimated using a mechanical power approach and investigated three different stroke rates (28, 34 and 40 strokes per minute). Within this protocol internal power was measured and tracked segmental movement of one side of the body using an active marker system. Their findings reported a 20 % gross efficiency regardless of the stroke rate. It is suggested that gross efficiency should increase with exercise intensity so it is unusual that the efficiency at all three stroke rates is the same. This appears to be the only study that has examined internal work (internal power) during rowing.

2.14 The Role of the Trunk

There are a number of issues unique to a total body model. One of these is the role of the trunk. The trunk is the link in the kinetic chain between the upper and lower body, and, as such, has responsibility for transferring forces and energy between the lower and upper body (Pollock *et al*., 2009). Plagenhoef *et al*. (1983) described the trunk as being massive and mobile hence, complex to deal with. The parts of the trunk move relative to each other and cannot be considered rigid (Zatsiorsky, 2002). Previous rowing specific research has considered the trunk to be a single segment (Caplan and Gardner, 2007; Cerne *et al*., 2013) or two segments, specifically examining the lumbo-sacral region due to the high inclidence of injury (Bull and McGregor, 2000). The total body included the role of the trunk in terms of its contribution to and its transfer of energy. The trunk plays an important role in force generation and velocity (Lamb, 1989). During rowing, the trunk is not acting as a single segment and this is important in terms of transfer of internal work and efficiency (Nelson and Widule, 1983). This has received little attention in the literature and is an important issue to both understanding rowing and total body efficiency.

In walking studies the trunk is usually modelled as a segment with mass but with no intervention or effects upon gait (Leardini *et al*., 2009). This approach has simplified gait analysis but does not help in non-gait situations i.e. rowing. Whilst trunk motion has been examined during rowing, it not commonly considered as more than one segment (Shiang and Tsai 1998; Baudouin and Hawkins, 2002; Cerne *et al*., 2013). It is acknowledged that segments of the trunk have different motion patterns and increased changes in lumbo-pelvic kinematics were seen with increases in rowing intensity (Bull and McGregor, 2000; McGregor *et al*., 2002; Holt *et al*., (2003); McGregor *et al*., 2004). There is limited understanding of trunk motion during rowing with a lack of studies examining the mechanical efficiency. Cerne *et al*. (2013) indicated a major limitation of their study was that it considered the trunk as a single, rigid segment, as this would cause errors in trunk angle. The trunk stabilises and aligns segments (Tanaka *et al*., 2007), generating and transferring force from the legs to the arms, which is considered imperative to performance (Pollock *et al*., 2009). High levels of forces are experienced, particularly in the lower trunk and it is a common site for injury, in trained rowers (Tanaka *et al*., 2007; Pollock *et al*., 2009). Trunk motion has been linked to skill level of the performer, where greater trunk stability and lower flexion extension ratio has been associated with higher levels of rowing performance (Muller *et al*., 1994). In a small sample of two elite and two novice rowers, higher angular trunk velocities in novice rowers were reported compare to elite, suggesting skilled rowers minimise trunk movement to enhance force production (Tanaka *et al*., 2007).

An important issue with measuring trunk kinematics is that vertebrae do not meet the assumption of being a rigid body and difficult to accurately attach markers for motion analysis and dependent on the motion, large skin movement artefacts may be present (Leardini *et al*., 2005). Fowler *et al*. (2006) suggested that the spine needs to be treated as separate units, not just a single unit. In studies that have used spinal markers, there is a variance in the positioning and number of markers used. For example, Chan *et al*. (2006) used five spinal markers (C7, T4, T9, T12 and L3) and Syczewska *et al*. (1999) placed markers on C7, T4, T7, T10, T12, L2, L4, S2. In both of these studies, the angle of the spinal segments was of interest but no justification for the choice of marker placement was given. Fowler *et al*. (2006) used surface markers placed on C7, T4, T7, T10, T12, L2 and L4, based on the work of Syczewska *et al*. (1999). C7 and T10 are part of the Vicon Plug-in-gait model, as such additional markers could be placed without issue. The L4 marker matches a landmark used in the de Leva (1996) body segment data set and would allow for the calculation of internal work of trunk segments.

2.15 Summary

Efficiency measures the ratio of mechanical work and energy expenditure. An increase in efficiency should lead to an increase in performance. Different definitions of efficiency have been used with both modifications to the numerator and denominator of the efficiency equation. Specifically, internal work is often ignored. Previous research has more commonly looked at either lower-body or upper-body efficiency, but there is little research focusing upon a total body action. A rowing action on a laboratory ergometer allows for the assessment of a total body model of efficiency and includes internal work measurements. This allows for the assessment of changes in exercise intensity, differences in skill level and, development of the model of efficiency to account for the trunk as more than one segment along with the issues of energy transfer between segments. Hence, the overreaching aim of this thesis was to develop a total body model of efficiency to examine a rowing action, by developing a model of efficiency incorporating internal work, external work and energy expenditure, testing the model against different ergometer results, across different intensities, with differing skill groups and developing the model to account for energy transfers.

CHAPTER 3 DEVELOPMENT OF TOTAL BODY MODEL

3.1 Introduction.

Previous research has estimated efficiency during cycling, arm cranking and rowing (Widrick *et al*., 1992; Goosey-Tolfrey and Sindall, 2007; Hofmijster *et al*., 2009). Studies commonly define efficiency differently, such as the inclusion or not of internal work and hence use different methodologies, making comparison of results difficult. There is limited research that has examined efficiency of different modalities (rowing, cycling and arm cranking) using the same methodology and cohort. In doing so, it is possible to compare results between modalities and to other research to evaluate the model of efficiency. A model of efficiency was developed which incorporated internal work, external work and energy expenditure for the same cohort, across a range of exercise intensities for cycling, arm cranking and rowing ergometry.

The aims of this chapter were to develop a model to calculate the internal work for cycling, arm cranking and rowing, and to assess the reliability of the internal work data and calculate efficiency for cycling, arm cranking and rowing using a healthy, unskilled population.

3.2 Method

This section details the methods and modelling procedures to determine internal work and efficiency for rowing, cycling and arm cranking. Ethical approval for all phases of the work was obtained from the Research Ethics Committee of the University of East London (Appendix 1).

3.2.1 Participant Recruitment

Participants were recruited from staff and students of the university, based on a opportunity sample of individuals who met the selection criteria: male, aged 18-45 from the university who were physically active, injury free, responded “no” to all questions on a Par-Q and You questionnaire, had not experienced any formal rowing training or on-water instruction.

Ten active, healthy male participants who had used a rowing ergometer previously, but had no formal rowing training were recruited. All participants completed an informed consent form (Appendix 2) before commencing in the protocol. The standard anthropometrics are reported in Table 3.1.

Table 3.1 Anthropometric data (Mean±SD, 95%CI) for age, mass and height.

	Mean±SD	95%CI
Age (yrs)	33.9±8.2	(28.0-39.9)
Mass (kg)	81.0±5.7	(76.9-85.1)
Height (m)	1.78±0.06	(1.78-1.82)

3.2.2 Equipment and setup

Kinematic recordings were collected using a 10 camera, three-dimensional motion analysis system (Vicon 612, Oxford Metrics Ltd, UK) at a rate of 100Hz (Hofmijster *et al.*, 2009; Attenborough *et al.*, 2012). Prior to data collection the capture system was calibrated according to the manufacturer’s specifications. A 1 second static calibration was conducted using an ‘L’ frame, the centre of the capture volume and dynamic calibration using a T wand was carried out for 10000 frames (Figure 3.1). The calibration was considered successful if it met the manufactures recommendations (Mean residual: <0.5, wand visibility >60%, static reproducibility <1%). The ‘L’ frame was used to define the origin of the laboratory and the global coordinate system (Z= vertical, Y = anterior posterior, X = lateral). Only data in the Y and Z direction were used within the analysis as an assumption of symmetry during ergometer rowing had been made (Hofmijster *et al*., 2009; Sforza *et al*., 2012).

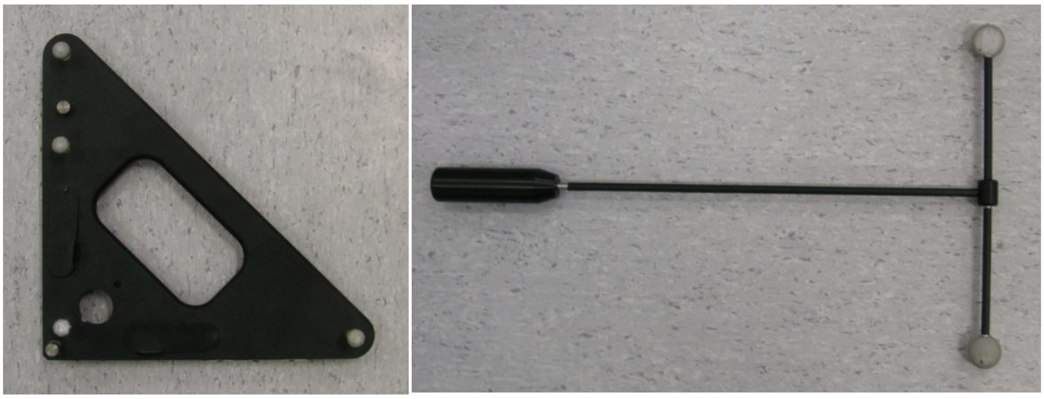

Figure 3.1 L-Frame and T-wand used for static and dynamic calibration of the Vicon 612 system

Expired oxygen and carbon dioxide were collected via an Oxycon-Pro metabolic cart (Jaeger, Germany), calibrated using known gas percentage and volumes as to the manufacturer’s instructions. Expired gas was collected on a breath-by-breath basis from a face mask that was secured via a headstrap. Three ergometers were used within the protocol: A Concept 2C (Concept 2, Morrisville, USA.) rowing ergometer with the drag factor set to 130 1.3[Nm.s^{-2}] (Volger *et al*., 2007; Gallagher *et al*., 2010; Benson *et al*., 2011), a calibrated Monark 874 cycle ergometer (Monark, Varberg) and a calibrated Monark 891 arm crank ergometer (Monark, Varberg).

3.2.3 Participant preparation

Participants wore shorts and shoes during the protocol. The following anthropomorphic measurements were taken bilaterally before testing:

- mass (kg) using Seca Model 761 scale (Seca, Germany)
- height (m) using Seca Model 213 stadiometer (Seca, Germany)
- Inter-ASIS distance (cm)
- leg length (cm, ASIS to lateral malleolus)
- knee width (cm) using 15 cm bicondylar Vernier Calliper (Holtain, Ltd. Uk) as mediolateral width, ankle width (cm, mediolateral width), elbow width (cm, mediolateral width of lateral and medial epicondyle), wrist thickness (cm, anterior-posterior width level with the styloid process), hand thickness (cm, dorsal-palmar distance), shoulder offset (cm, anterior –posterior width of humeral head/2), bilaterally where appropriate.

Fifty-three, spherical, reflective 14mm markers were attached with double sided adhesive tape to the anatomical landmarks, described in the Vicon Plug-in-Gait (PiG) total body marker set documentation (Figure 3.1.2), in the following locations: 7th cervical vertebrae, 10th thoracic vertebrae, clavicular notch, Xiphoid process, right scapula, acromio-clavicular joint, three markers on the upper arm, lateral epicondyle of the elbow, medial elbow, forearm, lateral and medial styloid (on a bar), second metacarpal, anterior super iliac spine (ASIS), posterior super iliac spine (PSIS), thigh, lateral epicondyle of the knee, lower leg, lateral malleolus, calcaneous and second metatarsal, bilaterally where appropriate. Four markers were placed approximately at the temple level at the front and rear of the head, held in place by a headband. The second metatarsal and calcaneous markers were placed on the outside of the participant's shoe.

Due to flexion of the spine during the rowing motion, two additional markers were placed on the left and right ilium (approximately at the superior apex of the iliac crest and mid-anterior -posterior line. These markers were used in conjunction with a gap filing algorithm reconstruct the ASIS markers that were obscured by the flexion and extension of the trunk during the rowing action.

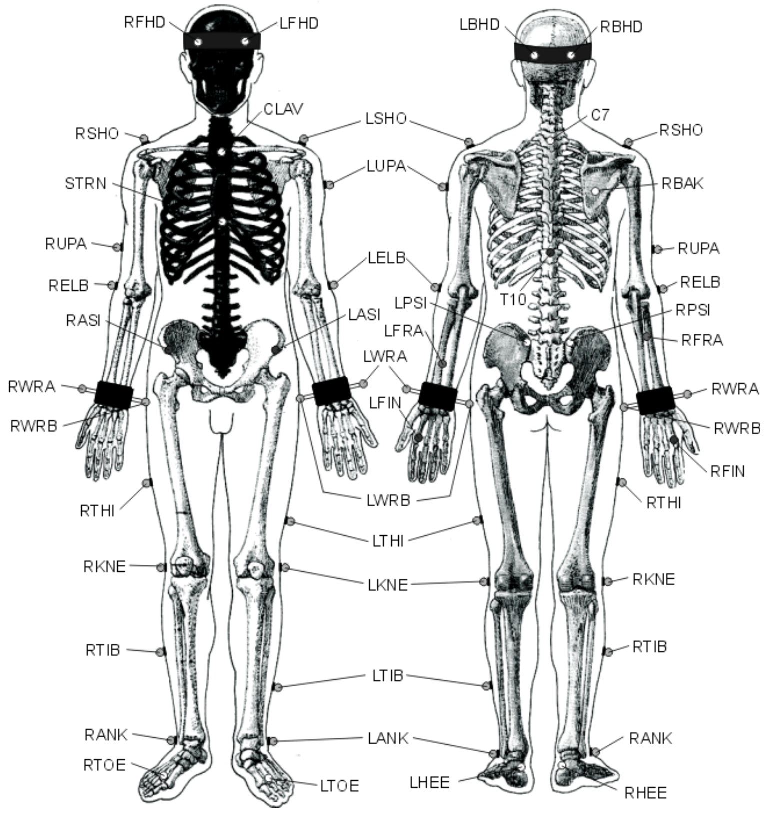

Figure 3.1.2 Plug-in-gait marker placement (Vicon, OMG, Oxford)

3.2.4 Procedure

A one-second static trial was captured using the motion capture system to allow for autolabelling and static model parameters to be calculated by the software (Vicon Workstation, OMG, Oxford). The participant stood in the anatomical position with shoulders abducted so all markers could be clearly seen. The relevant ergometer and metabolic cart were placed in the collection volume. Participants completed nine exercising trials in the following order 50, 100 and 150 W rowing, 50, 100 and 150 W cycling and 40, 60 and 80 W arm cranking.

Firstly, the participant sat on rowing ergometer and the feet straps were secured. The participant remained seated and still for a three to five minute period to become accustomed to the facemask. When the participant had become accustomed, a three minute resting stage began, where the final minute of expired gas was sampled to calculate resting energy expenditure.

The participant commenced a five-minute rowing period, at 50 W power output as indicated by the Concept 2C display unit. Participants were asked to keep the power output as close to the indicated level as possible and to attempt to maintain a self-selected rowing stroke that was consistent. After three minutes kinematic data were captured using the motion analysis system. Within the last minute of the trial expired gas was sampled. After a one-minute rest, the participant repeated the above five minute trial at 100 W and 150 W, respectively.

Secondly, after a 3 minute rest period the participant sat upon a Monarch 874 cycle ergometer for a period of 3 minutes. Expired gas was sampled within the last minute. Cycling trials corresponding to 50 W, 100 W and 150 W at 60 rpm were carried out. Each intensity level was five minutes in length and kinematic and expired gas data were sampled as above.

Thirdly, following a further 3 minute rest, participants sat at a height adjusted arm crank Monarch 891 ergometer. Expired gas was collected in the last minute of a 3 minute sitting period. Participants arm cranked at 80rpm for 3 minute periods, at 40 W, 60 W and 80 W where kinematic and expired gas data were collected.

3.2.5 Data Processing

Anthropometric data were inputted, markers were manually labelled and the Vicon PiG static model was run to create model parameters. In the dynamic trials, markers were manually labelled using Vicon Workstation. Where required the ‘replace4’ bodybuilder model was used to recreate the position of any obscured ASIS markers. Each trial was manually labelled. The data were smoothed using the Woltring smoothing algorithm (MSE=20) and data of position of joint centre against time were exported as an ASCII file.

3.2.6 Calculation of internal work

Three models were created to calculate the change in internal work during the drive phase of a rowing stroke, a cycle stroke and an arm crank stroke, based on previous research (Fedak *et al.*, 1982; Minetti *et al.*, 1993). Motion capture data and body segment parameter data based on published regressions (Winter, 2005) were used to calculate internal work using custom a scripted LabVIEW code (LabView 2012, National Instruments). As with previous research, an assumption of limbs symmetry was made (Consiglieri and Pires, 2009; Hofmijster *et al.*, 2009; Sforza *et al.*, 2012; Cerne *et al.*, 2013). Hence right hand side of the participant was analysed and the data doubled to represent the contralateral limb. Segment displacement was calculated relative to the centre of mass as per the Konig Theorem (Minetti *et al.*, 1993). Internal work (total kinetic energy) is considered the sum of translational and rotational kinetic energy during the drive phase of the rowing stroke and the top-dead-centre to bottom-dead-centre phases of cycling and arm cranking (Equation 3.1). Potential energy is accounted within external work.

$$KE_{tot} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{3.1}$$

In the first instance, the models were kept as simple as possible to address the above aims (Yeadon and King, 2007) and the following assumption were made:

- All segments are rigid bodies
- Segment lengths are from the calculated distances between the joint centres
- The segment centre of mass is located on the straight line between the joint centres
- Model looks at absolute change and has not accounted for positive and negative work
- The data capture model (PiG) adequately represents the motion of interest
- Movement was symmetrical for left and right limbs
- A 2D (Y and Z) representation was appropriate for the motion of interest
- Acceleration due to gravity is considered to be 9.81 $m.s^{-2}$

The modelling process was as follows: calculated the segment length; identified the segmental centre of mass; calculated the centre of mass of the body; calculated the displacement of segmental centre of mass from total body centre of mass; calculated the linear and angular velocity of segmental centres of mass; calculated the absolute change in total kinetic energy (linear and angular kinetic energy). This is summarised in figure 3.2. The models of internal work are combined with external work and energy expenditure to estimate gross and net efficiency.

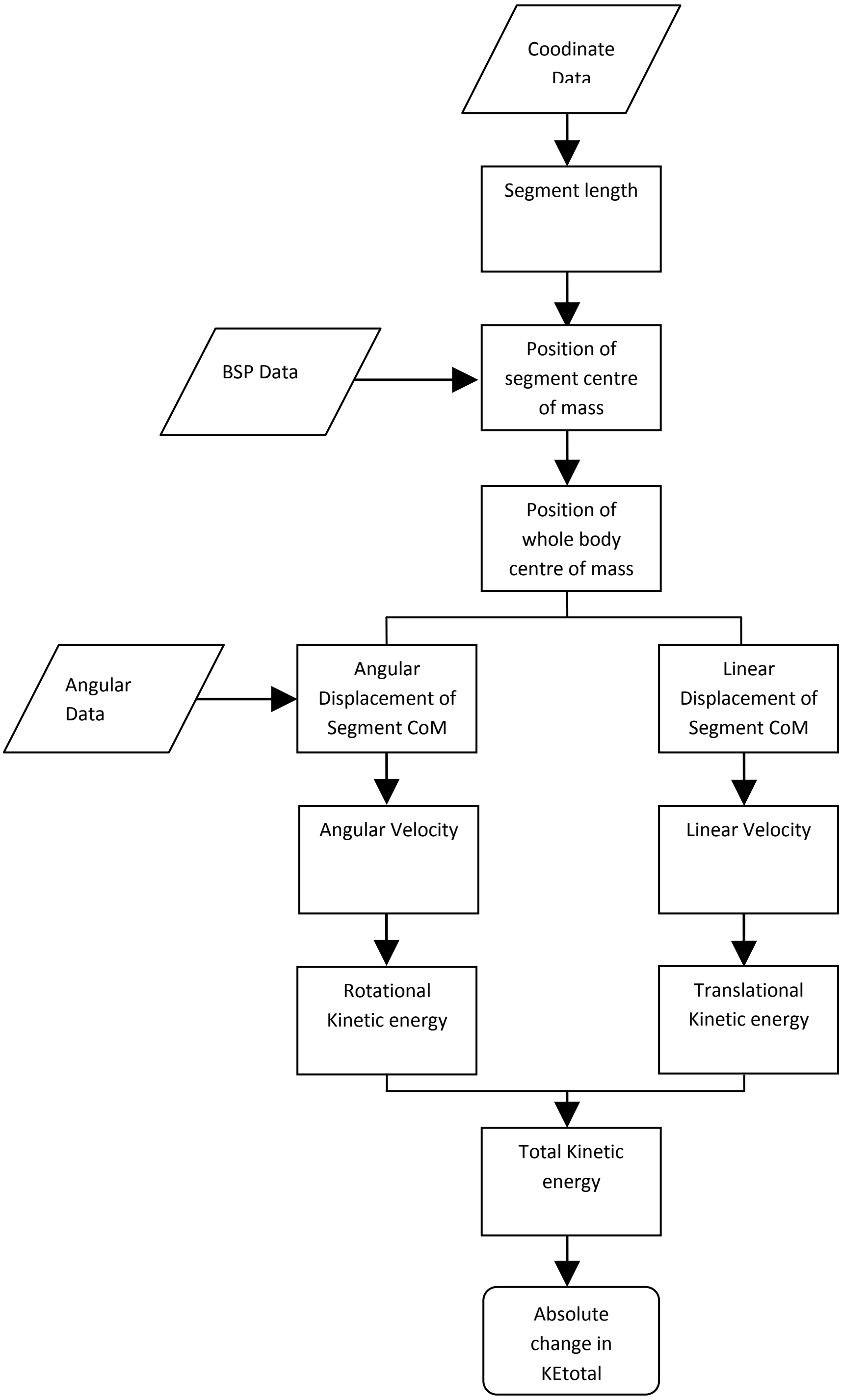

Figure 3.2 Schematic of workflow for estimates of internal work

The following steps will outline the basis of the calculations for the model of internal work

3.2.6.1 Joint centre identification

The y and z positional coordinates of the following joint centres (table 3.2) were identified from output of the PiG model from the Motion capture software:

Table 3.2 Joint centres used in model

Parameter	Joint Centre
Shoulder	LCLO & RCLO
Elbow	LHUO & RHUO
Wrist	LRAO & RRAO
Hand	LHNO & RHNO
Thigh	LFEP & RFEP
Knee	LFEO & RFEO
Ankle	LTIO & RTIO
Foot	LFOO & RFOO
Head	HEDO
Pelvis	PELO

By joining the following joint centres, the given segments were defined deriving a 13 segment body (Table 3.3).

Table 3.3 Segment determined from joint centres

Segment	Proximal	Distal
Right Upper arm	RCLO	RHUO
Right Forearm	RHUO	RRAO
Right Hand	RRAO	RHNO
Right Thigh	RFEP	RFEO
Right Shank	RFEO	RTIO
Right Foot	RTIO	RTOO
Trunk	HEDO	PELO

.2.6.2 Segmental length

Segment length was calculated by Pythagoras theorem from y and z coordinates of the proximal and distal joint centres for each segment (Equation 3.2).

$$Segment\ length = \sqrt{\left(\left|proximal_y - distal_y\right|\right)^2 + (|proximal_z - distal_z|)^2} \tag{3.2}$$

where proximal$_y$ = the y-coordinate of the proximal joint, distal$_y$ = the y-coordinate of the distal joint, proximal$_z$ = the z-coordinate of the proximal joint, distal$_z$ = the z-coordinate of the distal joint.

3.2.6.3 Position of segmental centre of mass

The position of the segmental centre of mass was calculated from regression data of Winter (2005) as a percentage of segment length. Segment length was multiplied by the given percentage from the distal end of the segment and this value was added to the original distal value. Position of segmental centre of mass was calculated at all of the time intervals of the stroke duration (Equation 3.3 and 3.4).

$$Y\ Position\ CoM_{seg} = (Segment\ length\ \times \%distal) + position\ of\ distal\ JC \tag{3.3}$$

$$Z\ Position\ CoM_{seg} = (Segment\ length\ \times \%distal) + position\ of\ distal\ JC \tag{3.4}$$

where Y Position CoM$_{seg}$ = y-coordinate of position of the segmental centre of mass, Z Position CoM$_{seg}$ = z-coordinate of position of the segmental centre of mass.

The results for all considered segments were used for two purposes: firstly, to determine the centre of mass of the whole body (CoMwb); secondly, to calculate the changes in the position of the segmental centres of mass.

3.2.6.4 Position of whole body centre of mass

The position whole body centre of mass was required to calculate the displacement of the segmental centre of mass. This was calculated based on a principle of moments approach (Watkins, 2007). The moment of each segment was calculated by multiplying the position of segmental centre of mass by the percentage weight of the segment and summed for all segments in both the y and z dimensions (Equation 3.5 and 3.6), determining the y and z coordinate for CoM$_{wb}$, at each time interval.

$$CoM_{wby} = \frac{Sum\ of\ segment\ Moments\ y}{W} \tag{3.5}$$

$$CoM_{wbz} = \frac{Sum\ of\ segment\ Moments\ z}{W} \tag{3.6}$$

where W= body weight (N), CoM$_{wby}$ is the y-coordinate of position of the whole body centre of mass, CoM$_{wbz}$ = z-coordinate of position of the whole body centre of mass.

Translational and rotational kinetic energy were considered separately and described below.

3.2.6.5 Linear displacement and velocity of segmental CoM

Segmental velocity (Equation 3.10) was determined from the displacement of the segmental mass relative to the whole body centre of mass with respect to time (Equation 3.7, 3.8 and 3.9).

$$Displacement_{CoMsegY} = \left(\left|CoM_{wby1} - CoM_{segy1}\right|\right) - \left(\left|CoM_{wby0} - CoM_{segy0}\right|\right)$$

(3.7)

where Displacement$_{CoMsegy}$ *= displacement of segmental centre of mass in y-direction, y1=final position, y0 = initial position*

$$Displacement_{Comsegz} = \left(\left|CoM_{wbz1} - CoM_{segz1}\right|\right) - \left(\left|CoM_{wbz0} - CoM_{segz0}\right|\right)$$

(3.8)

where Displacement$_{CoMsegz}$ *= displacement of segmental centre of mass in z-direction, z1=final position, z0 = initial position*

$$Displacement_{Comseg} = \sqrt{\left(Displacement_{CoMsegy} + Displacement_{CoMsegz}\right)^2}$$

(3.9)

where Displacement$_{CoMseg}$ *= resultant displacement of segmental centre of mass*

$$Velocity_{Comseg} = \frac{Displacement_{CoMseg}}{time\ interval}$$

(3.10)

3.2.6.6 Translation kinetic energy

Translation kinetic energy was calculated from the following equation for all segments considered and summed (Equation 3.11).

$$TKE = \Sigma \frac{1}{2} m v^2$$

(3.11)

where TKE=translational kinetic energy, m=mass, v=velocity

The absolute total change in TKE over the stroke duration was considered as ΔTKE.

3.2.6.7 Angular displacement and velocity of segmental CoM

Segmental angular velocity (rad.s^{-1}) was derived from the change in angular displacement from the outputted data via the Vicon PiG model with respect to the time interval (Equation 3.12).

$$\omega = \frac{\theta_f - \theta_i}{\Delta t} \tag{3.12}$$

where ω = angular velocity, θ_f = final angle, θ_i = initial angle, Δt = time interval.

The moment of inertia was calculated by equation 3.13

$$I = (M.m) \times (l.r)^2 \tag{3.13}$$

where M =mass, m= segmental mass, l = segment length and r =radius of gyration.

3.2.6.8 Rotational kinetic energy

Rotational kinetic energy was calculated for each segment and summed (Equation 3.14)

$$RKE = \Sigma \frac{1}{2} I\omega^2 \tag{3.14}$$

where RKE=rotational kinetic energy, I=moment of inertia, ω=angular velocity

3.2.6.9 Total body kinetic energy

The total change in kinetic energy hence internal work was calculated from the following equation 3.15 (Cavagna and Kaneko, 1977).

$$\mathrm{W_{int}} = \sum \left|\frac{1}{2}\mathrm{mv}^2\right| + \left|\frac{1}{2}\mathrm{I\omega}^2\right| \tag{3.15}$$

Where W_{int} = internal work, m= segment mass, v= velocity and ω= angular velocity.

3.2.7 External work

External work was taken from the rowing, cycling and arm-cranking ergometers, based on the desired power output. The power output was converted to kilojoules per minute (3, 6 and 9 kJ.min^{-1}) and multiplied by the stroke duration. This was summed with internal work to form total work.

3.2.8 Energy expenditure

Energy expenditure was assessed using expired-gas indirect-calorimetry. For all phases of data collection, the average concentration and volume of expired oxygen and carbon dioxide the final minute each trial, was measured. The respiratory exchange ratio (R-value, ratio of volume of carbon dioxide to volume of oxygen) is associated with a given energy expenditure, from data tables showing the energy released from the metabolism of carbohydrate, fat and protein (Peronnet and Massicotte, 1991), for the amount of oxygen consumed, to estimate the energy expenditure for a given work load (Robergs *et al.*, 2010). The average of the final minute of the trial was used to estimate the participant's energy expenditure. Resting energy expenditure was determined prior to the rowing trials, to calculate gross and net energy expenditure.

3.2.9 Gross efficiency

Gross efficiency was calculated from the sum of internal and external work divided by the energy expended as in equation 3.16

$$Gross\ efficiency = \frac{internal\ work + external\ work}{Energy\ expenditure}$$

(3.16)

3.2.10 Net efficiency

Net efficiency was calculated from the sum of internal and external work divided by the energy expended minus the resting energy expenditure as in equation 3.17

$$Net\ efficiency = \frac{internal\ work + external\ work}{Energy\ expenditure - resting\ energy\ expenditure}$$

(3.17)

3.2.11 Specific modelling methodology

For the rowing trials, the data from all segments were used. The analysis was completed on a single side of the body and doubled to reflect the contra-lateral limbs. In the cycling trials only the leg segments were considered to do work, and likewise in the arm cranking trials only arm segments were considered to do work.

3.2.13 Drive duration

In rowing, stroke duration is commonly used to determine intra-subject reliability of the rowing stroke determined by the displacement and time of the handle of the ergometer (Ng *et al.*, 2013). As the handle was not marked the left finger (RFIN) marker was used as an alternative marker to determine stroke duration.

The minimum y-coordinate position, per stroke, of the RFIN marker was identified by a custom LabVIEW code as the start position and time of each stroke. The maximum y-coordinate position and time was determined as the end of the drive phase. The time, in seconds, from minimum to maximum was considered the drive duration (Equation 3.18).

$$Drive\ duration\ (s) = Time\ at\ \mathrm{max_y} - Time\ at\ min_y \tag{3.18}$$

3.2.14 Data management

3.2.14.1 Determination of normality

Kolmogrov-Smirnov and Shapiro-Wilk tests, as well as a number of others, are commonly used to assess the distribution of data (Ghasemi and Zahediasl, 2012). Razali and Wah (2011) have suggested that the Shaprio-Wilk statistic is more appropriate with smaller sample size and the Kolmogrov-Smirnov is more conservative in rejecting non-normal distributions, due to the sensitivity to extreme values (Ghasemi and Zahediasl, 2012). As it is common in biomechanical studies to have a small number of participants (Knudson, 2009) and due to the recommendations of Ghasemi and Zahediasl, (2012), the Shapiro-Wilk test was used to assess normality of data. A significance value less than *p*<0.05 was indicative that data were not normally distributed and non-parametric analysis were used.

3.2.14.2 Statistical differences

The limitation that null hypothesis significance testing can only assess the probability of the results being due to chance, have been recently highlighted (Lew, 2012; Nuzzo, 2014; Winter *et al*., 2014). Probability based values are affected by the variance and sample size, hence missing important differences in small samples or inflating trivial differences in large samples (Rhea, 2004). The advantages of magnitude-based inferences have been suggested as superior analytic tools (Winter *et al*., 2014) and will be considered presently. Based on the above, inferential statistics will be reported but only be used to assess the likelihood of chance results occurring. Furthermore, the phrase ‘statistical difference’ will be used in favour of ‘significant difference’ (Cummings, 2013). In light of these criticisms, *p*-values will only be used to assess probability of chance, whereas differences will be assessed using effect size statistics.

3.2.14.3 Effect size

The magnitude of the differences have been suggested as more meaningful than *p* values (Hopkins, 2000; Winter *et al*., 2014). Effect size calculations, such as Cohen’s *d*, omega squared and eta squared, are commonly to assess the magnitude and meaningfulness of the differences. Cohen’s *d* is suggested as the most commonly used (Rhea, 2004, equation 3.19)

$$d = \frac{(m_1 - m_2)}{s} \tag{3.19}$$

Where m_1= mean of group 1, m_2 = mean of group 2 and s = standard deviation.

Often the standard deviation is considered a pooled standard deviation and is calculated as equation 3.20.

$$s_p = \sqrt{\frac{{s_1}^2(n_1 - 1) + {s_2}^2(n_2 - 1)}{n_1 + n_2 - 2}} \tag{3.20}$$

Where s_1 is the SD of group , s_2 is the SD of group 2, n_1 is number of participants in group 1 and n_2 is number of participants in group 2.

The result is reported in standard deviation units, where *d*=1.0 is equivalent to a difference of one standard deviation, *d*=0.5 is equivalent to half the standard deviation. This means results are in the units that were measured, as opposed to a percentage or ratio, and because they are normalised measures comparisons to similar studies are possible (Rhea, 2004). Effect size also offers the ability to determine the size (magnitude) of the differences or effects. Cohen (1969) proposed the following scale of the interpretation of magnitude; 0.0-0.2 as trivial, 0.21-0.5 as small, 0.51-0.8 moderate and 0.8 and above as large. The classification of results appears to be arbitrary in its construction, closely approximating correlation co-efficient interpretations. The scale has been criticised and alternative interpretations of the coefficients have been suggested, especially if changes in results are very small (Hopkins, 2000). Rhea (2004) provided guidance for modification of the interpretation of effect within strength and conditioning that accounted for the training experience of individuals. However, it has been recently suggested by Winter *et al*. (2014) that an effect size of 0.2 is the minimum practical difference level which is based on Cohen's (1988) modified scale and these will be the values used within this study, i.e. 0.2-0.4 =small, 0.41-0.7= moderate, >0.71 = large.

3.2.14.4 Measures of Reliability

Reliability is a measure of the reproducibility of a measurement by comparison of results in repeated trials, indicating the consistency and freedom from error of the measurement (Hopkins, 2000). Acceptable levels of reliability are needed to quantify changes across conditions and to assess whether an intervention has a greater effect than the measurement error (McGinley *et al*., 2009). Various statistical approaches have been used to estimate the level of reliability, however there is not a single, agreed-upon method (McGinley *et al*., 2009). Any measure will be made up of the true value plus measurement error. These errors commonly include marker placement, skin movement artefact, system errors (motion capture and reconstruction) calibration and biological variation (McGinley *et al*., 2009). Inter-session or between-session reliability quantifies the reproducibility of measurements over time. This establishes consistency of session to session measures and is affected by different experimenters, marker placement, health status of participants, temperature, maturation, etc (Hopkins, 2001). Where single-session testing is undertaken (i.e. no retest), it is more appropriate to examine the intra-session reliability. This examined the consistency of performance over a number of trials but is less reported than inter-session reliability (Hopkins, 2001).

3.2.14.5 Intraclass correlation coefficients

An intraclass correlation coefficient (ICC) is a ratio of the variance between participants and the variability (noise or error) of the data and attempts to measure the consistency of measures when used on the same individuals (Weir, 2005). An ICC of 0.8 would suggest 80 % of the observed variance is due to the true score variance and 20 % due to error variance. Generally the larger the ICC value, the lower the error. Intraclass correlation coefficient values greater than 0.75 are considered excellent reliability, 0.4-0.75 indicated fair to good reliability and less than 0.4 indicated poor reliability (Lexell and Downham, 2005).

Shrout and Fleiss (1979) outlined six models of ICC pertaining to the model of ANOVA and whether the value is a single value or a mean. Wilken *et al*. (2012) indicated ICC are regularly used to report reliability of kinematic and kinetic data. Lexell and Downham (2005) indicated that ICC can be used with small samples sizes that are common in biomechanical studies (Knudson, 2009). To determine intra-session (trial-to trial) reliability, the ICC(2,1) has been recommended by Lexall and Downham (2005) and Denegar and Ball (1993). Intra-session reliability has been assessed using an ICC(2,1) during EMG analysis and grip forces (Hashemi Oskouei *et al*., 2013), stability during walking (Kang and Dingwell, 2006), 3D kinematics during running (Ferber *et al*., 2002) and strength testing (Symons *et al*., 2005).

Intraclass correlation coefficients are not without contention, as there is little consensus on the interpretation of the derived ICC values. Furthermore, large ICC values can be reported when trial-to-trial consistency is poor due to large between-participant variability. A low ICC can occur when trial-to-trial variability is low and the between participant variation is low (Weir, 2005). The use of the ICC has been criticised and although useful in assessing the variation it does not use the original unit making it difficult to establish the magnitude of the variability (Knudson, 2009).

3.2.14.6 Standard error of the measurement

Whilst an ICC examines the differences between participants, it does not quantify the trial-to-trial variability of the data that would indicate consistency of performance. Standard error of the measurement (SEM) is an absolute measure of reliability, in the units of the original measurement, which assesses the stability of values in repeated data collection (Weir, 2005). The SEM represents the measurement error within the data. SEM can be calculated (Equation 3.21) from the ICC data:

$$SEM = SD\sqrt{1 - ICC}$$

(3.21)

where SD is the standard deviation of all samples and ICC is the reliability coefficient.

Lexell and Downham (2005)suggested SEM should be included in reliability data and this is also advocated by Hopkins (2001), who refers to SEM as ‘typical error’. Furthermore, in a systematic review of 3D gait analysis, McGinley *et al*. (2009) suggested that ICC alone was not able to derive enough information to determine reliability.

Graphical representation of data included 95% confidence interval (95%CI) as error bars as it allows a useful interpretation of the data without references to statistics (Cumming and Finch, 2005).

3.2.15 Data Analysis

Data management does not have single unified standards, hence the following was used for interpretation of results:

1. Normality was determined by Shapiro-Wilk statistic

2. Repeated measures ANOVA for normally distributed data and Friedman’s ANOVA for non-normally distributed data was used to indicate statistical differences between exercise intensities. Inferential statistics were used to assess the probability of chance results, rather than to indicate any differences between comparisons.

3. Effect sizes were used to interpret differences, using Cohen’s *d* and the following classifications: 0.2-0.4 =small, 0.41-0.7= moderate, >0.71 = large .

4. Reliability was considered from the ICC coefficient classification of Lexall and Downham (2005): <0.4=poor, 0.41-0.75=fair to good, >0.75 =excellent reliability and interpretation of SEM.

5. Error bars were based on 95% confidence intervals (Cumming and Finch, 2005).

3.3 RESULTS

3.3.1 Reliability of internal work during rowing

Internal work was calculated for the drive phase of the rowing stroke using 8 trials per intensity for each participant. Both 50 W and 150 W exercise intensity was normally distributed ($p>0.05$) but 100 W was not normally distributed ($p<0.05$), as determined by Shapiro-Wilk test (Appendix 3).The data were assessed for within-session reliability, per intensity, using ICC(2,1) and SEM. The data in Table 3.4 are within the good to excellent reliability category as suggested by Lexall and Downham (2005). The SEM was 2.9 to 5.8, approximate a 7 % measurement error.

Internal work was calculated for the drive phase of the rowing stroke using 8 trials per intensity for each participant. Internal work increased with respect to exercise intensity (Table 3.4). The 100 W trials were not normally distributed (Appendix 3), so differences were assessed using Friedman's ANOVA. Statistical differences were reported between conditions, $x^2(2)=18.2$, $p<0.05$. Wilcoxon signed rank test were used as post-hoc analysis, correcting for the number of comparisons (significance/number of comparisons $\therefore 0.05/3 = 0.017$). Statistical differences were reported between all conditions ($p<0.017$), supported by large effect sizes, (d= 50 vs 100 W = 2.54, 100 vs 150 W = 1.29, 50 vs 150 W = 5.76).

Table 3.4 Mean±SD, 95%CI, ICC and SEM for internal work during rowing

Intensity (W)	Mean±SD (J)	95%CI	ICC(2,1) value	SEM (J)
50	36.8±6.4	32.1-41.4	0.80(0.57-0.992)	2.9
100	63.7±16.6	51.8-75.5	0.91(0.81-0.971)	5.1
150	81.8±10.7	74.1-89.5	0.71(0.49-0.90)	5.8

3.3.2 Reliability of drive duration during rowing

Drive duration was used to assess the reliability of the rowing action as the participants were not trained in the movement pattern. Drive duration was determined as the time (s) of drive phase of the rowing stroke. The data were considered normally distributed and reliability was determined using ICC(2,1). The results suggested that the participants drive duration was considered reliable with ICC greater than 0.925 (Table 3.5). The SEM was less than 0.04s and represented a measurement error less than 0.04 %. Drive duration decreased with respect to intensity. The data were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=4.247$, $p>0.05$. A repeated measures ANOVA reported statistical differences between drive duration at 50, 100 & 150 W, F (2.0, 18.0) =71.86, $p< 0.05$. Bonferroni Post hoc comparisons indicated statistical differences between all intensities ($p<0.05$), supported by large effect sizes for all comparisons (*d*= 50 vs 100 W = 1.61; 100 vs 150 W = 0.95; 50 vs 150 W = 2.43).

Table 3.5 Mean±SD, 95%CI, ICC and SEM for drive duration (s) during rowing

Intensity (W)	Mean±SD (S)	95%CI	ICC(2,1) value	SEM (S)
50 W	1.35±0.15	1.26-1.44	0.951(0.892-0.985)	0.031
100 W	1.14±0.11	1.07-1.21	0.925(0.840-0.977)	0.029
150 W	1.04±0.10	0.98-1.10	0.955(0.901-0.987)	0.021

3.3.3 Reliability of internal work during cycling

Internal work of a single leg was measured, per intensity for eight trials from top-dead-centre to bottom dead centre for a single leg. The data were normally distributed ($p>0.05$), determined by a Shapiro-Wilk test (Appendix 3). Reliability from an ICC(2,1) was 0.84-0.87, above the excellent threshold of Lexall and Downham, (2005). Standard error of the measurement (SEM) approximated 2 J and suggested a measurement error up to six percent measurement error (Table 3.6). Data met the assumptions of sphericity using Mauchly's test, $x^2(2)=5.310$, $p>0.05$, and a repeated measures ANOVA reported non-statistical differences between internal work at 50, 100 & 150 W, F (2.0, 18.0) =2.564, $p> 0.05$. Small to moderate effect sizes were reported (*d*= 50 vs 100 W=0.28; 100 vs 150 W=0.43; 50 vs 150 W=0.67).

Table 3.6 Mean±SD, 95%CI, ICC and SEM for internal work during cycling

Intensity (W)	Mean±SD (J)	95%CI	ICC(2,1) value	SEM (J)
50	34.8±5.1	31.2-38.5	0.836 (0.680-0.947)	2.13
100	33.5±4.3	30.4-36.6	0.842 (0.690-0.949)	1.80
150	31.6±4.6	28.3-34.9	0.887 (0.963-0.995)	1.59

3.3.4 Reliability of internal work during arm cranking

Internal work of arm-cranking, from top-dead-centre to bottom dead centre for a single arm, decreased between intensities during the cranking conditions. Results showed an ICC(2,1) of greater than 0.7 minimum (Baumgartner and Chang, 2001) and were considered reliable. The SEM of approximately 1 J suggested an 8-12% measurement error (Table 3.7). The data were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $x^2(2)=0.807$, $p>0.05$. A repeated measures ANOVA reported statistical differences between work done at 40, 60 & 80 W, $F(2.0, 18.0) = 3.759$, $p < 0.05$. Bonferroni Post hoc comparisons indicated no statistical differences between all exercise intensities ($p>0.05$), although small to moderate effect sizes (*d*) were reported (40 vs 60 W = 0.25, 60 vs 80 W = 0.57, 40 vs 80 W = 0.75).

Table 3.7 Mean±SD, 95%CI, ICC and SEM for internal work during arm-cranking

Intensity (W)	Mean±SD (J)	95%CI	ICC(2,1) value	SEM (J)
40	12.7±3.6	10.0-15.4	0.918 (0.826-0.975)	1.07
60	11.9±2.9	9.8-14.0	0.812 (0.641-0.938)	1.33
80	10.4±2.2	8.9-12.0	0.720 (0.508-0.901)	1.28

3.3.5 Gross and net efficiency for rowing

Gross and net efficiency was calculated by total work during rowing ($kJ.min^{-1}$) divided by gross and net energy expenditure ($kJ.min^{-1}$), respectively. Gross efficiency increased with respect to intensity ranging from ≈17-25 % (Figure 3.3). Net efficiency increased between 50 W (≈24 %) and 100 W (≈30 %) but decreased to ≈29 % in the 150 W condition (Figure 3.3).

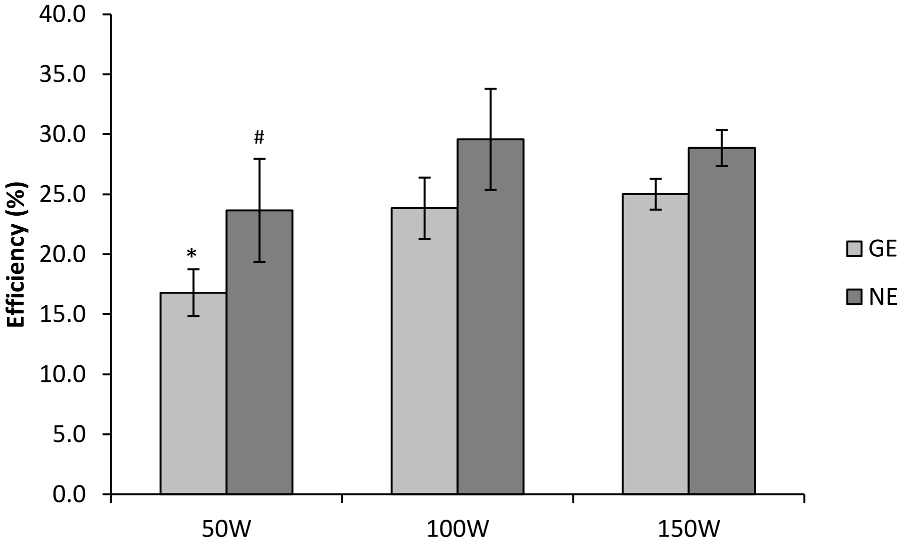

Figure 3.3 Mean (±95%CI) gross and net efficiency during rowing at 50, 100 and 150 W
* =statistical differences (p<0.05) between GE conditions
# =statistical differences (p<0.05) between NE conditions

Gross efficiency data were normally distributed (Appendix 3) but assumption of sphericity was violated according to Mauchly's test, $x^2(2)=8.417$, $p<0.05$, hence the Greenhouse-Geisser correction was utilised. Statistical differences were indicated for gross efficiency estimates (F (1.212, 10.904) = 43.432, $p<0.05$). Bonferroni post hoc comparisons showed statistical differences with large effect sizes ($p<0.05$), between 50 & 100 W (d = 1.91) and 50 & 150 W (d = 3.08). Non-statistical differences were reported between 100 and 150 W ($p>0.05$) with a moderate effect size (d = 0.36).

For net efficiency, the 50 and 100 W trials were not normally distributed (Appendix 3), so differences were assessed using Friedman's ANOVA. Statistical differences were reported between conditions ($X^2(2)=12.6$, $p<0.05$). Wilcoxon signed rank test were used as post-hoc analysis, correcting for the number of comparisons (significance/number of comparisons $\therefore 0.05/3 = 0.017$). Statistical differences were seen between 50 and 100 W ($p<0.017$), however no other statistical differences were reported ($p>0.017$). Conversely, large effect sizes were reported for 50 vs 100 W (d = 2.94) and 50 vs 150 W (d = 7.8) but only a trivial effect size reported between 100 vs 150 W (d = 0.14).

3.3.6 Gross efficiency for cycling and arm cranking

Gross efficiency for cycling was calculated from total work (kJ.min^{-1}) divided by energy expenditure (kJ.min^{-1}) for each exercise intensity. Gross efficiency increased with respect to energy expenditure and ranged from ≈23-26 % (Figure 3.4).

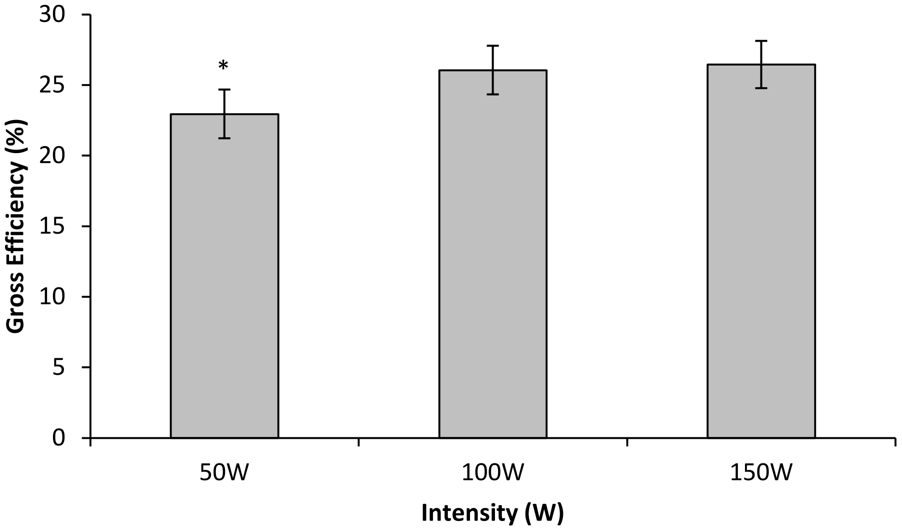

Figure 3.4 Mean (±95%CI) Gross efficiency during cycling at 50, 100 and 150 W
* =statistical differences (p<0.05) between GE conditions

Gross efficiency during cycling was normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=0.590$, $p>0.05$. A repeated measures ANOVA reported statistical differences in energy expenditure between 50, 100 and 150 W, ($F(2.0, 18.0) = 9.795$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences between 50 & 100 W and 50 & 150 W intensities ($p<0.05$) supported by large effect sizes (d = 50 vs 100 W = 1.12; 50 vs 150 W = 1.27). Non-statistical differences with very small effect sizes were reported between, 100 vs 150 W ($p>0.05$, $d = 0.14$).

Gross efficiency for arm cranking was calculated from total work (kJ.min^{-1}) divided by energy expenditure (kJ.min^{-1}) for each exercise intensity. Gross efficiency increased with respect to energy expenditure (Figure 3.5).

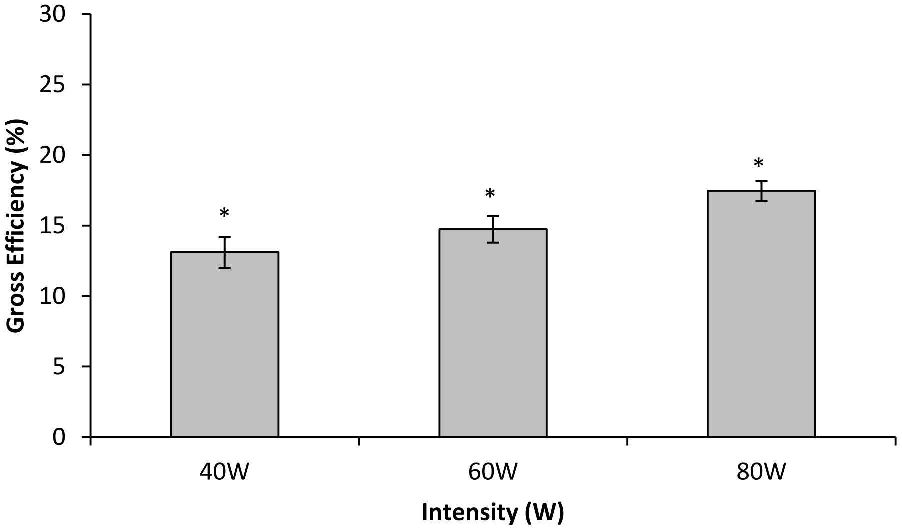

Figure 3.5 Gross efficiency during arm-cranking at 40, 60 and 80 W
* =statistical differences (p<0.05) between GE conditions

The data were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=4.355$, $p>0.05$. A repeated measures ANOVA reported statistical differences in efficiency estimates between 40, 60 & 80 W, ($F(2.0, 18.0) =43.66$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences between all intensities ($p<0.05$), supported by large effect sizes for all comparisons (d = 40 vs 60 W = 0.99; 60 vs 80 W = 2.02; 40 vs 80 W = 2.91).

3.3.7 Total work done

Total work done was considered the sum of internal work and external work. External work was determined from the target power output (exercise intensity) for the participants. Exercise intensity in watts (50, 100 and 150 W) for the rowing protocol was converted to energy was converted to kJ.min^{-1} (i.e. 3, 6 or 9 kJ.min^{-1}) and was considered as a constant for each exercise intensity. The internal work values were converted from joules per stroke to kJ.min^{-1} and summed to the external work constant for each intensity. Total work increased with respect to intensity (Table 3.8), was normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=0.393$, $p>0.05$. A repeated measures ANOVA reported statistical differences total work done between 50, 100 and 150 W, ($F(2.0, 18.0) = 956.47$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences in total work done between 50, 100 and 150 W (p<0.05), supported by large effect sizes between intensities (d = 50 vs 100 W = 4.9; 100 vs 150 W = 4.4; 50 vs 150 W= 9.33).

Table 3.8 Mean±SD, internal (W_{int}), External (W_{ext}) and Total (W_{tot}) work during rowing

Intensity (W)	W_{int} (kJ.min^{-1})	W_{ext} (kJ.min^{-1})	W_{tot} (kJ.min^{-1})
50	1.44 ± 0.23	3.0	4.44 ± 0.23
100	3.36 ± 0.80	6.0	9.36 ± 0.80
150	4.77 ± 0.78	9.0	13.77 ± 0.78

The external work target for the cycling protocol also was 50, 100 and 150 W and was converted to kJ.min^{-1} (i.e. 3, 6 or 9 kJ.min^{-1}). The internal work values were converted from joules per cycle to kJ.min^{-1} and summed to the external work constant for each intensity. Total work increased with respect to intensity (Table 3.9), was normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=5.411$, $p>0.05$. A repeated measures ANOVA reported statistical differences total work done between 50, 100 and 150 W, ($F(2.0, 18.0) = 2253.85$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences in total work done between 50, 100 and 150 W (p<0.05) supported by large effect sizes between intensities (d = 50 vs 100 W = 10.0; 100 vs 150 W = 11.0; 50 vs 150 W = 20.0).

Table 3.9 Mean±SD, internal (W_{int}), External (W_{ext}) and Total (W_{tot}) work during cycling

Intensity (W)	W_{int} (kJ.min^{-1})	W_{ext}(kJ.min^{-1})	W_{tot}(kJ.min^{-1})
50	2.09 ±0.31	3.0	5.09 ±0.31
100	2.01 ±0.26	6.0	8.01 ±0.26
150	1.90 ±0.28	9.0	10.90 ±0.28

The external work target for arm cranking was 40, 60 and 80 W, which were converted to kJ.min^{-1} (i.e. 2.4, 3.6 or 4.8 kJ.min^{-1}). Internal work values were converted from joules per cycle to kJ.min^{-1} and summed to the external work constant for each intensity. Total work increased with respect to intensity (Table 3.10), were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, $X^2(2)=1.781$, $p>0.05$. A repeated measures ANOVA reported statistical differences in total work between 40, 60 & 80 W, ($F(2.0, 18.0) =1960.17$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences between all intensities (p<0.05), as indicated by large effect sizes between intensities (d = 40 vs 60 W = 8.2; 60 vs 80 W = 7.3; 40 vs 80 W = 18.5).

Table 3.10 Mean±SD, internal (W_{int}), External (W_{ext}) and Total (W_{tot}) work during arm-cranking

Intensity (W)	W_{int} (kJ.min^{-1})	W_{ext} (kJ.min^{-1})	W_{tot} (kJ.min^{-1})
50	0.71 ±0.12	2.4	3.11 ±0.12
100	0.71 ±0.17	3.6	4.31 ±0.17
150	0.62 ±0.13	4.8	5.42 ±0.13

3.3.8 Energy Expenditure

Gross and net energy expenditure was calculated from VO_2, VCO_2 and R-value data (Figure 3.6). Resting energy expenditure was assessed with participants sitting on the ergometer. Net energy expenditure was calculated by subtracting resting energy expenditure from gross energy expenditure. Gross and net energy expenditure increased with respect to exercise intensity (Table 3.11).

Table 3.11 Metabolic energy expenditure during rowing

	Rest	50W	100W	150W
VO_2 (L.min^{-1})	0.35±0.06	1.28±0.18	1.86±0.21	2.60±0.29
VCO_2(L.min^{-1})	0.29±0.05	1.13±0.21	1.82±0.34	2.83±0.57
R-value	0.83±0.07	0.88±0.07	0.97±0.08	1.08±0.11
Energy Equivalent (kJ)	20.91±0.33	21.15±0.33	21.47±0.24	21.67±0.05
Gross Energy Expenditure (kJ.min^{-1})	7.35±1.16	27.05±2.49	39.92±4.87	55.26±3.71
Net Energy Expenditure (kJ.min^{-1})		19.70±2.35	32.58±4.89	47.92±3.35

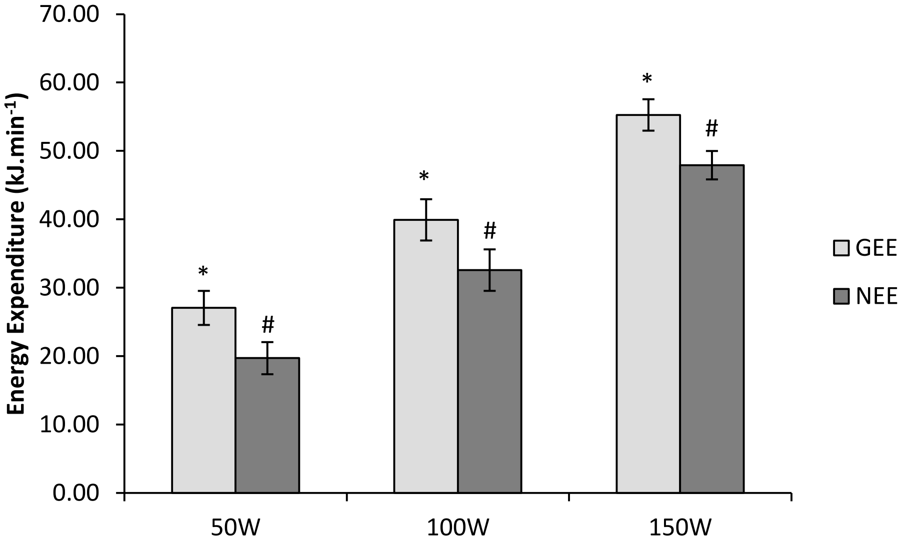

Figure 3.6 Mean (±95%CI) gross and net energy expenditure (kJ.min^{-1}) during rowing at 50, 100 and 150 W

* =statistical differences ($p<0.05$) between GEE conditions

=statistical differences ($p<0.05$) between NEE conditions

Gross energy expenditure increased with respect to exercise intensity. The data were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test ($X^2(2)=5.988$, $p>0.05$). A repeated measures ANOVA reported statistical differences between gross energy expenditure at 50, 100 & 150 W ($F(2.0, 18.0) =404.7$, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences between all exercise intensities ($p<0.05$), supported by large effect sizes (d = 50 vs 100 W = 2.88; 100 vs 150 W = 3.55, 50 vs 150 W = 7.30).

Net energy expenditure increased with respect to exercise intensity, but was less in magnitude than gross energy expenditure. The 50 and 100W trials were not normally distributed (Appendix 3), so differences were assessed using Friedman's ANOVA. Statistical differences were reported between conditions ($X^2(2)=20.0$, $p<0.05$). Wilcoxon signed rank test were used as post hoc analysis, correcting for the number of comparisons (significance/number of comparisons $\therefore 0.05/3 = 0.017$). All three results were statistically different $p<0.017$ supported by large effect sizes that were reported for all comparisons (d = 50 vs 100 W = 2.94; 100 vs 150 W = 3.65; 50 vs 150 W = 7.88).

The mean VO_2, VCO_2, R-value and calculated energy expenditure during cycling from the last minute of each exercise intensity are reported in Table 3.12, demonstrating increased oxygen consumption and energy expenditure with respect to exercise intensity. Energy expenditure was calculated as in Peronnet and Massicotte, (1991) using the energy equivalent of the R-values and the volume of oxygen consumed. Energy expenditure during cycling was normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test, ($X^2(2)=4.676$, $p>0.05$). A repeated measures ANOVA reported statistical differences between energy expenditure at 50, 100 & 150 W, ($F(2.0, 18.0) =133.89$, $p<0.05$). Bonferroni post hoc comparisons showed statistical differences between all exercise intensities ($p<0.05$) with supporting large effect sizes (d = 50 vs 100 W = 3.45; 100 vs 150 W = 3.17; 50 vs 150 W = 6.13).

Table 3.12 Metabolic energy expenditure during cycling

	50W		100W		150W	
	Mean(±SD)	95%CI	Mean(±SD)	95%CI	Mean(±SD)	95%CI
VO_2 (L.min^{-1})	1.06(±0.1)	1.0-1.1	1.5(±0.12)	1.4-1.5	1.9(±0.17)	1.8-2.0
VCO_2 (L.min^{-1})	0.93(±0.1)	0.9-1.0	1.3(±0.17)	1.2-1.4	2.0(±0.27)	1.8-2.1
R-value	0.87(±0.05)	0.84-0.91	0.92(±0.06)	0.88.0.95	1.0(±0.1)	0.97-1.10
Energy Equivalent (kJ)	21.1(±0.2)	21.0-21.0	21.3(±0.3)	21.2-21.5	21.6(±0.11)	21.6-21.7
Energy Expenditure (kJ.min^{-1})	22.4(±2.2)	21.0-24.0	31.0(±2.74)	29.3-32.7	41.5(±3.8)	39.2-43.9

The mean VO_2, VCO_2, R-value and calculated energy expenditure from the last minute of each exercise intensity are reported in Table 3.13, demonstrating increased oxygen consumption and energy expenditure with respect to exercise intensity. The data were normally distributed (Appendix 3) and met the assumptions of sphericity, using Mauchly's test ($X^2(2)=1.087$, $p>0.05$). A repeated measures ANOVA reported statistical differences between energy expenditure estimates at 50, 100 & 150 W, ($F(2.0, 18.0) =42.552$, $p< 0.05$). Bonferroni post hoc comparisons indicated statistical differences between 50 & 100 W and 50 & 150 W ($p<0.05$), supported by large effect sizes for all comparisons (d = 40 vs 60 W = 2.08; 60 vs 80 W = 0.81: 40 vs 80 W = 3.27).

Table 3.13 Metabolic energy expenditure during arm-cranking

	40W		60W		80W	
	Mean(±SD)	95%CI	Mean(±SD)	95%CI	Mean(±SD)	95%CI
VO_2 (L.min^{-1})	1.1(±0.1)	1.1-1.2	1.4(±0.1)	1.3-1.4	1.4(±0.07)	1.4-1.5
VCO_2 (L.min^{-1})	1.1(±0.1)	0.97-1.1	1.4(±0.2)	1.3-1.5	1.4(±0.1)	1.4-1.5
R-value	0.9(±0.1)	0.87-0.96	1.0(±0.04)	1.0-1.02	1.0(±0.03)	0.98-1.02
Energy Equivalent (kJ)	21.3(±0.3)	21.1-22.0	21.6(±0.1)	21.5-21.7	21.6(±0.1)	21.6-21.7
Energy Expenditure (kJ.min^{-1})	24.4(±2.4)	22.9-25.9	29.4(±2.45)	28.0-31.0	31.2(±1.6)	30.1-32.2

3.4 Discussion

This chapter examined the efficiency estimates for three different modalities: cycling, arm cranking and rowing. Due to the multiple definitions of efficiency and methodological differences, the results from these estimates would be used to compare to other published estimates in an attempt to validate the modelling procedure. This section will consider the reliability of internal work, gross and net efficiency of rowing, comparisons of efficiency during cycling arm cranking and rowing and the effects of increasing work rates.

3.4.1 Reliability of internal work

In order to develop a model of efficiency that included internal work done, the reliability of work done needed to be established. There is little research which examines the work done during the drive phase of the rowing stroke. To aid the evaluation of how reliably the model was measuring internal work, additional modalities of cycling and arm cranking were used for comparison. The within-session reliability of the internal work done during the drive phase of the rowing stroke was assessed using an intraclass correlation (2,1) and assessed according to the categories of Lexall and Downham (2005). The ICC(2,1) correlation ranged from 0.71 to 0.91, equating to good to excellent reliability. The standard error of the measurement (SEM) was used to examine the measurement error within the protocol. SEM ranged from ≈3-6 J representing an approximate seven percent measurement error. As rowing intensities increased, the change in internal work was larger than the SEM, suggesting differences in internal work were not as a result of measurement error. The participants in this chapter were untrained at using a rowing ergometer, and to that end it was deemed important to assess the consistency of this unaccustomed movement action. The consistency of rowing performance was assessed from drive duration, using an intraclass correlation coefficient (ICC 2,1), where excellent correlations (R>0.93), with SEMs indicating a measurement error of 0.04 seconds were reported. Based on the data above, the internal work during rowing was considered reliable.

Internal work was calculated for the cycling trials, from eight leg cycles, per exercise intensity. As a measure of reliability, the internal work data were assessed using an intraclass correlation coefficient (2,1). The internal work showed high reliability, ICC (2,1) > 0.84, across the intensities (Baumgarter and Chang, 2001), and the SEM suggested approximately a six percent measurement error. Exercise intensity increases were achieved using increased resistance on the ergometer, whilst participants cycled at the same cadence, in all trials. Hence, internal work data were similar across all work loads. Based on the results the internal work of cycling was considered reliable.

The internal work of arm cranking was also assessed using an ICC(2,1) and showed good to excellent reliability of internal work across eight cycles, with all ICC values being greater than 0.72. However the SEM was 8-12 %, which was larger than the rowing or cycling trials. Arm cranking exercise was unfamiliar to most of the participants, contributing to the larger SEM. Based on the above the trials are considered to have acceptable reliability for internal work during arm cranking.

3.4.2 Comparison of gross and net efficiency for rowing

To estimate the efficiency of a total body action, the drive phase of a rowing motion on a laboratory based ergometer was used. Comparison to previous research is somewhat difficult due to the many different definitions, methods of calculation and modalities used. On-water rowing efficiency is the interaction of the rower, the characteristics of the oar, the blade water interaction and boat factors. Each of these is a potential source of inefficiency. As the data collected within this chapter were based on an ergometer, it simplifies the issue, but it becomes difficult to compare to on-water rowing. It is more appropriate to consider the work of this thesis as the efficiency of the 'rower' than 'rowing' (Affeld *et al*., 1986). Literature examining rowing will be used as a guide rather than direct comparator. There is also a limited amount of literature that has reported efficiency for a total body action, compared to the lower body. In elite and sub-elite dragon boat paddlers, total body paddling efficiency was estimated to be between 12-38 % dependent on paddle position (Ho *et al*., 2009). The results of this chapter fall within the range reported by Ho *et al*. (2009) but modality and calculation methods are quite different.

Gross efficiency in this chapter was estimated at ≈ 17, 24 and 25 % for ergometer rowing with untrained participants. Gross efficiency of ergometer rowing has been reported between 10 and 25 % (Henry, 1995) and 20 % in elite female rowers, irrespective of stroke rate (Hofmijster *et al*., 2009). On-water rowing, usually with skilled, trained participants, has been reported between 14 % (Hagerman *et al*., 1978) and 26 % (Fukunga *et al*., 1986). Efficiency has also been reported to increase with rowing speeds (Nozaki *et al.,* 2003) but often these studies had relatively small sample size (n=4-6). As internal work is not always accounted for in previous studies, efficiency without including internal work derives efficiency estimates approximating 11, 15 & 16 % for 50, 100 and 150 W, respectively (Appendix 4). These values are similar to the efficiency ranges above. The inclusion of internal work increased the numerator value, thus increasing the calculated efficiency, but these still remained within the ranges previously suggested.

Gross efficiency increased with respect to intensity, concurring with the results of Nozaki *et al*. (2003) who reported an increase in gross efficiency with exercise intensity. Participants were free to choose the stroke rate, length and force applied to meet the target exercise intensity at each progressive stage. The increasing pattern of efficiency estimates differed to the results of Hofmijster *et al*. (2009) where gross efficiency did not alter across three increasing exercise intensities when stroke rate was constant. Sandbakk *et al*. (2012) showed an increase in gross efficiency of cross-country skiers as both speed and incline changed, where participants freely altered their kinematics to maintain target intensity. It is further suggested that changes in efficiency with respect to intensity are parabolic in nature (Nakai and Ito, 2011; Dean and Kuo, 2011). As gross efficiency increased with respect to intensity, the results could be the ascending arm of the parabola or a peak may occur between the intensities tested.

Net efficiency was estimated at ≈24, 30 and 29 % at 50, 100 and 150 W, respectively. Net efficiency reduced the size of the denominator hence values are larger than gross efficiency for the same data. Net efficiency is considered more appropriate when comparing skill levels (Sidiossis *et al*., 1992) and changes in exercise intensity (Ettema and Loras, 2009). Net efficiency increased between 50 and 100 W, but showed a small decrease from 100 to 150 W, differing from the linear relationship shown by gross efficiency. This could indicate that net efficiency was parabolic as suggested by Dean and Kuo (2011) and that exercise intensities used were near the apex. There does not appear to be any ergometer based data reporting net efficiency. On-water net efficiency has been estimated at 20 and 24 % at 2 $m.s^{-1}$ and 4 $m.s^{-1}$ for two participants (Nozaki *et al*., 1993) and 10-11 % for female rowers (Mohri and Yamamoto, 1985). Nakai and Ito (2011) reported net efficiency values of 20-38 % dependant on velocity of roller skiing where as the total body model for net efficiency ranged from 24-30 %. Differences in posture between rowing (i.e. sitting) and roller skiing (i.e. standing) will influence the oxygen cost between studies. Nakai and Ito (2011) used elite cross country skiers who were accustom to the roller skiing protocol whereas participants in this study were neither trained for, nor accustomed, to the rowing modality. Whilst direct comparison is difficult, it appears that the values reported fit within the ranges reported in the literature.

3.4.3 Comparison of gross efficiency for rowing, cycling, and arm cranking

In the cycling trials, the efficiency estimates approximated 23, 26 and 26 % for exercise intensities of 50, 100 and 150 W, respectively. Efficiency increased between 50 and 100 W before suggesting a plateau. A large effect size between 50W to 100 W suggested an important increase in efficiency. There was a very small increase in efficiency between 100 and 150 W. The effect size did not meet the minimum practical difference level (Winter *et al*., 2014) suggesting no difference in efficiency between these intensities. The efficiency of cycling has been reported as 20-25 % (Lucia *et al*., 2004; Ettema and Loras, 2009). The results in this chapter are within and exceeding these suggested boundaries. However Lucia *et al*. (2004) and Ettema and Loras (2009) did not include measures of internal work and so direct comparison is difficult. If efficiency results in this chapter were calculated without including internal work measures, then the efficiency estimates were 14, 20 and 22 %, a change of 4-9 % (Appendix 4). This suggested that the calculated efficiency results are similar to these other reported levels.

Gross efficiency (GE) of arm cranking increased with intensity and ranged from 13 to 17 % for 40, 60 and 80 W arm cranking. This was similar to Goosey-Tolfrey and Sindall (2007), who reported a GE of approximately of 17 % at 60 and 80 W cranking for 13 male trained wheel chair athletes. The reported GE was larger than 6.98-9.02 % gross efficiency reported by Van Drongelen *et al*. (2009) which used lower power outputs (20-35 W) and 8 % suggested by Hintzy and Tordi (2004). There does not appear to be any research that has examined arm cranking efficiency including internal work to make direct comparison. Calculating efficiency in this chapter, without the inclusion of internal work resulted in efficiency estimates of 10, 12 and 15% for 40, 60 and 80 W, respectively, suggesting it is within the range of arm-only efficiency estimates, outlined above (Appendix 4). Goosey-Tolfrey and Sindall’s (2007) participants were specifically trained which could explain the larger efficiency figure, when calculated without internal work. Arm-crank efficiency was lower than cycling efficiency, however the protocols differed in resistive loads, velocity of movement and size of active muscle mass.

Net efficiency was not measured for cycling and arm cranking, as it would not be possible to return the participants to resting levels within the testing session. Gross efficiency of cycling and rowing were matched for exercise intensities, and gross efficiency was similar between them. In untrained individuals, the additional oxygen uptake by adding arms to a leg action is limited (Secher and Volianitis, 2006). Hence gross efficiency estimates should be similar.

The rowing trials had a higher efficiency than the arm cranking trials. It was not possible to match the exercise intensities, so the differences in efficiency may represent different amount of muscle mass being used (Volianitis and Secher, 2009). It was expected that due to the smaller exercise intensities (work done) and a smaller muscle mass, hence less oxygen extraction, that the efficiency of arm cranking was lower than rowing (Volianitis and Secher, 2009). Additionally, for the same reasons arm cranking efficiency was lower than cycling

3.4.4 The effect of work intensity on work done, energy expenditure and efficiency

The calculated internal work for the rowing trials increased with respect to intensity, as also reported by Ettema and Loras (2009) and Saibene and Minetti (2003). Large effect sizes suggested that changes in exercise intensity required important increases in internal work. This differs from the results in cycling and arm-cranking where internal work slightly declined with respect to intensity. Within the rowing trials, the participants were not instructed to maintain a stroke rate, as a constant stroke rate was reported not to affect gross efficiency (Hofmijster *et al.*, 2009). Ng *et al.* (2013) commented that using power output from the ergometer was a preferred and appropriate method of establishing and monitoring exercise intensity. This approach allowed the participant to establish their preferred stroke length and stroke rate to meet the target intensity and is considered not to influence gross efficiency (Korff *et al.*, 2007). As drive duration decreased, an increase in velocity would have occurred (Cerne *et al.*, 2013). This would lead to an increase in velocity of the body segments, increasing segmental translational and rotational kinetic energy, partially explaining the increase in work done. Drive duration decreased as intensity increased, suggesting that the increase in intensity was partially met by a quicker stroke rate. Participants were asked to row at the target power output, without any constraints on stroke rate or stroke length, as it is indicated that asking participants to perform away from their preferred cadence may impair efficiency (Korff *et al*., 2007). The consistency of non-rowers has previously been examined by Cerne *et al*. (2013) who established that non-rowers could perform with a consistent movement pattern, concurring with the findings presented here. This indicated that the participants were rowing with consistent drive duration within each exercise intensity, suggesting that the performance showed a good degree of reliability.

There is limited research that has examined internal work of a total body action, with which to make comparison. Slawinski *et al*. (2010) reported the segmental kinetic energy of elite runners performing a sprint start. This activity is more explosive than the rowing action and the values for segmental energy fell within the range given by Slawinski *et al*. (2010). Additionally, Bechard *et al*. (2009) examined the kinetic energy of elite Olympic rowers, reporting peak kinetic energy for each segment at greater rowing intensities than used in this chapter. The kinetic energy values from this chapter were within the ranges reported by Bechard *et al.* (2009). Whilst this was an indirect assessment of the ability of the model to correctly report kinetic energy, this does suggest that the values obtained are appropriate.

During the cycling trials, the upper body was assumed not to be contributing any movement, hence no work. The work done decreased, by a small amount, with respect to intensity. In previous, studies the internal work has increased with respect to intensity (Saibene and Minetti, 2003). Increases in internal work are seen in protocols such as walking, where increased intensity is accompanied by an increase in stride length and stride rate, hence requiring more work to be done (Minetti, 1998). Within this study the increased intensity was achieved by raising the resistance on the ergometer flywheel, whilst maintaining a constant cadence throughout the trials. By keeping the same cadence, there would be little variation in velocity and mass of active segments, which are the variables used to calculated internal work. Hence changes in power output are due to increased muscle activity rather than changes in kinematics, so it is plausible that the internal work values should be similar across the intensities. Small to moderate effect sizes between exercise intensities support that internal work across intensities were similar.

Widrick *et al*. (1992) examined the internal work and efficiency of cycling and reported gross efficiency of approximately 15 % at 49 W and 18 % at 98 W using a cadence of 60 rpm. Whilst the exercise intensity is matched to the exercise intensity used in ths chapter, Widrick *et al's*. (1992) efficiency values are lower than reported above (23 % at 50 W and 26 % at 100 W). The inclusion of internal work should suggest efficiency estimates greater than those based on external work only. However Widrick *et al*'s. (1992) values are lower than suggested by Ettema and Loras (2009) or Lucia *et al*. (2004), which did not include internal work. The inclusion of internal work within this chapter changed efficiency by 4-9 %. If the lowest of these suggested percentage change (i.e. 4 %) was applied to figures of Widrick *et al*., (1992), then the estimates of cycling efficiency, based on external work only, are very low (9-12 %) compared to suggesting other reported values in the research literature. This may indicating some questions over the results Widrick et al. (1992) presented. Ettema and Loras (2009) questioned the results of Widrick *et al*. (1992), indicating that errors in determining work had been made.

External work was derived from the ergometer and added to the internal work. As the protocol used constant workloads, 3, 6 and 9 kJ.min^{-1} was added to the internal work values with respect to intensity. This resulted in the total work increasing with respect to intensity. Large effect sizes were seen between exercise intensity and total work done. As small changes in internal work with respect to exercise intensity, the influence of external work is suggested as the cause of the total work differences between intensities.

During the arm cranking trials internal work showed small decreases with respect to intensity, but as the movement pattern and speed were constant, this has the same explanation as to this observation in the internal work of the legs, with respect to intensity. Repeated measures ANOVA indicated statistical differences, but Bonferroni post-hoc did not suggest differences between the conditions, supported by small to moderate effect sizes between 40 & 60 W and 60 & 80 W. This suggested that a similar level of work was done, regardless of intensity. The internal work of the arms approximated one-third of the values for the legs, largely explained by the difference in proportional masses of the legs and arms and the difference in rotational velocity. Internal work was converted to kJ.min^{-1}, and constants of 2.4, 3.6 and 4.8 kJ.min^{-1} for 40, 60 and 80 W were summed to derive total work. Very large effect sizes were reported for the differences between exercise intensity. As effect sizes for internal work were small, it is suggested that the external work changes were an important cause of total work done. The total work done was smaller, at each intensity, than in the lower body condition, however there were differences in resistive load, RPM, muscle mass and familiarity of the exercise.

Gross and net energy expenditure was derived to calculate gross and net efficiency for the rowing trials using the methods of Peronnet and Massicotte (1991). Resting energy expenditure was assessed with the participant sat in a stationary position, on the rowing ergometer. Gross and net energy expenditure increased with respect to intensity showing statistical differences (p<0.05) and large effect sizes between each intensity. This suggested that the changes in exercise intensity had important effects upon gross and net energy expenditure. The single resting measure was subtracted from all exercising intensities. Roberts *et al*. (2005) reported baseline values of VO_2 ≈0.7 L.min^{-1}, obtained with participants moving along the rowing ergometer with no resistance. The data in this chapter were obtained during a seated, stationary position are approximately half the value of Roberts *et al*. (2005), suggesting the data were within an expected range. McArdle *et al*. (2010) suggested basal metabolic rate ranged from 3.3-6.0 J.min^{-1}. The results showed resting metabolic rate to approximate 7 J.min^{-1}, indicating appropriate results. Net energy expenditure was determined by subtraction of the resting energy expenditure from the gross energy expenditure. Both gross and net energy expenditure were determined in order to calculate gross and net efficiency. It has been suggested that net efficiency should be used when investigating different exercise intensities (Ettema and Loras, 2009). During the rowing trials, six participants had R-values greater than one at 100 W and 150 W. For those participants the maximal energy equivalent (i.e. R=1.0) was used (Hettinga *et al*., 2007; van

Drongelen *et al*., 2009; Sandbakk *et al*., 2012) and it is likely to have caused a small underestimation of energy expenditure in some trials, as any anaerobic energy expenditure has not been accounted for (Scott *et al.,* 2008). All participants had an R-value of ≤1.0 during the 50 W intensity. Gross energy expenditure increased with respect to intensity showing statistical differences ($p<0.05$) and large effect sizes between each intensity. This suggests that the increased work done is supported by important changes in metabolic cost. Gross energy expenditure during rowing was larger than the values obtained during the cycling and arm-cranking protocols. This is representative of a greater muscle mass being used, and compared to arm-cranking, a difference in intensity. Roberts *et al*. (2005) reported VO_2 of 3.40 ± 0.34 $L.min^{-1}$ for maximum rowing. The largest value in this chapter was 2.60 $L.min^{-1}$ at 150W, which indicated the data were within expected levels.

In the cycling trials, energy expenditure increased with respect to exercise intensity and showed statistical differences between intensities ($p<0.05$). The effect sizes for energy expenditure for increasing intensities were large, indicating that the increases in exercise intensity had important effects on energy demand, and increased work done was met by an increase in metabolic cost. This may suggest that the steps between intensities were large, especially as the R-values exceeded 1.0 in the highest exercise intensity. Whilst the internal work remained relatively constant across intensities, this may indicate that the response to increased external work had the largest impact on metabolic cost. Roberts *et al*. (2005) reported VO_2 of 3.38±0.42 $L.min^{-1}$ for maximum cycling. The data in this chapter were within these values, suggesting VO_2 was within expected ranges. At 150 W, five participants exceeded the R-value threshold of 1.0. Where this occurred, a maximum R-value energy equivalent was applied, as indicated by Hettinga *et al*. (2007) and Sandbakk *et al*. (2012). This did not occur at 50 or 100 W. It is acknowledged that this likely underestimated the energy expenditure in the 150 W condition and was a limitation of the procedure.

During the arm crank trials, energy expenditure increased with respect to intensity and statistical differences were seen between 40 & 60 W and 40 & 80 W ($p<0.05$). Large effect sizes were reported between all exercise intensities suggesting the work rate was an important determinant of metabolic cost. Six participants at 60 W and six participants at 80 W exceeded the threshold for R-value of 1.0, hence their energy expenditure was calculated using an energy equivalent value of 1.0, indicating some underestimation of the energy expenditure at 60 and 80 W. This may be partially due to the unfamiliarity of the modality, the inexperience of the upper body to be used as a constant, propulsive segment (Secher and Volianitis, 2006) and the step size in exercise intensity.

Gross efficiency of rowing was calculated as total work done divided by gross energy expenditure. Gross efficiency increased with respect to exercise intensity, indicating large differences between 50 W and both 100 and 150 W. A moderate effect size was shown between 100 and 150 W. Figure 3.3 showed a 1 % difference in efficiency between these intensities.

Gross efficiency reported statistical differences ($p<0.05$) between 50 and 100 W and 50 and 150 W. The statistically smaller GE for 50 W may have been affected by the protocol design. 50 W is a low intensity and participants could more easily maintain the target power output. However, as a number of participants exceeded the 1.0 R-value threshold, it could be argued that the intensity rose sharply, particularly for an unaccustomed form of exercise such as rowing (Robergs *et al*., 2010).

Gross efficiency of rowing was greater than arm-cranking at all intensities but with such a large difference in muscle mass being used, comparison is limited. Gross efficiency of rowing was lower than at the same intensity during cycling. Differences in posture, velocity of segment movement and general movement patterns may account for this. Additionally, the movement pattern of cycling is consistent, where one leg is active and the other is recovering (Ettema and Loras, 2009) during different part of the cycle but force being applied almost constantly.

Cycling has force being exerted to the cranks by one leg or the other, suggesting there is a nearly constant effort being applied (Ettema and Loras, 2009). Rowing has an active drive phase followed by an almost passive recovery, per stroke (Soper and Hume, 2004). In this chapter the mechanical work data for rowing were only calculated on the active, drive phase, ignoring the recovery. The energy expenditure was a mean of the final minute and as such is composed from the drive and recovery phases.

Hence, to describe the above efficiency as rowing, it is probably erroneous as it only applies to the drive phase of rowing.

Gross efficiency in cycling was calculated as total work over metabolic cost. The results showed an increasing efficiency with respect to intensity, where efficiency at 50 W was statistically different with large effect sizes from 100 & 150 W. As indicated previously the values are around the expected range of cycling efficiency (Ettema and Loras, 2009; Lucia *et al*., 2004). Efficiency at 100 W and 150 W were very similar (26.1 and 26.4 %). This may indicate a plateau of efficiency, that is, for a given activity there was a maximum efficiency prior to a decline (Nakai and Ito, 2011; Dean and Kuo, 2011). Dean and Kuo (2011) suggested that efficiency is parabolic in nature, in that estimates would rise and subsequently fall as intensity increased. The data, as is, could suggest a plateau or possibly indicated a decrease. As mentioned earlier, five participants had R-values greater than 1.0 at 150 W, suggesting an underestimation of the energy expenditure. Had the additional energy been measured, it would have increased the size of the denominator in the efficiency equation, decreasing the reported estimate for 150 W. This coincides with other physiological data, in particular R-values which were approaching or equalling 1.0 for the other 7 participants. It is further possible that the peak efficiency value occurred between the tested intensities.

Gross efficiency estimates for arm cranking increased with respect to exercise intensity, and were considered statistically different from each other (p<0.05). Large effect sizes suggested that exercise intensity was an important determinant in gross efficiency. Although not matched in intensity, the results followed a similar pattern to the cycling efficiency estimates which saw increased efficiency with increasing intensity. There did not appear to be a plateauing effect in arm crank efficiency as suggested in the cycling efficiency. The efficiency of the arm-crank was less than for cycling, but as they differ in intensity this is difficult to compare. Arm crank efficiency for 40 and 60 W approximated 13 and 15 %. During cycling, the 50 W trial, which was closest in intensity to the 40 and 60 W arm-crank trials, was 23 %. These differences were likely due to the increased muscle mass of the lower body and the familiarity of cycling compared to arm-cranking. Gross efficiency (GE) of arm cranking increased with intensity and ranged from 13 to 17 % for 40, 60 and 80 W arm cranking. This was similar to Goosey-Tolfrey and Sindall (2007), who reported a GE approximate of 17% at 60 and 80 W cranking for 13 male trained wheel chair athletes. The reported GE was larger than 6.98-9.02 % gross efficiency reported by Van Drongelen *et al*. (2009) which used lower power outputs (20-35 W) and 8 % suggested by Hintzy and Tordi (2004). There does not appear to be any research that has examined arm cranking efficiency including internal work to make direct comparison. Calculating efficiency in this chapter, without the inclusion of internal work resulted in efficiency estimates of 10, 12 and 15 % for 40, 60 and 80 W, respectively, suggesting it is within the range of arm-only efficiency estimates, outlined above (Appendix 4). Goosey-Tolfrey and Sindall's (2007) participants were specifically trained which could explain the larger efficiency figure, when calculated without internal work. Arm-crank efficiency was lower than cycling efficiency, however the protocols differed in resistive loads, velocity of movement and size of active muscle mass.

3.4.5 Validation of the model of efficiency.

A mathematical model was created to assess the efficiency of a total body movement. There are limited models within the literature with which to make comparison. It is important to validate a model, in as much as it produces reasonable results. Comparison to the results of other studies has been suggested as one method of validating a model (Nigg, 2007). Three models were created, a leg, arm and total body model and were assessed using modalities which matched these divisions, namely cycling, arm-cranking and rowing. By using a leg model and an arm model, validation of these segments could be carried out independently by comparing to results within the literature. The model could then be developed to include a trunk to combine the two limb models.

Comparison of efficiency is difficult due to the many variations in definition, methods of calculation, modalities of testing and status of participants. As outlined above, the efficiency measures for all models showed close agreement with previously reported research. As such, this is a strong validation for the model. All models appeared to respond to changes in intensity and showed an acceptable level of reliability. Furthermore the values for internal work during rowing did not exceed the values suggested by Slawinski *et al*. (2010) and Bechard *et al*. (2009).

Research using isolated muscle preparation suggested the limit to muscle efficiency is approximately 25 % (Smith *et al*., 2005). However, it is not clear how efficiency values respond to changes in exercise intensity. Furthermore, Dean and Kuo (2011) suggested that mammalian efficiency can exceed the 25 % limit of muscle, through use of the tendon structures to achieve higher efficiency figures, *in vivo*. The efficiency results are comparable to these suggested values of efficiency. Whilst the results are not being compared to muscular efficiency it does give a comparator for the results, as they are approximating the 25 % suggestion of Smith *et al.*, (2005) moderated by the suggestions of Dean and Kuo (2011). Based on the issues above and results collected is it suggested that the model is appropriate for the assessment of efficiency of a total body action.

3.4.6 Further work

3.4.6.1 Changes with exercise intensity

The protocol in this chapter used three fixed intensities. Specifically with the rowing action, gross efficiency increased where as net efficiency increased then decreased. Due to the 50 W step size in intensity, it is not clear what happens at intermediate intensities (i.e. 75 and 125 W). Additionally, as some participants had R-value greater than 1.0 the size of these steps may be too large. By increasing the number of stages, a more complete picture of total body efficiency could be obtained. Previous research has indicated that efficiency is constant with respect to exercise intensity (Marsh *et al*., 2000; Moseley *et al*., 2004; Hofmijster *et al*., 2009), increased with respect to intensity (Nozaki *et al*., 2003; Sandbakk *et al*., 2012) or is parabolic in nature (Nakai and Ito, 2011; Dean and Kuo, 2011).

3.4.6.2 Participant skill level

Participant skill level is thought to be an important component of efficiency (Sidossis *et al*., 1992). The effect of rowing experience on efficiency has not been clarified, as Cunningham *et al*. (1975) indicated similar efficiencies between experienced and non-experienced rowers, where as Asami *et al*., (1981) suggested efficiency increases with rowing experience. The skill level or techniques has been suggested to be an important contributor to efficiency (Sidossis *et al*., 1992; Purkiss and Robertson, 2003). There are only a few studies that have examined the effect of experience on rowing efficiency; there are more studies that have considered this within cycling. Previous research has argued that elite and novice cyclists have similar efficiencies, suggesting no significant difference in terms of cycling efficiency and experience (Marsh and Martin, 1993; Nickleberry and Brooks, 1996; Marsh *et al*., 2000; Moseley *et al*., 2004). However, studies have demonstrated changes in efficiency with training and experience (Hintzy *et al*., 2005; Hopker *et al*., 2009; Santalla *et al*., 2009; Hopker, 2012).

3.4.6.3 Trunk segmentation

One simplification in the previous data collection was the modelling of the trunk and head as a single, rigid segment. Whilst this simplification may be valid for activities such as walking, in rowing where there is flexion and extension of the spine it does not appear appropriate (Kleshnev, 2011). The trunk was indicated to be instrumental in energy transfer from the legs to the upper body in rowing (Nelson and Widule, 1983). The model used is a very simple model in that is assumes that the trunk and head are one rigid segment, and that there is no energy transfer between any segments. Previous research has identified that energy transfer assumptions can affect the estimation of internal work (Frost *et al*., 2002). The model was based on the commonly used body segment data set of Winter (1990) which has been argued to be inappropriate (Bartlett and Bussey, 2011). A further development to the model would be to use a multi-segment trunk however this needs to consider the body segment parameter data set used.

3.4.6.4 Body segment parameter data

The calculation of internal work requires the mass, position of centre of mass and moment of inertia for each body segment. These data are also used to calculate the body centre of mass. The data set used so far was that of Winter (2005), which is largely based on the data of Dempster (1955). Whilst regularly used (Minetti, 2003) it has been criticised based on the age and sample, questioning its appropriateness for sporting populations (Bartlett and Bussey, 2011). de Leva (1996) reworked Zatsiosky’s data, from a large sample of athletic individuals. The inertial data for segments was reworked to correspond to joint centres rather than to anatomical landmarks, which corresponds to current motion capture models. Winter’s data set also considered the trunk to be a single rigid segment. By having a multi segment trunk model, more realistic efficiency could be obtained. de Leva (1996) sectioned the trunk, into three segments. The differences in BSP model have been explored in appendix five, where the rowing data from this chapter have been reworked to compare Winter’s (2005) BSP data against de Leva’s (1996) to ascertain the differences for internal work and efficiency. Results indicated moderate to large effect size differences in gross efficiency as a results of the BSP model selection.

3.5 Summary

The aims of the chapter were to:

- develop a model to calculate the internal work for cycling arm cranking and rowing;
- assess the reliability of the internal work data;
- calculate efficiency for cycling, arm cranking and rowing using a healthy, unskilled population.

A model to determine internal work, external work and energy expenditure was developed. Internal work for cycling, arm cranking and rowing displayed good reliability from ICC and SEM data. The internal and external work have no direct comparison but their use in the efficiency calculations suggested they were appropriate, although limited to not including energy transfers within internal work. The efficiency estimates compares with values in literature for cycling, arm cranking and rowing. This suggested that the chapter aims were met.

CHAPTER 4 GROSS AND NET EFFICIENCY OF NOVICE AND SKILLED PARTICIPANTS

4.1 Introduction

The efficiency model in the previous chapter, was reliable and derived efficiency estimates that were comparable to published results. Gross and net efficiency are thought to be parabolic in relationship to exercise intensity (Dean and Kuo, 2007). Whilst the results in the previous chapter suggested increasing gross efficiency with respect to exercise intensity, net efficiency appeared to be reducing at the higher intensity. The use of 50 W increments in exercise intensity may have missed peak values at intermediate exercise intensities. Hence this chapter will assess 2 additional exercise intensities, 75 and 125 W, using a rowing ergometer.

Models are required to represent reality as closely as possible without becoming overly complex (Yeadon and King, 2007). The model in the previous chapter used Winter's (2005) BSP data set, whose use has been questioned by Bartlett and Bussey (2011) as it may not be appropriate to current anthropometric norms. Additionally, the trunk was modelled as a single rigid segment, which has been suggested to be an important limitation in studies that involve a rowing action (Cerne *et al*., 2013). The remodelled BSP data set of de Leva (1986) uses a larger, more contemporary population as the basis of the regression model and has a multi-segmented trunk.

Cavanagh and Kram (1985b) recommended experimental techniques should be refined on an unskilled cohort as they are likely to show the greatest effects in the measures. By including skilled participants it would be possible to assess differences due to skill level (Sidossis *et al*., 1992; Purkiss and Robertson, 2003) and apply the information gained from the results, to enhance sporting performance.

This chapter describes the methodology to determine the internal work and efficiency for skilled and novice participants during rowing ergometry, at five increasing exercise intensities. The BSP data set of de Leva (1996) was used in this chapter as it allows for a multi-segmented spine and is more appropriate to the cohort.

The aims of this chapter were to

- further develop the internal work model to incorporate a multi-segmented trunk, using the data set of de Leva (1996)
- compare the gross and net efficiency for a total body action for skilled and novice populations, over an extended range of exercise intensities.

4.2 Method

The methods for this chapter followed the procedures outlined in Chapter 3. Changes to the method are detailed below. Specifically, the body segment parameter (BSP) data set was altered from Winter (2005) to de Leva (1996) to support the multi-segmented trunk model. Ethical approval was obtained from the Research Ethics Committee of the University of East London (appendix 2).

4.2.1 Participant Recruitment

An opportunity sample of students from the university who were physically active, injury free, who had used a rowing ergometer in fitness settings but were not trained for rowing were recruited. Skilled participants were recruited by email invitation from the university and local rowing clubs, were required to have a minimum of two years formal rowing instruction, regularly use ergometer as part of their training and be actively training for rowing. All participants were male, aged 18-40, responded no to all questions on a Par-Q and You questionnaire and gave written informed consent to participate.

Twenty four male participants were recruited to this study. Twelve active and apparently healthy males, who had used a rowing ergometer previously, but had no formal rowing training, were operationally defined as ‘novice’ participants. Twelve currently active and trained men with a minimum of 24 months specific rowing training were operationally defined as ‘skilled’ participants. The standard anthropometrics are reported in Table 4.1.

Table 4.1 Anthropometric data (Mean±SD, 95%CI) for age, mass and stature.

	Novice (n=12)		Skilled (n=12)	
	Mean±SD	(95%CI)	Mean± SD(	(95%CI)
Age (yrs)	26.7 ± 4.9	(23.6-29.8)	25.58 ± 4.6	(22.56-28.61)
Mass (kg)	79.6 ± 9.93	(73.7-85.9)	82.03 ± 9.5	(76.69-87.48)
Height (m)	1.79± 0.06	(1.79-1.82)	1.83 ± 0.06	(1.79-1.86)
BMI	24.8 ± 3.34	(22.7-27.0)	24.50 ±3.2	(23.1-26.0)

4.2.2 Equipment and setup

Motion data were captured with an eight camera Vicon Nexus M3 three-dimensional (3D) camera system sampling at 200 Hz, calibrated as per the manufacturer's directions using the five marker wand and L-frame (Figure 4.1). The capture volume was orientated so that the global coordinate system of the lab followed the convention of a right-handed orthogonal system where the X-axis was lateral, Y-axis was anterior-posterior and Z-coordinates were vertical (Richards, 2008).

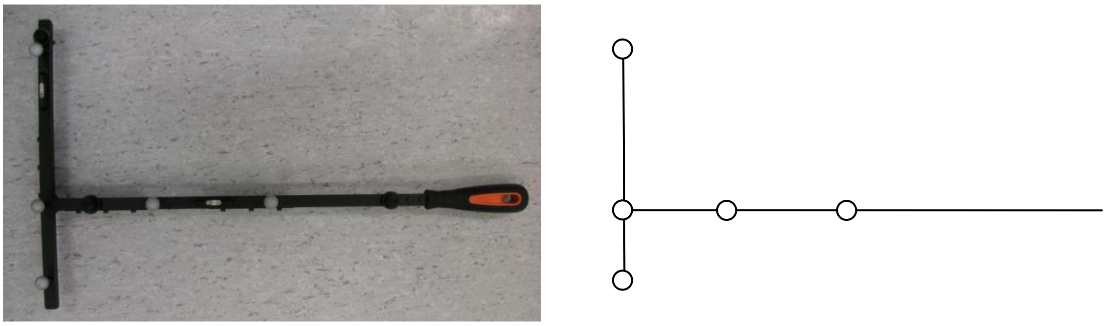

Figure 4.1 Five marker wand and L-Frame

Expired gas analysis was collected using the same Oxycon-Pro metabolic cart (Jaeger, Germany) as detailed in the previous chapter. Additionally, the same Concept 2C (Concept 2, Morrisville, USA.) rowing ergometer with the drag factor set at 130 [1.3Nm.s^{-2}] (Volger *et al.*, 2007; Gallagher *et al.*, 2010; Benson *et al.*, 2011) was used for all trials, as in the previous chapter.

4.2.3 Participant preparation

Participants wore shoes and shorts. Anthropometric data collection and marker placement followed the same protocol as outlined in the previous chapter. In this phase of the research no additional markers were placed on the iliac spine. Instead, three additional markers were placed on the sacrum (SACR) and left and right iliac crests (LHIP, RHIP) as these would be used with a digitizing pointer (C-Motion, Digitizing pointer, 60 cm) to identify left and right anterior supra-illiac spines (ASIS). Additionally, the left and right ASIS were identified but no markers were attached. The availability of the digitizing pointer allowed a modification of the protocol which was considered less interfering to the rowing action than additional markers. Trunk markers were placed on the following spinal processes; T4, T7, T12, L2 and L4 for all phases of data collection, based on the marker set used by Fowler et al. (2006). Additionally a heart rate monitor belt (Polar T31, Oy, Finland) was attached around the thorax was added to monitor the exertion of the participants and as an additional record of physiological response.

4.2.4 Procedure

A static trial with the participant standing in the anatomical position with shoulders abducted at centre of the motion capture volume was conducted. During this trial the digitising pointer was used by the researcher to mark the position of the anterior supra-iliac spines. The tip of the digitising pointer was placed and ‘plunged’ on the left and right ASIS landmark, respectively. The plunge minimises the distance between the markers, determining the position of ASIS land marks.

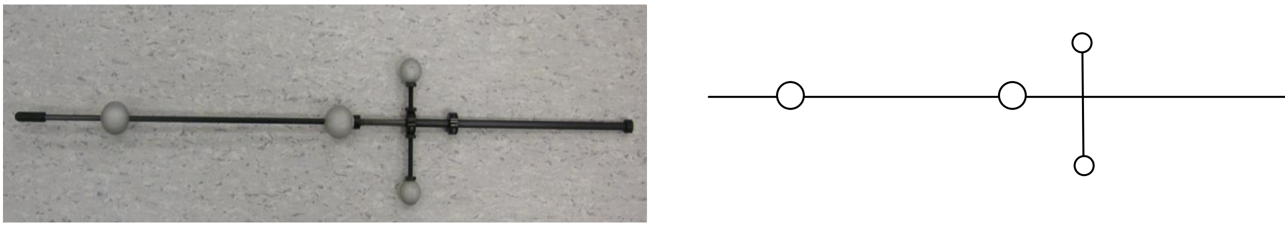

Figure 4.2 60 cm Digitizing Pointer (C-Motion)

The rowing ergometer and metabolic cart were placed in the volume. Participants sat on the ergometer for five minutes, to accustomise to the setup. When heart rate was consistent, a three minute resting phase was started where participant sat still on the ergometer to determine resting energy expenditure. Participants completed five, three minute rowing trials, 50, 75, 100, 125 and 150 W, with a 30 second rest period between intensities. Power output was determined by the ergometer display and participants were verbally encouraged to stay as close to the target power output as possible.

4.2.5 Data Processing

Motion capture data -Static trials

Prior to labelling the markers in the static trial, the position of the left and right ASIS markers was determined. Within the static trial, the SACR, LHIP, and RHIP markers were identified on the participant. The four points of the digitising pointer (PointerTip, PointerShaft, PointerLong, PointerShort) were labelled and a time point between the 'Plunge' on the left and right hip was identified. A bespoke BodyBuilder model calculated the position of the virtual ASIS markers for use in the statics Plug-in-Gait model. All other markers were identified and the static trial was completed as normal.

Motion capture data - Dynamic trials

The Bodybuilder model was used to reconstruct the virtual ASIS markers during the subsequent dynamic trials. LHIP, RHIP and SACR markers were labelled and any gaps filled, prior to running the dynamic version of the model to create virtual markers for the ASIS. The remaining markers were identified in the normal PiG model, gaps filled (20-point maximum), filtered using a Woltring smoothing algorithm (MSE=20), modelled and exported as ASCII data as previously detailed.

4.2.6 Calculating internal work

The multi-segmented trunk model was developed using the trunk segmentation in the body segment parameter model of de Leva (1996). To calculate the kinetic energy of any segment the segmental mass, position of centre of mass and radius of gyration are required. These are all provided by the de Leva (1996) data and hence the multi segment trunk model was created to match these data as closely as possible. A four segment trunk (Head, upper trunk, mid trunk, lower trunk) using five landmarks identified de Leva (1996) was developed within a LabVIEW model. The landmarks were derived from marker positions and calculated values from the Plug-in-Gait model. The position of a lumbar spine L4 marker was additionally used. The head segment was defined as the vertex of the head to cervical spine (C7). This output from the Vicon Motion capture system was considered HEDP and C7, defining the proximal and distal ends of the segment. Head angle was taken from the Plug-in-Gait output. The translational and rotational kinetic energy of the head was calculated as per the single trunk section above. The three segments of the trunk (upper, mid and lower trunk) were not standardly defined in the Plug-in-Gait model and their derivation is detailed below.

The upper trunk was defined by de Leva (1996) as the suprasternale to the xyphion (or substernale) which were considered as analogous to CLAV marker and STRN marker in the Vicon PiG Model and considered the proximal and distal ends of the upper trunk, respectively. The mid trunk was defined by de Leva (1996) as xyphoid to omphalion, which are analogous to the STRN and L4 markers. Omphalion is not a standard marker as has been accounted for by use of the marker placed on L4. The lower trunk was defined by de Leva (1996) as omphalion to mid-hip. Mid hip is analogous to PELO within the Plug-in-Gait model. The lower trunk was defined as L4 to PELO. There is a small area C7 to CLAV that is not included and this may create a small error in the calculations. The segments and body segment parameters are summarised in Table 4.1.

Table 4.2 BSP for trunk segments (de Leva, 1996)

Segment	Markers	%Mass	% from Distal	RoG
Head	HEDP-C7	6.94	0.4998	0.315
Uppertrunk	CLAV-STRN	15.96	0.4934	0.320
Midtrunk	STRN-L4	16.33	0.5498	0.383
Lowertrunk	L4-PELO	11.17	0.3885	0.551

For each of the defined segments the proximal and distal end of each segment were identified and combined with the BSP parameter to derive the translational kinetic energy of the trunk, as previously detailed. As the PiG model does not include these trunk segments, angular displacement was calculated as follows.

At each time interval, the position of the proximal and distal segment ends were identified and used to create a line (Seg_{p0}:Seg_{d0}, figure 4.3a). The position of the proximal segment end at the next time interval was identified (Seg_{p1}) and was used to create a line to the distal segment end of the previous time interval (Seg_{p1}:Seg_{d0}, figure 4.3b). As it was assumed that the segment length was constant, by joining Seg_{p0} to Seg_{p1}, an isosceles triangle is formed (figure 4.3c).

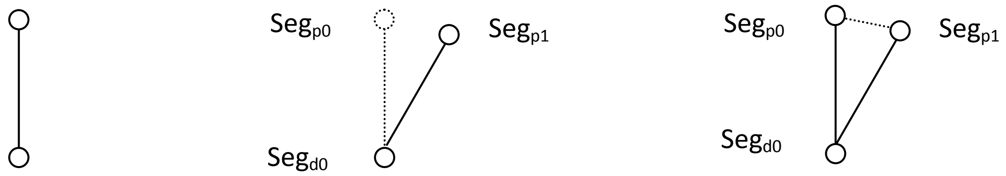

Figure 4.3a, 4.3b and 4.3c Calculation of trunk segment displacement

Using the cosine rule (Equation 4.1), angular displacement per time period was calculated for all three trunk segments, independently. Angular velocity and kinetic energy were calculated, as previously stated for each trunk segment and added together. Moment of inertia for each segment was derived from de Leva (1996).

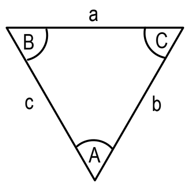

Figure 4.4 The cosine rule triangle

$$CosA = \frac{b^2 + c^2 - a^2}{2bc} \tag{4.1}$$

Internal work was determined by segment displacement from the centre of mass of the body. This is usually located near to the umbilicus region of the trunk and is determined form the positions of all segments of the body (Bartlett and Bussey, 2011). The trunk model was created independently to the other segments of the body. Hence, there was no whole body centre of mass, to determine trunk segmental displacements from. Instead, the displacement of the trunk segmental centre of mass relative to the origin of the 3D motion capture system was used. A similar approach was used by Cavagna and Kaneko (1977) who acknowledged this was not a perfect methodology, but, they considered it an appropriate method in some circumstances and estimated a 10 % error due to this procedure.

Stroke parameters

The LFIN marker was used to determine drive length (Equation 4.2) and drive duration (Equation 4.3) for further analysis of rowing performance.

$$Drive\ length\ (m) = position\ of\ \mathrm{max_y} - position\ of\ min_y \tag{4.2}$$

$$Drive\ duration\ (s) = Time\ at\ \mathrm{max_y} - Time\ at\ min_y \tag{4.3}$$

4.2.7 Data analysis

The following data analysis standards, as discussed previously, were used for interpretation of results.

1. Normality was determined by Shapiro-Wilk statistic.

2. Independent T-test and Mann –Whitney U test were used to compare between novice and skilled participants, for normal and non-normal distributions, respectively. Inferential statistics were used to assess the probability of chance results rather than as an indicator of differences.

3. Effect sizes were used to interpret differences, using Cohen's *d* and the following classifications 0.2-0.4 =small, 0.41-0.7= moderate, >0.71 = large.

4. Reliability was assessed from the ICC coefficient classification of Lexall and Downham (2005, <0.4 =poor, 0.41-0.75= fair to good, >0.75 = excellent reliability) and interpretation of SEM.

4.3 Results

4.3.1 Participants

Age, height and BMI of participants were considered normally distributed (Appendix 3) and independent T-tests indicated no statistical differences between age, mass and BMI between groups. Mass of novice participants was not normally distributed, thus Mann-Whitney U-test showed no statistical differences between mass of groups (Table 4.4). Effect size statistics (Cohen's *d*) were small for age, mass and BMI, but moderate for height (Table 4.3). All effect sizes were larger than the minimum practical difference (Winter *et al.*, 2014). The effect size statistics suggested that the 2 groups were similar in terms of age, mass and BMI. The results suggested that on average, the skilled participants were 0.04 m taller.

Table 4.3 Inferential & effect size statistics for anthropometric parameters between novice and skilled participants

	t	df	Sig.	Cohen's *d*
Age	0.550	22	0.588	0.22
Stature	-1.657	22	0.112	0.68
BMI	0.285	22	0.788	0.11

* indicates statistical difference *p*<0.05

Table 4.4 Inferential & effect size statistics for anthropometric parameters between novice and skilled participants

Mann-Whitney	U	Z	Sig.	Cohen's *d*
Mass	61.5	-0.608	0.543	0.27

* indicates statistical difference *p*<0.05

4.3.2 Rowing Performance

Stroke parameters such as drive length and drive duration are useful indicators of the consistency of performance of the drive phase of the stroke, particularly when using novice participants. Five trials per intensity, for each participant were used to determine the drive length and consistency of drive length. Drive length for novice participants was considered normally distributed, but the data for skilled rowers was not normally distributed (Appendix 3). The drive length data for skilled participants showed small differences in the group mean drive length with respect to exercise intensity, with little variation in the standard deviation (SD range = 0.10-0.12) which explained the non-normal distribution. The reliability of drive length was assessed using an ICC(2,1) based upon five strokes, per intensity, for each participant and ranged from 0.952-0.99s (Table 4.5). The coefficients exceeded 0.75 threshold, therefore were considered excellent. The SEM indicated a less than 0.03 m error suggesting a small measurement error. Large effect sizes (d > 0.7) indicated important differences between the groups in terms of drive length at each comparative intensity, indicating skilled rowers had a longer drive length per exercise intensity.

The mean data, represented in Figure 4.5, indicated skilled participants had a longer mean drive length (1.34-1.4 m) than novice participants (1.04-1.19 m) for intensity. Drive length showed small increases with respect to exercise intensity. Moderate to trivial effect sizes (*d*=0.13-0.52) for changes in drive length were shown between successive exercise intensities for novice participants, indicating small changes is drive length with respect to intensity. Trivial effect sizes (*d*=0.02-0.19) for drive length for successive exercise intensities were reported for the skilled participants indicating no differences in drive length with respect to exercise intensity.

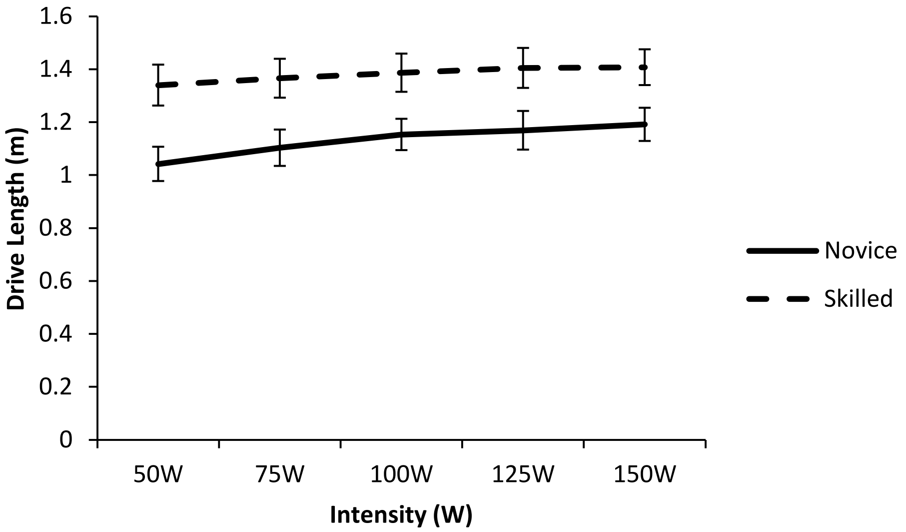

Figure 4.5 Mean (±95%CI) drive length (m) against intensity for novice and skilled participants

Table 4.5 Intraclass correlation coefficients and SEM for drive length for novice and skilled participants.

	Novice		Skilled	
Intensity	ICC(2,1) value	SEM (m)	ICC(2,1) value	SEM (m)
50 W	0.981 (0.957-0.994)	0.015	0.987 (0.969-0.996)	0.015
75 W	0.979 (0.952-0.993)	0.017	0.982 (0.960-0.994)	0.016
100 W	0.958 (0.907-0.986)	0.021	0.991 (0.979-0.997)	0.012
125 W	0.979 (0.953-0.993)	0.018	0.992 (0.982-0.997)	0.012
150 W	0.952 (0.894-0.984)	0.024	0.991 (0.980-0.997)	0.011

Table 4.6 Inferential and effect size statistics for difference in drive duration between novice and skilled participants

Mann-Whitney	U	z	Sig.	Cohen's *d*
50 W	11.0	-3.522	0.000*	2.36
75 W	12.0	-3.464	0.001*	2.09
100 W	12.0	-3.464	0.001*	2.00
125 W	14.0	-3.349	0.001*	1.79
150 W	16.0	-3.233	0.001*	1.87

* indicates statistical difference $p<0.05$

Five trials per intensity, for each participant were used to determine the drive duration (s) and consistency of drive duration. Drive duration was considered normally distributed (Appendix 3). The reliability of drive duration was assessed using ICC(2,1). Novice participants ranged from ICC=0.922-0.972, with a small measurement error of 0.02-0.03 s. Skilled participants ranged from ICC=0.800-0.962, with a small measurement error of 0.02-0.06 s. With high ICC values (>0.75,) and small SEMs (0.02-0.06 m), the data were considered reliable. The mean data presented in Figure 4.6 shows skilled participants had a longer stoke duration (1.23-1.68 s) compared to novice participants (1.09 -1.38 s) at each exercise intensity. Drive duration decreased with respect to intensity for both groups. An independent samples T-test reported statistical differences ($p<0.05$) between the participant groups at each intensity. Large effect sizes were reported (d = 1.66-2.50) indicating important differences between drive duration between groups, as per Cohen (1988). Within groups, moderate to large effect sizes (d = 0.55-0.88) for changes in drive duration were shown between successive exercise intensities for novice participants, indicating important changes is drive duration with respect to intensity. Moderate to large effect sizes (d=0.67-1.6) for drive length for successive exercise intensities were reported for the skilled participants indicating important differences in drive length with respect to exercise intensity.

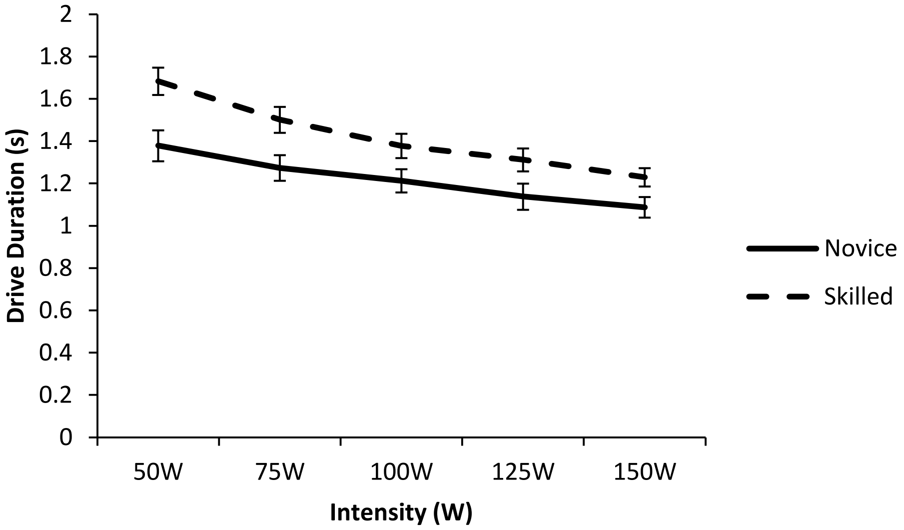

Figure 4.6 Mean (±95%CI) drive duration (s) against intensity for novice and skilled participants

Table 4.7 Intraclass correlation coefficients for drive duration for novice and skilled participants.

	Novice		Skilled	
Intensity	ICC(2,1) value	SEM (s)	ICC(2,1) value	SEM (s)
50 W	0.948 (0.887-0.982)	0.03	0.800 (0.618-0.926)	0.06
75 W	0.944 (0.878-0.981)	0.03	0.871 (0.739-0.955)	0.05
100 W	0.922 (0.834-0.973)	0.03	0.962 (0.858-0.978)	0.03
125 W	0.972 (0.938-0.991)	0.02	0.934 (0.858-0.978)	0.04
150 W	0.962 (0.917-0.987)	0.02	0.953 (0.897-0.984)	0.02

Table 4.8 Inferential and effect size statistics for difference in drive duration between novice and skilled participants

	t	df	Sig.	Cohen's *d*
50 W	-6.142	22	0.000*	2.50
75 W	-5.171	22	0.000*	2.51
100 W	-4.067	22	0.000*	1.66
125 W	-4.142	22	0.000*	1.69
150 W	-4.266	22	0.000*	1.74

* indicates statistical difference $p<0.05$

Drive length and drive duration of the skilled and novice participants were considered reliable with ICC coefficients greater than 0.75 and small SEMs. This suggested that the following data were based on a reliable stroke pattern. Additionally there were differences between the participant groups where the skilled participants had a longer drive length and greater drive duration than the novice participants, at each intensity.

4.3.3 Internal work

Total internal work was calculated by the sum of the internal work for the limbs and multi segment trunk using the de Leva BSP data set and the work done per stroke is reported in kJ. Data were normally distributed except for the novice participants at 100 and 125 W (Appendix 3). Data were considered reliable as ICCs were greater than 0.75 and small SEMs of 0.003-0.005 kJ (Table 4.9). Total internal work increased with respect to exercise intensity for both groups across all intensities (Figure 4.7). The skilled participants showed higher values of internal work than novice participants at each intensity. Independent T-tests and Mann-Witney U-test showed no statistical differences of internal work between participants groups (*p*>0.05, Tables 4.10 and 4.11). Effect size calculations showed small differences for all comparisons except 50 W which was considered moderate. This suggested there was little difference in internal work between participant groups. Within groups, novice participants showed large effect sizes differences between successive increasing intensities (*d* = 0.82-1.31). Skilled participants also showed large effect size differences for successive exercise intensities (*d*=0.84-1.20). This indicted that increased workloads caused important changes in internal work.

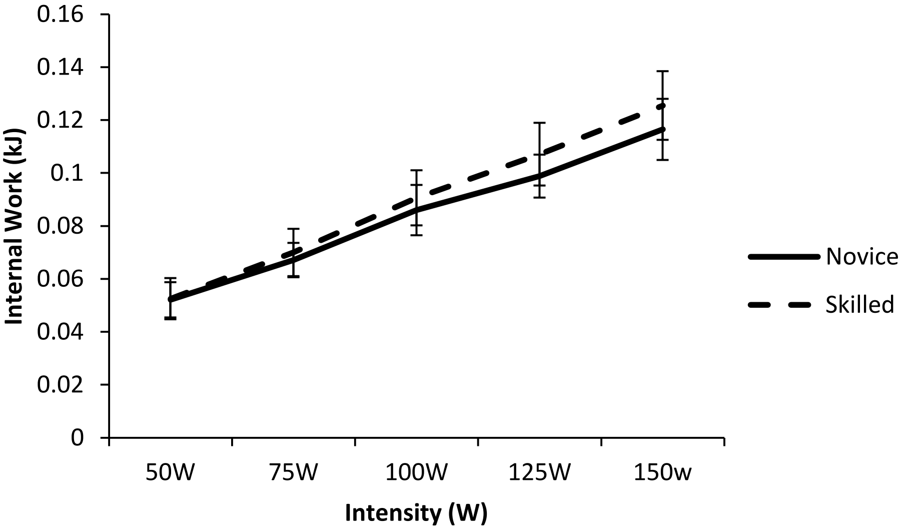

Figure 4.7 Mean (±95%CI) internal work (kJ) against intensity for novice and skilled participants

Table 4.9 Intraclass correlation coefficients for internal work for novice and skilled participants

	Novice		Skilled	
Intensity	ICC(2,1) value	SEM (kJ)	ICC(2,1) value	SEM (kJ)
50 W	0.922 (0.834-0.973)	0.003	0.940 (0.870-0.980)	0.003
75 W	0.827 (0.663-0.938)	0.004	0.956 (0.902-0.985)	0.003
100 W	0.878 (0.751-0.957)	0.005	0.968 (0.929-0.989)	0.003
125 W	0.902 (0.795-0.966)	0.005	0.938 (0.865-0.979)	0.005
150 W	0.918 (0.827-0.972)	0.005	0.960 (0.912-0.987)	0.004

Table 4.10 Independent T test results and Effect size statistics for total internal work between novice and skilled participants

	T	df	Sig.	Cohen's *d*
50 W	1.273	22	0.216	0.52
75 W	0.705	22	0.488	0.29
150 W	-0.41	22	0.968	0.02

* indicates statistical difference p<0.05

Table 4.11 Mann-Whitney and Effect size statistics for total internal work between novice and skilled participants

Mann-Whitney	U	z	Sig.	Cohen's *d*
100 W	59.0	-0.761	0.446	0.05
125 W	49.0	-1.347	0.178	0.08

* indicates statistical difference p<0.05

4.3.4 Comparison of gross and net efficiency

Gross efficiency was calculated as the ratio of total work done and gross energy expended per stroke. Gross efficiency increased for both novice and skilled groups across the intensity, ranging from 20-27 % for novice and 16-25 % for skilled participants. Novice participants reported higher efficiency at each intensity level (Figure 4.8). Gross efficiency was normally distributed (Appendix 3) and statistical differences were reported between novice and skilled participants for 50, 75 and 100 W (p<0.05, Table 4.12). Effects sizes were large (d>0.71) for all intensities indicating important differences in efficiency between novice and skilled participants. Novice participants reported a large increase in gross efficiency between 50 and 75 W (d = 1.4). Gross efficiency increased with respect to exercise intensity, showing moderate differences (d= 0.48-0.55) in gross efficiency with successive workloads. Skilled participants displayed moderate differences in gross efficiency with successive exercise intensities (d=0.43-0.51).

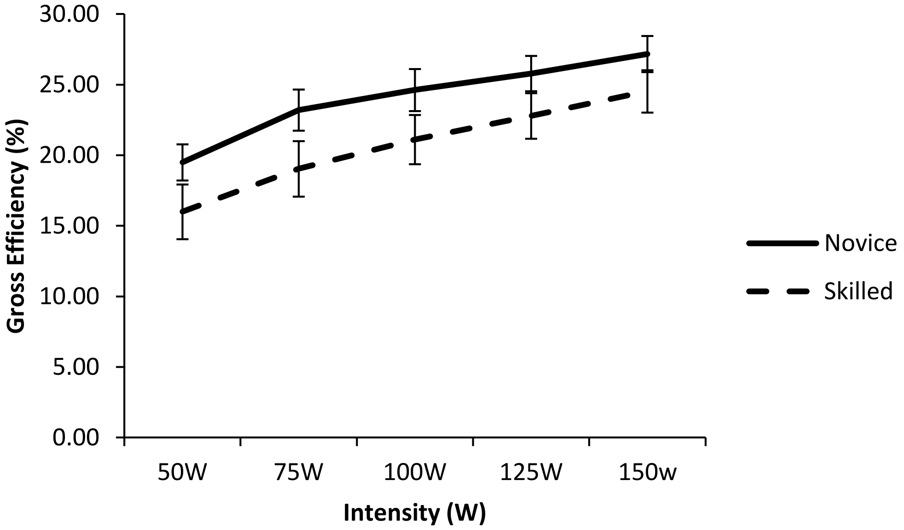

Figure 4.8 Mean (±95%CI) gross efficiency (%) against intensity for novice and skilled participants

Table 4.12 Inferential and effect size statistics for differences gross efficiency between novice and skilled participants

	t	df	Sig.	Cohen's *d*
50 W	2.687	22	0.013*	1.13
75 W	2.548	22	0.018*	1.05
100 W	2.394	22	0.026*	0.91
125 W	1.762	22	0.092	0.75
150 W	1.873	18.2	0.077	0.72

* indicates statistical difference $p<0.05$

Net efficiency was calculated as the ratio of total work done and net energy expended. Net efficiency increased with respect to exercise intensity for skilled participants, ranging from 21-28 %. Novice participants displayed an increase in efficiency between the first two intensities (28-31 %), followed by a plateau of ≈31 % for the remaining intensities (Figure 4.9). Data were normally distributed, with the exception of 50 W for novice participants (Appendix 3). As with gross efficiency, at each intensity, the novice participants reported higher net efficiency values than the skilled participants. Independent t-tests and Mann Whitney U-test showed statistical differences ($p<0.05$, Table 4.13) supported by large effect sizes (Table 4.13) suggesting important differences in net efficiency between novice and skilled participants. Within the novice participants, a moderate increase in net efficiency between 50 and 75 W ($d = 0.46$) was reported. Trivial effect sizes ($d = 0.03\text{-}0.17$) were reported for differences in successive exercise intensities indicating no important changes in net efficiency with further increases in workload. Skilled participants displayed small to moderate differences in net efficiency with successive exercise intensities ($d = 0.27\text{-}0.46$).

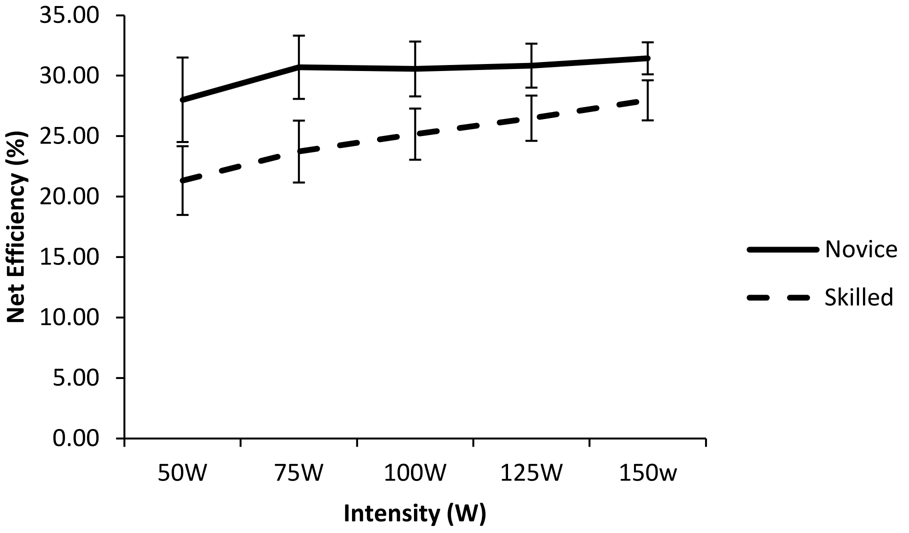

Figure 4.9 Mean (±95%CI) net efficiency (%) against intensity for novice and skilled participants

Table 4.13 Inferential and effect size statistics for difference between net efficiency between novice and skilled participants

	t	df	Sig.	Cohen's *d*
75 W	2895	22	0.008*	1.17
100 W	2.481	22	0.021*	1.00
125 W	2.198	22	0.039*	0.85
150 W	2.220	17.189	0.040*	0.89

* indicates statistical difference *p*<0.05

Mann-Whitney	U	z	Sig.	Cohen's *d*
50 W	28.5	-2.524	0.012*	1.14

* indicates statistical difference *p*<0.05

4.3.5 Total Work

Total work is the sum of the internal and external work calculated, for each intensity. External work was derived from the target power output of the rowing ergometer. The power output in watts was converted to kJ.min^{-1} (Table 4.14), scaled to the drive duration (time in seconds) and added to the internal work values to derive total work.

Table 4.14 Conversion of power output to work

Target power output	External work (kJ.min^{-1})
50 W	3.0
75 W	4.5
100 W	6.0
125 W	7.5
150 W	9.0

Total work increased with respect to intensity for both groups (Figure 4.10). Skilled participants did more total work per stroke than novice participants. The data were normally distributed (Appendix 3) and independent T-tests indicated statistical differences (*p*<0.05) between 50, 75 and 125 W (Table 4.15). Large effect sizes were reported for each comparison suggesting important differences in the levels of work done by skilled and novice participants (Table 4.15). Important increases in total work done with respect to exercise intensity, were reported for skilled (*d* = 1.48-2.53) and novice participants (*d* = 1.82-3.22) between successive exercise intensities.

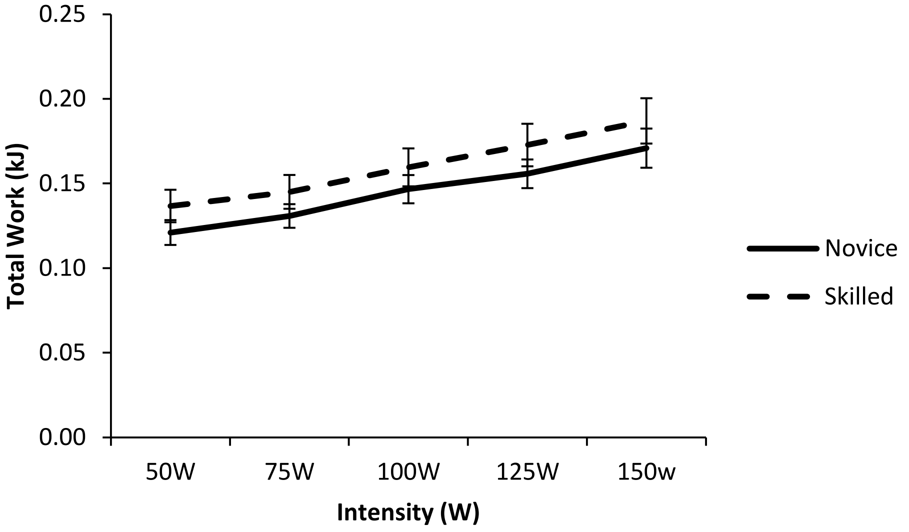

Figure 4.10 Mean (±95%CI) total work (kJ) against intensity novice and skilled participants

Table 4.15 Independent T test results and Effect size statistics for total work between novice and skilled participants

	t	df	Sig.	Cohen's *d*
50 W	-2.545	22	0.019*	1.04
75 W	-2.291	22	0.032*	0.94
100 W	-1.809	22	0.084	0.74
125 W	-2.198	22	0.039*	0.90
150 W	-1.785	22	0.088	0.73

* indicates statistical difference *p*<0.05

4.3.6 Energy Expenditure

Energy expenditure was calculated from the volume of oxygen and the energy equivalent of the R-value obtained in the last minute of each exercise intensity and is reported in $kJ.min^{-1}$. N.B. In the novice cohort, six of the participants had R-values greater than 1.0 for some of the exercise intensities (100, 125 and 150 W). Where this has occurred the maximum energy equivalent from the R-value has been applied. This did not occur for any participants at 50 and 75 W, nor for any of the skilled cohort at any intensity.

Gross energy expenditure increased with respect to exercise for both participant groups (Figure 4.10). Skilled participants displayed greater energy expenditure at each intensity than novice participants. Whilst at each intensity the R-value and hence energy equivalent was lower for the skilled participants, the volume of oxygen consumed was larger, making the calculated gross and net energy expenditure larger than the novice participants (Table 4.16). Novice participants' end of phase heart rate was higher at each intensity than the skilled participants (Figure 4.13) suggesting that the skilled participants were working at a lower percentage of their maximum despite higher energy expenditure. The data were normally distributed, except for 75 W for the novice participants (Appendix 3). Independent T-tests and Mann Whitney U-tests displayed statistical differences ($p<0.05$) and large effect sizes for all comparison suggesting important differences in energy expenditure between novice and skilled participants (Table 4.17). Large effect sizes were reported for increased gross energy expenditure for both skilled (d = 0.96-1.41) and novice participants (d = 2.06-2.69) with respect to successive increased exercise intensities.

Net energy expenditure was calculated by subtracting the resting energy expenditure from calculated energy expenditure. The resting energy is a constant value subtracted from all exercise intensities. The resting energy expenditure was normally distributed (Appendix 3) and showed no statistical differences with trivial effect sizes between novice and skilled performers (Table 4.17). Net energy expenditure increased with respect to exercise intensity for both novice and skilled participants (Figure 4.11). Skilled participants had larger net energy expenditure at all exercise intensities compared to novice participants. The data were normally distributed (Appendix 3) and independent T-tests showed statistical differences ($p<0.05$) between novice and skilled participants at each intensity (Table 4.18). Large effect sizes suggested important differences in net energy expenditure between skill levels (Table 4.18). Large effect sizes were reported for increased net energy expenditure for both skilled (*d* = 0.96-1.41) and novice participants (*d* = 2.06-2.68) with respect to successive increased exercise intensities.

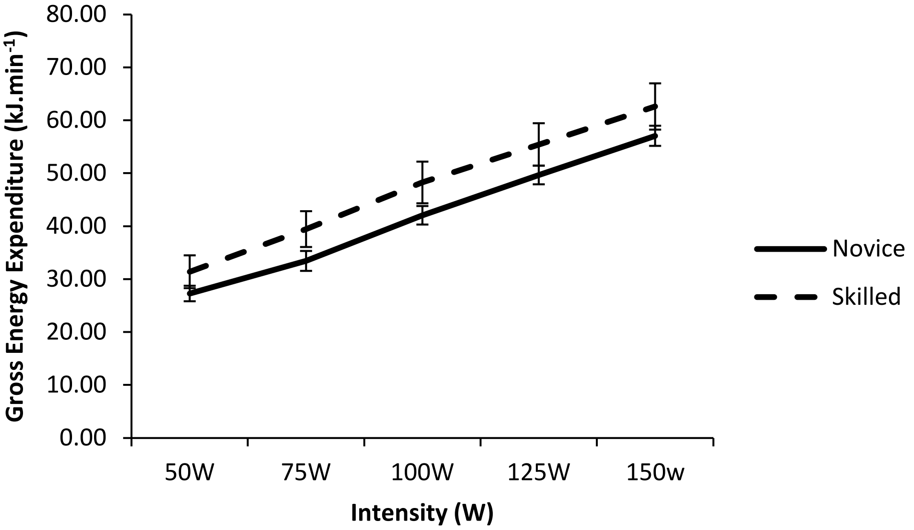

Figure 4.11 Mean (±95%CI) gross energy expenditure (kJ.min^{-1}) against intensity for novice and skilled participants

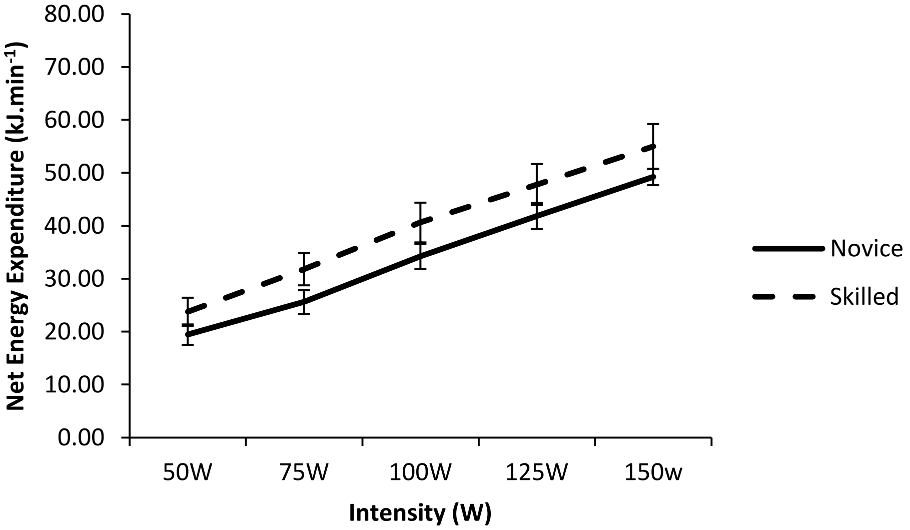

Figure 4.12 Mean (±95%CI) net energy expenditure (kJ.min^{-1}) against intensity for novice and skilled participants

Table 4.16 Mean (±SD) Expired gas data and gross energy expenditure for novice and skilled participants.

Intensity (W)	Group	VO_2 L.min^{-1}	VCO_2 L.min^{-1}	R-Value	Energy Equivalent (kJ)	Energy Expenditure (kJ.min$^{-1)}$
Rest	Novice	0.37±0.13	0.31±0.09	0.85±0.07	21.01±0.36	7.80±2.57
Rest	Skilled	0.37±0.09	0.32±0.09	0.85±0.07	21.01±0.35	7.75±1.90
50	Novice	1.30±0.13	1.11±0.12	0.86±0.07	21.02±0.32	27.28±2.63
50	Skilled	1.54±0.24	1.23±0.18	0.80±0.05	20.77±0.25	32.01±4.80
75	Novice	1.57±0.16	1.43±0.16	0.92±0.07	21.31±0.33	33.47±3.38
75	Skilled	1.91±0.25	1.61±0.21	0.84±0.03	20.95±0.17	40.04±5.21
100	Novice	1.96±0.15	1.87±0.19	0.95±0.06	21.46±0.25	42.14±3.20
100	Skilled	2.32±0.29	2.00±0.28	0.86±0.03	21.05±0.15	48.78±6.21
125	Novice	2.32±0.15	2.30±0.15	0.99±0.06	21.56±0.17	49.96±3.10
125	Skilled	2.64±0.31	2.35±0.28	0.89±0.04	21.20±0.20	55.90±6.56
150	Novice	2.65±0.17	2.67±0.25	1.10±0.07	21.57±0.17	57.24±3.69
150	Skilled	2.96±0.36	2.67±0.32	0.91±0.05	21.25±0.23	62.90±7.42

Table 4.17 Inferential and effect size statistics for difference in gross energy expenditure between novice and skilled participants

	t	df	Sig.	Cohen's *d*
GEE 50 W	-2.348	15.718	0.032*	0.96
GEE 100 W	-2.822	15.191	0.013*	1.15
GEE 125 W	-2.568	15.191	0.021*	1.05
GEE 150 W	-2.279	15.016	0.038*	0.93

* indicates statistical difference $p<0.05$

Mann-Whitney	U	z	Sig.	Cohen's *d*
GEE 75 W	27.0	-2.599	0.009*	1.24

* indicates statistical difference $p<0.05$

Table 4.18 Inferential and effect size statistics for differences in net energy expenditure between novice and skilled participants

	t	df	Sig.	Cohen's *d*
Rest	0.215	22	0.832	0.09
NEE 50 W	-2.568	22	0.018*	1.05
NEE 75 W	-3.216	22	0.004*	1.31
NEE 100 W	-2.818	18.7	0.013*	1.15
NEE 125 W	-2.536	22	0.021*	1.04
NEE 150 W	-2.482	13.9	0.036*	1.01

* indicates statistical difference $p<0.05$

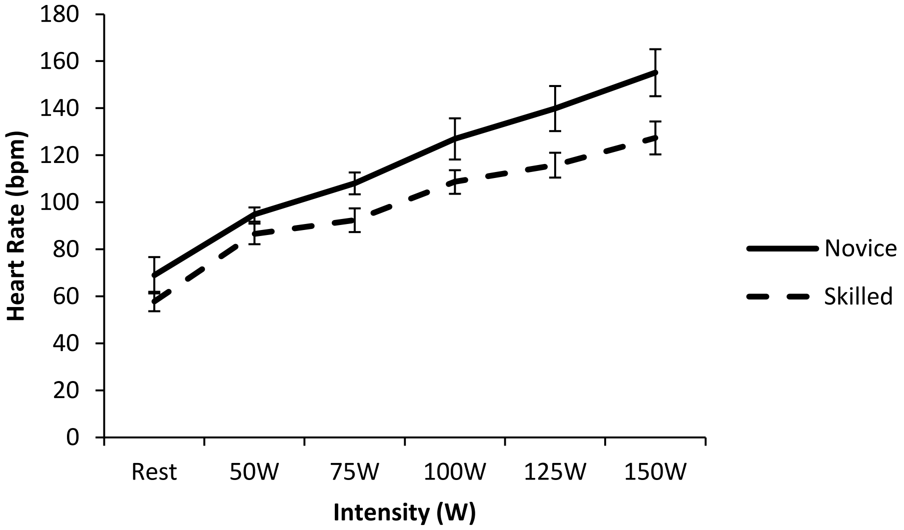

Figure 4.13 End of stage heart rate for novice and skilled participants

Table 4.19 Inferential and effect size statistics for heart rate between novice and skilled participants

	t	*df*	Sig.	Cohen's *d*
Rest	2.497	22	0.020*	1.02
50W	3.039	22	0.006*	1.24
75W	4.475	22	0.000*	1.83
100W	3.559	17.528	0.002*	1.45
125W	4.310	17.116	0.000*	1.76
150W	4.445	22	0.000*	1.82

* indicates statistical difference *p*<0.05

4.4 Discussion

To examine how skill level may influence total body efficiency, two groups of participants were recruited. Novice participants had no formal rowing training and skilled participants were active rowers. Twelve novice and twelve skilled male participants were used for this study. The anthropometric data showed no statistical differences in age, BMI or mass, although the difference in stature was considered important (*d* = 0.68). This indicated that the two groups were similar, except for a small difference in height and experience of rowing. This partially agreed with the observation that rowers tend to be taller and heavier than the 'normal' population (Shephard, 1998). Consistency of movement pattern was examined as variations of work and efficiency are less likely to be as a results of inconsistent movements. This is probably more important for the novice participants as it is suggested their movement pattern will be more variable (Smith and Spinks, 1995; Cerne *et al.*, 2013).

4.4.1 Rowing performance

Drive length was considered a reliable measure for both novice and skilled participants. Novice group reported ICC values greater than 0.952 with small standard errors of the measurement (SEM) of about 2.5 cm over a range of 1.04-1.19 m for all exercise intensities. Skilled participants reported an ICC of 0.982-0.991 with an SEM of less than 2 cm. The data were not normally distributed, due the lack of variation within, and similar and consistent drive lengths, between the skilled participants (1.34-1.4 m). Ng *et al*. (2013) reported excellent reliability for drive length (ICC range 0.989-0.998), which was similar to the values reported for both groups, even though the present study included novice rowers. This suggests good reliability of the rowing action. Drive length increased with respect to intensity for all participants, however, the mean data indicated statistical differences with large effect sizes (*d*>1.79) in drive length between groups with the skilled participants having longer strokes. The novice participants showed an increase of 0.15 m (range 1.04-1.19 m) whereas the skilled participants demonstrated small increases of 0.07 m (range 1.34-1.41 m) in drive length with respect to intensity Drive length was examined for elite, junior and non-rowers from maximum to minimum handle displacement (Cerne *et al.*, 2013). The elite group (n=5) had mean drive lengths of 1.60±0.05 m, 1.61±0.07 m and 1.59±0.08

m for 20, 26 and 34 strokes per minute, respectively. The non-rowers group (n=5) had mean drive lengths of 0.97±0.16 m, 1.09m±0.12 m and 1.16±0.18 m for 20, 26 and 34 strokes per minute, respectively. Comparing the results to Cerne *et al*. (2013), the novice participants had a similar drive length whereas the skilled rowers differed by approximately 0.2 m, most likely due to differences in exercise intensity or as a function of greater mean height (1.92-1.83 m). Kleshnev (2005) reported the drive lengths of 1.44 and 1.41 m at stroke rates of 20 and 32 strokes per minute, respectively for five female trained rowers. Participants' height was 1.80±0.4 m, which is a very similar height of the skilled group in this study but, the participants were female.

Drive duration was longer for the skilled participants than the novice participants at all exercise intensities and drive duration decreased with respect to intensity. Drive duration of the novice participants ranged from 1.09-1.38 seconds for the novice and 1.23-1.68 seconds for the skilled participants. These differences indicated that trained rowers used a different stroke pattern. The data were considered normally distributed and ICC(2,1) data ranged from 0.948-0.972 and 0.800-0.962 for novice and skilled participants, respectively, with small SEMs 0.02-0.06 seconds. As exercise intensity increased, drive duration decreased in both groups. Statistical differences (p<0.05) were seen between the groups at each intensity. Large effect sizes (range Cohen's d= 1.69-2.50) indicated the magnitude of the differences are important and that for the given intensities skilled rowers use a longer stoke duration than novice participants. This is similar to increased cadence as a responses to increasing workloads in cycling (Korff *et al*., 2007) or an increased stride rate in gait. Drive duration of novice participants (range 1.09-1.38 seconds) was similar to reported drive duration of non-rowers (1.16-1.53 seconds; Cerne *et al*., 2013). Drive duration for skilled participants (range 1.68 s to 1.23 s) was similar to the reported drive time of trained rowers (1.21 s and 1.41 s; Kleshnev, 2005) but longer than reported (0.76-0.95 s) by Cerne *et al*. (2013); however, this was at a higher intensity than that of the current study. Based on the evaluation of the metrics of reliability used above, the drive duration of novice and skilled participants was considered reliable.

Drive length and drive duration are fundamental measures used to assess rowing performance (Cerne *et al*., 2013; Ng *et al*., 2013), but have been used within this chapter to assess the consistency of the movement pattern. The results agreed with Hase *et al*. (2004) skilled and novice participants row an ergometer with similar kinematics and skilled rowers have lower levels of variation when compared to non-rowers. The drive length and drive duration of skilled rowers was statistically different and large effect sizes were seen, similar to previously reported data (Kleshnev, 2005; Izquierdo-Gabarren *et al*., 2009; Turpin *et al*., 2011; Cerne *et al*., 2013). Overall this suggests that the collected data were not affected by the use of more exercise intensities, nor different skilled groups and was considered reliable for further calculations of work and efficiency.

4.4.2 Internal Work

Internal work increased with respect to exercise intensity, for both novice and unskilled participants. Effect size differences for successive exercise intensities ranged from d=0.82-1.31, for novice participants and d=0.84-1.20, for skilled participants, suggesting important differences in internal work as exercise intensity increased. Internal work has been shown to increase with respect to velocity in horses (Minetti *et al*., 1999), cross-country skiers (Nakia and Ito, 2011) and walking and running (Saibene and Minetti, 2003). The reliability of internal work was interpreted using an intraclass correlation coefficient (2,1) based on five drive phases of the stroke. Intraclass correlation coefficients of 0.878-0.922 for novice participants and 0.938-0.968 for skilled participants suggested excellent reliability of internal work (Lexall and Downham, 2005). Standard error of the measurement ranged from 0.003-0.005 kJ for both groups, suggesting a measurement error of 3-6% of mean internal work. Based in the high ICC and low SEM the data for internal work was considered reliable.

The internal work within this chapter ranged from ≈52 J to ≈120 J per stroke. Slawinski *et al*. (2010) reported the total kinetic energy of a sprint start to be approximately 540 J. A sprint start is more explosive than the rowing intensities used, hence the maximal values (≈120 J) are considered to be in an acceptable range. Effect size differences were between novice and skilled participants, at each intensity (i.e. 50, 75, 100, 125 and 150 W), were small (*d*= 0.02-0.52), indicating little difference in the internal work done between the participant groups. Although the differences were small, skilled participants did more work than novice participants. Maximising internal work is suggested an important factor for effective movement patterns (Bechard *et al*., 2009; Slawinski *et al*., 2010). Increased internal work starts to indicate mechanical differences between skilled and novice performers and considered positive in terms of efficiency (Purkiss and Robertson, 2003; Bechard *et al*., 2009). Any increase in internal work would increase the numerator of the efficiency equation, increasing overall efficiency, if all other factors remain the same. Bechard *et al*. (2009) reported increased peak kinetic energy between low (18-22 spm) and high (32-40 spm) for elite rowers during a water based trial. The data in this chapter is following the pattern of results reported by Bechard *et al*., (2009) that work done increased with respect to exercise intensity.

The internal work values in this chapter are higher than the comparable exercise intensities used in the previous chapter, although they follow the same increasing pattern with respect to intensity. There are a number of differences between the protocols including differences in the mean age of the participants, the frame rate of the motion capture system (100 vs 200 Hz), the BSP data set used and the use of a multi-segmented trunk. However there is little other published data with which to compare. The absolute change of kinetic energy was calculated for each rowing stroke, from the catch to the end of the drive phase (Cavagna and Kaneko, 1977; Minetti, 1990). To allow for consistent units, internal work, external work and energy expenditure, were calculated for each stroke in kJ, as opposed to a time base in the previous chapter. As indicated in the previous chapter, the rowing stroke has a period of high activity (the drive) and low activity (the recovery). By normalising the drive data to time it suggested there was a constant rowing intensity, rather than periods of high intensity (i.e. drive) followed by low intensity (i.e. recovery) (Soper and Hume, 2004). Different methods for stroke normalisation have been used within rowing (McGregor *et al*., 2004; Tanaka *et al*., 2007; Pollock *et al*., 2009; Turpin *et al*., 2011, Ng *et al*., 2013), however as these studies were not attempting to quantify internal work, the work done per stroke approach of Martindale and Robertson (1984) was adopted in this chapter. From the data presented in table 4.7, the multi-segmented trunk did not negatively affect reliability of internal work.

In contrast to the previous chapter, the internal work was calculated using the BSP data set of de Leva rather than Winter. Bartlett and Bussey (2011) has criticised the continued used of the Winter data based on Dempster (1955) due to the age of the work, the small size of the sample, as methodological issues within. Appendix 5 showed differences in internal work and gross efficiency dependant on the BSP set employed using the total body data from the previous chapter. Furthermore the Winter data set used a single trunk which does not account for the movement of different parts of the trunk during the rowing action (Pollock *et al*., 2009). The de Leva (1996) data set allows for a multi-segmented trunk to be included. The use of the multi segment trunk model may identify performance characteristics of skilled rowers. Bull and McGregor (2000) indicated that there is a limited understanding of the trunk in rowing studies as often the trunk is considered a single segment (Shiang and Tsai, 1998; Baudouin and Hawkins, 2002). Studies have examined kinematics of the trunk during rowing, indicating that the regions of the spine are not acting as a single segment (Bull and McGregor, 2000; McGregor *et al*., 2002; McGregor *et al*., 2004, Pollock *et al*., 2009) causing such an approach to be questioned. However, there does not appear to be any studies that have reported the internal work of a segmented trunk, with which to make a comparison. Kleshnev (2006) has indicated that within skilled rowers, different styles of rowing exist and trunk motion will differ between these styles. No controls or measurements were placed on style or trunk movement for any participant in the present study.

The change in BSP data set from Winter to de Leva (1996) showed that internal work increased with respect to intensity for both the skilled and unskilled participants. The additional exercise intensities (75 and 125 W) derived internal work values that followed a linear pattern to the existing exercise intensities and did not suggest any peaks in internal work between the previously tested intensities. The multi segmented trunk did not appear to change the relationship of internal work and exercise intensity from the previous chapter.

4.4.3 Efficiency

Gross efficiency of novice participants ranged from 20-27 %, increasing with respect to intensity and showed a large effect size between 50 and 75 W (*d* = 1.4) and moderate effect sizes between remaining successive intensities (*d*=0.48-0.55) showing agreement with the suggestion that gross efficiency increases with respect to exercise intensity (Ettema and Loras, 2009). Net efficiency for novice participants ranged from 28-31 % efficiency. Net efficiency increased between 50 and 75 W, supported by a moderate effect size (*d*=0.46). However, for the remaining exercise intensities (75, 100, 125 and 125 W), net efficiency plateaued at ≈31 %, with trivial effect sizes between intensities (*d*=0.03-0.17). Net efficiency did not increase with respect to exercise, unlike gross efficiency.

Skilled participants showed moderate increases in gross (16-25 %, *d* = 0.43-0.51) and net (21-28 %, *d* = 0.27-0.51) efficiency with respect to exercise intensity. The results concurred with Sandbakk *et al*. (2012) who indicated that gross efficiency is low at lower work levels and higher at higher work levels in skilled cross-country skiers. Gross efficiency was shown to increase with increases in treadmill speed, GE ranging from 20 % to 36 % suggesting very high reported efficiencies (Schuch *et al*., 2011). However, Hofmijester *et al*. (2009) reported that gross efficiency was constant during rowing, despite increasing stroke rate, differing from the increasing efficiency presented in this chapter.

There are limited studies to compare the results to as the aim of this thesis is to examine the efficiency of the total body, and as such the rowing ergometer was used as the modality to make that assessment. Hence, even with the relatively limited previous studies which have examined rowing, the comparison is limited as often this has included issues to do with the boat and oar/water interaction.

There is a dearth of total body efficiency studies to compare the results with. Where rowing has been assessed, differences in methodology, particularly the inclusion of internal work, and whether the results are from ergometer or on-water rowing, make comparison difficult. With ergometer rowing it is possible to ‘row’ without any real regard to technique. Gross efficiency of 15 % for tank rowing at 3.0 $m.s^{-1}$ was reported by Fukunga *et al*. (1986) based on five trained participants using methodology that measured the forces generated by oar against the water, which would be highly dependent on skill level. The results in this chapter suggested efficiency was higher than reported by Fukunga *et al*. (1986) but there was less skill involved in producing power on a land based ergometer than on water. Additionally, the intensities used would have been different and it has been indicated that the intensity plays an important determining role in efficiency (Leirdal *et al*., 2013). Gross efficiency from ergometer rowing was estimated at 20 % for 28, 34 and 40 strokes per minute in 17 competitive female rowers (Hofmijster *et al*., 2009). The efficiency values reported in this chapter incorporate the 20 % figure but change with intensity. The stroke rates in Hofmijster *et al*., (2009) were much higher than those used in this study, returning to the issue of intensity and efficiency. Efficiency has been demonstrated to be parabolic in nature (Dean and Kuo, 2011; Nakia and Ito, 2011). This could suggest that the results of Hofmijster *et al*. (2009) were near the apex of the curve and results presented within this chapter on the ascending arm. Alternatively, the gross efficiency did not change as stroke rate increased hence increase in work was matched by a proportional increase in energy expenditure, explaining why efficiency remained the same.

The reported gross efficiency for rowing is larger than other studies that have examined total body motion, such as cross-country skiing. Gross efficiency of 14-16 % for well-trained skiers (Leirdal *et al*., 2013), 13-17 % for elite skiers (Lindinger and Holmberg, 2011), 10-16 % dependant on incline and intensity of elite skiers (Sandbakk *et al*., 2010), and 15-17 % with elite male and female cross-country skiers (Sandbakk *et al*., 2013) have been reported. However, it has been suggested that efficiency is increased in situations where body weight is supported such as rowing (Ettema and Loras, 2009) compared to cross-country skiing. Gross efficiency reported is similar to that of cycling of 20-25 % (Ettema and Loras, 2009). The levels of gross efficiency reported are higher than upper body exercise where wheelchair propulsion was suggested to be between 2 and 10 % efficient (van de Woude *et al*., 2001).

Gross Efficiency ranged from 20-27 % and 16-25 % for novice and skilled groups, respectively. In vitro, muscular efficiency is suggested to be around 25-30 % (Smith *et al*., 2005). However, it has been argued that muscle does not have a single value for efficiency (Umberger and Martin, 2007) and it is possible that this may be altered by elastic energy (Neptune *et al*., 2009), momentum of other segments, energy transfer (Winter, 1979) and levers (Zatsiorsky, 2002). Furthermore, it should be noted that muscular efficiency is not analogous to mechanical efficiency (Ettema and Loras, 2009). The indicated values for muscular efficiency may provide a useful point for evaluation of the results. The values of the novice and skilled group encompass the 25-30 % values suggested by Smith *et al*. (2005). This indicated some confidence in the results, reporting values consistent with theory.

Net efficiency increased with respect to intensity from 28-31 % and 21-28 % for novice and skilled participants, respectively. Net efficiency for the novice participants demonstrated a plateau unlike the linear increase shown in gross efficiency. Net efficiency is suggested as a more appropriate measure when the issue of skill is involved (Sidossis *et al*., 1992) and more appropriate when changes of exercise intensity are used as it adjusts for the total load on the body, not just external work (Ettema and Loras, 2009). Significant increase in the cost of unloaded cycling with increasing intensities has been noted where unskilled cyclists have been suggested to expend more energy in movements that do not contribute to the work done especially as intensities increase (Sidossis *et al*., 1992). Although using gross efficiency, Hofmijster *et al*. (2009) did report a plateau of efficiency, so this is not without precedent in the literature. The use of net efficiency has revealed a different pattern to gross efficiency. Skilled participants demonstrated an increasing net efficiency with respect to exercise intensity, following the trend of gross efficiency.

There is a dearth of research on net efficiency using a total body model. However net efficiency of 20 % and 24 % values reported by Nozaki *et al*. (1993) for two participants rowing on the water at 2 $m.s^{-1}$ and 4 $m.s^{-1}$, are smaller in magnitude than the results of the present study for novice participants but are similar to the skilled participants. Mohri and Yamamoto (1985) reported net efficiency of 10-11 % for female rowers, differing considerably to the results in this or the previous chapter. This is also very different from the gross efficiency values of Hofmijster *et al*. (2009), especially when net efficiency is larger than gross efficiency. However, Nozaki *et al*. (1993) and Mohri and Yamamoto's (1985) research was collected during on-water rowing, which will derive different results as it is the efficiency of rowing, where as opposed to the efficiency of the rower (Affeld *et al*., 1993).

Nakai and Ito (2011) reported net efficiency values of eight male collegiate cross country skiers ranging from approximately 20 % to 38 %. These results start within the range presented in this chapter but exceed them and are larger than any other study reviewed. Nakai and Ito (2011) suggested their work was difficult to compare to other studies as efficiency had been calculated in different way across studies, but without referencing suggested that their figures were comparable with level running.

Within the results presented in this chapter, the most unusual result is that, at every exercise intensity, for both gross and net efficiency, the novice participants were more efficient than the skilled participants. There does not appear to be any comparative data for gross or net efficiency between novice and skilled rowers to compare with. However, comparisons of rowers with different levels of training and skill, suggested better rowers have greater efficiencies (Nelson and Widule, 1983; Mohri and Yamamoto, 1985). This is supported by the different kinetic and kinematic responses of with respect to skill level (Hase *et al.,* 2002; Cerne *et al.,* 2013). The results are contrary to the literature, in that skilled rowers have presented lower efficiency values than novice participants. In other total body models, such as cross country skiing 'better' performers have been shown to have a higher efficiency. Sandbakk *et al*. (2010) reported significant differences in gross efficiency between international and national level skiers across different inclines and speeds. Performance ranking and gross efficiency of a cross-country skiers were found to be related, suggesting the more successful skier was more efficient (Sandbakk *et al*., 2013). No differences were seen for gender. Ainegren *et al*. (2013) showed elite skiers had greater efficiency than recreational skiers. This suggests that skilled performers should have higher efficiencies than novice performers.

Literature examining efficiency between different skilled or trained groups is most abundant within cycling. However, results are not clear due to differing methodologies and choice of efficiency (gross, net, delta) used. Studies reported no significant difference of cycling efficiency and experience of the participant, where elite cyclists and novices have similar efficiencies (Marsh and Martin, 1993; Nickleberry and Brooks, 1996; Moseley *et al*., 2004). Delta efficiency does not alter with increasing cadence in trained cyclists, trained runners and 'less-trained' cyclists and there were no differences between the three groups of participants (Marsh *et al.*, 2000). Conversely, differences in efficiency of 1.2 % have been reported between elite and professional cyclist (Lucia *et al*., 1988) and 1.4 % between training and untrained cyclist (Hopker *et al*., 2007). Gross efficiency of a cyclist has been shown to increase during one season (Hopker *et al*., 2009), over multiple seasons (Santalla *et al*., 2009), as a response to training in untrained women (Hintzy *et al*., 2005), and due high intensity training in professional cyclists (Hopker *et al*., 2010). Technique has also been linked to efficiency, suggesting skilled technique should be more efficient (Korff *et al*., 2007; Camara *et al*., 2012). The ability to change efficiency suggests that trained and skilled participants should have higher efficiencies than novice participants. Although the results of efficiency are equivocal with regards to skill and cycling, there are no reports of skilled participants being less efficient than novice.

In summary, the additional exercise intensities (75 and 125 W) did not reveal any peaks in efficiency, which may have occurred using the previous chapter's exercise intensities. The gross and net efficiency estimates in this chapter were comparable to the previous chapter but the novice participants reported 2-3 % increases in efficiency. These values were comparable to literature indicating the changes of intensity, methods and BSP model, derived acceptable results. However the novice participants reported higher efficiencies than the skilled participants and does not concur with previous research findings. The component issues of efficiency will now be examined.

4.4.4 Total work

Total work was the sum of the previously discussed internal work and external work. External work was based upon the target power output from the display unit of the ergometer (Ettema and Loras, 2009), and were converted to work (kJ) and normalised to the drive duration so the units were consistent with the other components of the efficiency equation. There is a degree of difficulty in maintaining the exact desired power output, on a rowing ergometer. Power output was calculated from stroke velocity and force applied to the ergometer. Any change in one or more of the variables will change the power output and the work done. Participants were instructed to maintain the desired power output, and asked to correct any deviations from the power output. However, the three-minute trials allowed the development of a consistent stroke and this is supported by the reliability of the drive length and duration results. This is a common approach that is used in friction braked cycle ergometry (Widrick *et al.*, 1992) and arm-cranking (Smith and Price, 2007). It is acknowledged that there will have been some variation around the desired work levels, but all encouragement was used to obtain the power outputs desired. Anecdotally, skilled participants found the lower work levels 50 and 75 W initially difficult to find a consistent pattern as this was an intensity far lower than their training used. Conversely, some of the novice participants reported the 150 W condition difficult, suggesting they would have found any further increase in intensity difficult to achieve.

Total work increased with respect to exercise intensity and external work was the larger contributor to total work done compared to internal work. Skilled participants did more total work than novice participants and large effect sizes were shown between the cohorts. This concurs with Purkiss and Robertson (2003) who suggested that higher work done was representative of higher skill levels. Unfortunately, there is very little rowing specific literature to compare these finding with. As total work, numerator of the efficiency equation, was larger for the skilled participants, it would suggest that the unusual result of novice participants having a higher efficiency was related to the denominator of the equation, energy expenditure.

4.4.5 Energy expenditure

Energy expenditure was measured via expired gas analysis, where the volume of oxygen consumed (L.min^{-1}) was multiplied by the 'energy equivalent' of the R-value (Péronnet and Massicotte, 1991) to determine energy expenditure per minute (kJ.min^{-1}). Six of the novice participants, exceeded an R-value of 1.0 at intensities of 100 W and greater. In these instances, the maximum energy equivalent (R=1.0) of 21.700 was used and it is acknowledged that this will underestimate the energy expenditure (Hettinga *et al.*, 2007; van Drongelen *et al.*, 2009; Sandbakk *et al.*, 2012). None of the skilled participants exceeded an R-value of 1.0.

The gross energy expenditure increased with respect to intensity for both groups. Increases in energy expenditure were expected as there is increased metabolic cost associated with the increase speed for shortening of the muscle (Kram, 2000), which is supported by the decrease in drive duration and increase in drive length with respect to intensity, indicating an increase in stroke velocity. The results displayed statistical differences with large effect sizes between the groups at each intensity. Net energy expenditure was calculated by subtracting the resting energy expenditure from the gross energy expenditure at each exercise intensity. Net energy expenditure increased with respect to intensity, displaying statistical differences and large effect sizes between both groups. This closely follows the trends of gross energy expenditure as the individual participants' resting energy expenditure is subtracted from the gross energy expenditure at each intensity level. The assumption of this method is that the resting energy expenditure remains the same, irrespective of the exercise intensity (Ettema and Loras, 2009). The resting energy expenditure was very similar, 7.80 and 7.75 kJ.min^{-1} with trivial effect size (d=0.09), for novice and skilled participants, respectively. This suggested that at rest their energy expenditure did not differ and that changes were due to the protocol. The resting energy expenditure was similar to the values presented in the previous chapter, and similar to the previously reported values of Roberts *et al.*, (2005).

The results indicated that, at each intensity level, the novice participants had lower gross and net energy expenditure than skilled rowers for the same exercise intensity (Figure 4.11. and 4.12). From a basic physiological perspective, training tends to decrease the energy expenditure for the same levels of work (Sparrow *et al.*, 1999; Lay *et al.*, 2002) so it would be reasonable to expect that the skilled group who train specifically for this action would have lower energy expenditure. Whilst there will be some underestimation of the energy expenditure in some trials for some of the novice participants of 100 W and above, none of the novice participant had an R>1.0 at 50 or 75 W, yet the differences still exist. With the novice participants having less energy expenditure than skilled at the lower intensities where R<1.0 and the resting rate being comparable to Roberts *et al*. (2005), it is suggested that this is a direct result of the activity, rather than a measurement issue. The underestimation of energy at 100 W may increase the values of the novice group, but as oxygen consumption, and by association energy expenditure, at sub-maximal intensities increases in a linear pattern it is likely that the trend would differ from the presented results. This may indicate that the underestimation of the energy expenditure has not made a major influence on these results. Skilled participants had statistically lower (p<0.05) heart rate than novice participants at each intensity support by large effect sizes (d = 1.02-1.82, Figure 4.13), which suggested a lower energy expenditure. Whilst the R-values and hence energy equivalent are smaller in the skilled participants, the volume of oxygen was much greater influencing the calculations. Anecdotally, none of the skilled participants found the testing intensities taxing or difficult and felt that they could continue to increasing intensities if it was warranted. As some of the novice participants had an R-value greater than 1.0 this indicated that the novice participants found the exercise intensity more challenging than the skilled participants. There are a number of issues which may have contributed to the unexpected differences in energy expenditure.

i. Movement Pattern

Hase *et al*. (2002) indicated that although similar in kinetics, skilled rowers exert larger forces during the stroke compared to less skilled rowers. Higher forces in the quadriceps muscle and higher contact forces at the knee accelerating the skilled rower at the beginning of the drive phase requiring greater moments of force in the lumbar spine and knee to decelerate at the end of the drive phase compared to less skilled rowers. These differences in kinetics could raise the energy expenditure of skilled rowers compared to novice participants (Hase *et al*., 2004; Bateman *et al*., 2006).

ii. Muscle And Muscle Mass Used

Oxygen consumption is linked to the muscle mass involved in the action (Yoshiga and Higuchi, 2003). As trained rowers, on average, are bigger and heavier than non-rowers (Shephard, 1988), it could be hypothesised that higher energy expenditure of the skilled participants is linked to increased muscle mass. This may be somewhat mitigated by using net energy expenditure. Within walking it has been suggested mechanical cost is not the only determinant of metabolic cost. Muscular work has a large metabolic cost but the total cost is not just the change in energy levels (Umberger and Martin, 2007). The load and speed of shortening will vary the efficiency with which the muscle will work. Considering the rowing stroke, whilst it may be considered a cyclic activity, it essentially starts from a static position, accelerates through the drive, before stopping and reversing direction. This differs the activity compared to movement patterns such as running and walking where there is no start, change in direction or stop. Hence the energy cost of the rowing stroke will vary throughout the drive phase. It is probable that the skilled rowers have a different pattern of segmental movement, which has been optimised for on water rowing. This may differ significantly from the novice participants' pattern of movement which would have had the movement goal of maintaining the desired power output.

iii. Stretch shortening cycle

The stroke cycle of the skilled rowers was slower as they adopted a stroke pattern similar to on-water rowing, as evidenced by the drive duration times. The speed of movement was lower than novice participants suggesting little use of the stretch shortening cycle (SSC) as a metabolically free method of enhancing work done. The novice rowers used a shorter and quicker stoke and may have used the SSC more than skilled participants. Essentially the novice saved energy by using the SSC, where they more quickly repeated the rowing stroke cycle (van Ingen Schenau *et al*., 1997)

iv. Total body physiology

One of the unusual aspects of this protocol was a motion that involved the total body for propulsion. There is evidence to suggest that this is challenging to the hemodynamic system particularly for novice participants. This may explain why some novice participants exceeded an R value of 1.0 at relatively low work rates (Volianitis and Secher, 2002). Participants who train their arms have been shown to have increased oxygen consumption compared to untrained participants (Volianitis *et al*, 2004). Arm trained participants also show an increase in oxygen consumption with respect to exercise intensity. This may account for the increased oxygen consumption of the skilled participants. Rowers have reported to have entrained their breathing patterns to coincide with parts of the rowing stroke, therefore not having a constant breathing pattern (Siegmund *et al*., 1999). This may in effect alter the pattern of the volume of oxygen measurement by the metabolic cart (Robergs *et al*., 2010), hence influencing energy expenditure.

v. Body size and scaling.

The methods of Péronnet and Massicotte (1991) calculate energy expenditure by multiplying the energy equivalent of the R-value by the volume of oxygen consumed. This is done by an absolute measure ($L.min^{-1}$) as opposed to a relative measure ($mL.kg.min^{-1}$). Hence the effects of body size (smaller individuals consume less oxygen than larger individuals) are not accounted for (Glazier, 2008). It is uncommon to account for differences in body size in cohorts that are similar such as cyclists, runners or cross-country skiers (Yoshiga and Higuchi, 2003; Moseley *et al.*, 2004; Sandbakk *et al.*, 2012), although it has been used when comparing animal species of different sizes (Taylor *et al.*, 1982). Although use of scaling, adjusting for body size, is used when examining different groups such as adults and children (Zakeri *et al.*, 2006), it is relatively unused in the assessment of efficiency between groups of differing skills or abilities. However, within rowing research where trained rowers have been assessed there is a suggestion that heavyweight and lightweight rowers should be scaled (Hill and Davies, 2002). Commonly scaling is completed based on the mass of participants. However, the anthropometrics of the two groups do not suggest there are meaningful differences in mass or stature. Effect size analysis showed moderate differences between stature, but trivial effect size for mass, arguing that scaling procedures would not be appropriate. The current data as it stands will be used to assess efficiency from the study. Whilst absolute exercise intensities were used within the study, the heart rate data suggested that these intensities were a different proportion of metabolic power for the two groups. This may suggest that comparison by absolute intensity is difficult and each group has is being examined as different parts along their efficiency curve (i.e. novice are near the apex for the curve whereas skilled participants are on the ascending arm). Absolute intensities allow for a standardised testing procedure and are arguably more applicable to a rowing crew where intensity will be dictated on stroke rate, rather than any relative index (i.e. percentage of VO_2max).

4.5 Summary

In summary, the energy expenditure of skilled participants was greater than novice participants. Examination of the data indicated that skilled participants had a lower R-value and heart rate at each exercise intensity. However, the volume of oxygen consumed was far greater than the novice participants and this caused the indirect calorimetry calculation to suggest higher energy expenditure. This is linked to a number of possibilities such as higher work load (Hase *et al*., 2004), training adaptation allowing for increased oxygen uptake (Volianitis *et al*., 2004) and entrainment (Siegmund *et al*., 1999). Whilst it may be possible to scale the data, no real differences in the anthropometrics of the two groups, suggested that this would not affect the results. The higher energy expenditure causes efficiency values to suggest the skilled participants were less efficient despite larger work done and lower heart rates. An assumption made in the current efficiency model was that all work done is new work and hence the energetic cost is for new work. Skilled participants are able to effectively do work for free by energy transfer (Norman and Komi, 1987), which if transfer was accounted for, then the ratio would be altered. The current models have assumed no transfer of energy, which has been suggested to be a fundamental limitation to the analysis of efficiency (Williams and Cavanagh, 1983).

4.5.1 Examining intermediate intensities

In the previous chapter, three work intensities were considered (50, 100 and 150 W), which demonstrated an increase in efficiency with respect to intensity. However, it was not clear whether any of the points were a plateau or a decrease from a plateau. The inclusion of intermediate intensity levels (75 and 125 W) allowed further understanding of the patterning of both gross and net efficiency. Gross efficiency increased for both skilled and unskilled groups. Dean and Kuo (2010) indicated that efficiency is parabolic in nature, but no plateau or decline was seen which may suggest that the exercise intensities were too low to evoke such a response. The net efficiency for the skilled participants continued to increase with respect to intensity, whereas the novice participants increased then plateaued suggesting a maximum efficiency. The suggestion that net efficiency is a more appropriate measure when using participants of different skill and different intensities reduces (Sidiossi *et al*., 1992; Ettema and Loras, 2009) displayed very different pattern of change of efficiency for novice participants.

4.5.2 Efficiency estimates

In terms of gross efficiency, the current results were higher than other total body models such as rowing (Fukunga *et al*., 1986) and cross country skiing (Sandbakk *et al*., 2010; Lindinger and Holmberg, 2011; Leirdal *et al*., 2013; Sandbakk *et al*., 2013), but were similar to cycling (Ettema and Loras, 2009). The methodology used would also suggest that the value for efficiency is for that of the rower (i.e. the individual) rather than rowing, which is more difficult to ascertain due to the interaction of the rower, boat, oar and water.

In terms of net efficiency, there was some similarity to on water rowing (Nozaki *et al*., 1993) and to cross country skiing (Nakai and Ito, 2011). However, the pattern of efficiency between the two groups, with the skilled participants increasing efficiency with respect to intensity and the novice participants plateauing. This may suggest that net efficiency is a more appropriate method to assess efficiency as it addresses issues of skill level and a change in intensity. Additionally, the results are close to some of the suggested physiological responses to exercise. Net efficiency reported that novice participants were more efficient than skilled participants and for the reasons alluded to above requires further enquiry.

Energy expenditure suggested that novice participants used less energy than skilled, hence affecting the efficiency results as described above. The difference in energy expenditure is not supported by heart rate and anecdotal evaluation of the perceived intensity of the work. In order to address this, the energy expenditure may need to be scaled, although the anthropometrics do not indicate difference in mass which is the standard scaling exponent.

The model is based on an absolute change in energy levels. This simplification allows the model to be constructed and evaluated. As such it appears to be returning values in the expected range, although the issue of energy expenditure needs to be reviewed. Development of the simple model will give greater understanding of the efficiency of the rower. Areas that other researchers are focussing on include the role of positive and negative work, and energy transfers within and between segments (Winter, 1979). These have the potential to change the internal work done, hence modifying the efficiency of the movement. These will be addressed in the next phase of the study.

4.5.3 Novice vs Skilled participants

Whilst absolute exercise intensities were used within the study, the heart rate data suggested that these intensities were a different proportion of metabolic power for the two groups. This may suggest that comparison by absolute intensity is difficult and each group has been examined at different parts along their efficiency curve (i.e. novice are near the apex for the curve whereas skilled participants are on the ascending arm). Absolute intensities allow for a standardised testing procedure and are arguably more applicable to a rowing crew where intensity will be dictated on stroke rate, rather than any relative index (i.e. percentage of VO_2max).

The aims of the chapter were to further develop the internal work model to incorporate a multi-segmented trunk, using the data set of de Leva (1996); and to compare the gross and net efficiency for a total body action for skilled and novice population, over an extended range of exercise intensities.

The model was refined by using the more cohort appropriate data of de Leva (1996), which also allowed the construction of a multi-segmented trunk model, however, this still did not include any transfer of energy. The results were similar to the previous chapter. The efficiency values were similar to the literature and the previous chapter suggesting the model is appropriate. Gross and net efficiency differed between the skilled and novice cohort, but unexpectedly, the skilled participants were less efficient than the novice. Although the results were unexpected, modification will allow further investigation of the results, suggesting the aims of this chapter were met.

CHAPTER 5 ENERGY TRANSFER AND EFFICIENCY ESTIMATES

5.1 Introduction

The data calculated in the previous chapters has not considered energy transfer within or between segments. This may allow the construction of a simple model but assumes that all work done has a metabolic cost. Williams and Cavanagh (1983) stated that the assumption of no transfers of energy cannot be recommended. By allowing for transfer of (mechanical) energy, work done may occur without metabolic cost. These assumptions of internal work of the model may have an effect on the subsequent efficiency estimations. Whilst Martindale and Robertson (1984) have calculated the work done during a rowing stroke with different energy transfer assumptions, there does not appear to be any research that includes this in efficiency calculations. To this end, internal work will be calculated three different ways using the nomenclature of Caldwell and Forrester (1992). Firstly, Wn, representing the work done assuming no energy transfers; Secondly, Ww, representing work done assuming transfers within the segments and thirdly, Wwb, representing work done assuming energy transfer within and between segments. Energy transfer between segments can occur between non-contiguous segments (Lees *et al*., 2004). The three methods of calculation (Wn, Ww and Wwb) will be used in the calculation of gross and net efficiency. This chapter will use the 50, 100 and 150 W data for novice and skilled participants, from Chapter 4.

The aims of this chapter were to:

- model internal work to account for energy transfers within and between segments
- examine the changes in efficiency from different energy transfer models.

5.2 Method

The data used in this chapter is the 50, 100 and 150 W data from chapter 4. The 75 and 125 W data were excluded due to the small differences in gross and net efficiency estimates, when increases of 25 W were used. The BSP data used in this study was taken from de Leva (1996).

5.2.1. Participants

Twelve male novice participants (age 26.7±4.9 yrs; mass 79.6±9.9 kg; stature 1.79±0.06m, mean±SD, respectively) and twelve male skilled participants (age 25.6±4.6 yrs; mass 82.0±9.5kg; stature 1.83±0.06m, mean±SD, respectively) were recruited.

5.2.2 Procedure

The data were collected as detailed in chapter 4. The positional data for the joint centres of the left shoulder elbow, wrist, hand, hip, knee, ankle, foot and the positions of the vertex of head, C7, sternum, L4 were exported from the motion capture system, as previously detailed. The position of the segmental centre of mass was determined and used, firstly to calculate the position of whole body centre of mass and secondly, to calculate the displacement and velocity of the segmental centre of mass relative to the whole body centre of mass. The data were calculated for one upper and one lower limb and doubled to represent the contra-lateral limb. The trunk and head were considered as four segments, as used in the previous chapter. Calculations for external and internal work were based on the average of five trials per intensity for each participant using a custom scripted LabVIEW code. The metabolic energy expenditure was taken from the data used in the previous chapter.

5.2.3 Modification of mechanical work calculations

Total work done was calculated from the internal and external work done for each stroke analysed. Internal work was based on the work of Caldwell and Forrester (1992) and the different equations were used to represent the degree of transfer within and between segments. In the previous chapter potential energy was measured as part of work done to the ergometer. However, instantaneous potential energy of each segment was necessary for the different calculation methods, hence in this chapter it was calculated in its own right and included as a component of internal work. External work was based a rowing specific protocol of Martindale and Robertson (1984).

5.2.4 Internal work

The internal work done was calculated from the instantaneous potential (PE), translation kinetic (TKE) and rotational kinetic energy (RKE) using the methods of Caldwell and Forrester (1992). The three methods differ in the order that the changes in energy are summed (Williams and Cavanagh, 1983). Using the nomenclature of Caldwell and Forrester (1992), Wn represented the work done assuming no energy transfers, Ww represented work done assuming transfers within the segments and Wwb represented work done assuming energy transfer within and between segments.

Wn: Work with no transfers

The absolute change in PE, TKE and RKE of a segment from the start to the finish of the drive phase was calculated using equations 5.1, 5.2 and 5.3. The change in energy for the segment was determined as the sum of the changes in energy from the above equations, as in equation 5.4. The total energy change was determined by the summation of all 16 segments as in equation 5.5.

$$W_{PEi} = \sum_{j=2}^{k} \left| PE_{ij} - PE_{i-1j} \right| \tag{5.1}$$

where W_{PEi} is the PE of a segment i at time j, summed across time period 1 to k

$$W_{TKEi} = \sum_{j=2}^{k} \left| TKE_{ij} - TKE_{i-1j} \right| \tag{5.2}$$

where TK_{Ei} is the TKE of a segment i at time j, summed across time period 1 to k

$$W_{RKEi} = \sum_{j=2}^{k} \left| RKE_{ij} - RKE_{i-1j} \right| \tag{5.3}$$

where W_{RKEi} is the RKE of a segment i at time j, summed across time period 1 to k

$$W_{ni} = W_{PEi} + W_{TKEi} + W_{RKEi}$$

(5.4)

where W_{ni} is the work done on segment i assuming no transfer of energy

$$W_n = \sum_{i=1}^{16} W_{ni}$$

(5.5)

where W_n *= work done on by a total body of 16 segments assuming no transfer of energy*

Ww: Work assuming transfers within segments

At each time period, the instantaneous PE, TKE and RKE were summed, the change in each segments was calculated and all the segments were summed (Equation 5.6). The change in segment energy (Equation 5.7) and the change in all segments of interest are summed (Equation 5.8).

$$SE_{ij} = PE_{ij} + TKE_{ij} + RKE_{ij}$$

(5.6)

where SEj = total energy of a segment at time j, PEj = potential energy of a segment at time j, TKEj = translational kinetic energy of a segment at time j and RKEj = work due to changes in rotational kinetic energy of a segment at time j.

$$W_{Wi} = \sum_{j=1}^{K} |\Delta SE|$$

(5.7)

where ΔSE = change in segmental energy from time j to k, j = start, k = finish

$$W_w = \sum_{i-1}^{n} W_{Wi}$$

(5.8)

where Ww = work of total body, Wwi = work of segment assuming transfers within segments and n = number of segments in the body.

Wwb: Work assuming transfers within and between segments

At each time period the instantaneous PE, TKE and RKE for each segment was summed for all segments (Equation 5.9). The change in total body energy was calculated and summed over the time period (Equation 5.10). Total body energy was calculated from the sum of the changes in energy for all segments (Equation 5.11).

$$SE_j = PE_j + TKE_j + RKE_j$$

(5.9)

where SEj = total energy of a segment at time j, PEj = potential energy of a segment at time j, TKEj = translational kinetic energy of a segment at time j and RKEj = work due to changes in rotational kinetic energy of a segment at time j.

$$TBE_j = \sum_{i=1}^{n} SE_j$$

(5.10)

where WWBi = work of total body assuming transfers within and between segments, ΔTBE = change in total body energy from time j to k, j = start, k = finish

$$W_{WBi} = \sum_{j=1}^{K} |\Delta TBE|$$

(5.11)

where WWBi = work of total body assuming transfers within and between segments, ΔTBE = change in total body energy from time j to k, j = start, k = finish

5.2.5 External work

External work was calculated as the change in total energy of the body, at the start and finish of the stroke (Equation 5.12), using the methodology of Martindale and Robertson (1984). Total energy of the body (Equation 5.13) was the sum of instantaneous potential, translational kinetic and rotational kinetic energy levels of all segments of the body (Equation 5.14).

External work done:

$$W_{ext} = E_{totn} - E_{tot0}$$

(5.12)

where W_{ext} = external work, E_{totn} = finishing energy and E_{tot0} = starting energy

Total body energy:

$$E_{tot} = \sum_{s=1}^{16} E_{seg}$$

(5.13)

where E_{tot} *= total energy of the body and* ΣE_{seg} *= sum of segmental energy for all segments*

Segmental energy:

$$E_{seg} = mgh + \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

(5.14)

where E_{seg} *= segment energy, m= segment mass, v= segment velocity, I= segmental moment of inertia and ω= segmental angular velocity*

5.2.6 Energy transfer

Quantification of the energy transfer within (Tw), between (Tb) and total (Twb) was assessed per stroke using the methods of Norman *et al*. (1985), where

$$Tw = Wn - Ww$$

(5.15)

Where Tw = transfer within segments, Wn = work done assuming no transfer, Ww = work done assuming energy transfer within segments

$$Tb = Ww - Wwb$$

(5.16)

Where Tb = transfer between segments and Ww = work done assuming energy transfer within segments Wwb = work done assuming energy transfer within and between segments.

$$Twb = Tw + Tb$$

(5.17)

Where Tw = transfer within segments, Tb = transfer between segments and Twb = total transfer within and between

5.2.7 Data Management

To assess how the method of calculation (i.e. the assumption of transfer within the model), affected the calculations of internal work and efficiency, the results were compared for each intensity against the different methods of calculation (i.e. internal work at 50 W) calculated as Wn, Ww and Wwb. Secondly, to evaluate the effects of exercise intensities calculated by each method (i.e. 50 W, 100 W and 150 W) using Wn were compared. Additionally, external work, total work and transfer of energy were assessed.

Unless stated, data were considered normally distributed and thus parametric statistics were used. Where the data were not normally distributed, it was assessed by Shapiro-Wilk statistics. Statistical alpha level was set at 0.05. Effect sizes were evaluated as per Cohen (1998) as <0.19 = trivial, 0.2-0.4 = small, 0.41-0.70 = moderate and >0.71 = large.

5.2.8 Data analysis

To ascertain the effects of the assumption of energy transfer, the data were examined in two ways. Firstly, 'method of calculation' examined differences between results for a single exercise intensity (i.e. 50W calculated using Wn, Ww and WWb, 100 W using Wn, Ww and WWb Wn and 150 W using Ww and WWb). Secondly, 'Exercise Intensity' examined the results of a single method of calculation across all exercise intensities (i.e. Wn at 50, 100 and 150 W, Ww at 50, 100 and 150 W, Wwb at 50, 100 and 150 W).

Within this chapter the 2 participants groups were considered separetly, hence no between groups analysis has been conducted. As with previous chapters, normality was determined by Shapiro-Wilk statistic. Repeated measures ANOVA for normally distributed data and Friedman's ANOVA for non-normally distributed data was used to indicate statistical differences between the methods of calculation and between exercise intensity. Inferential statistics were used to assess the probability of chance results, rather than to indicate any differences between comparisons. Effect sizes were used to interpret differences, using Cohen's *d* and the following classifications 0.2-0.4 =small, 0.41-0.7= moderate, >0.71 = large.

5.3 Results

5.3.1. Calculation of internal work

Internal work was estimated by three different methods of calculation: work assuming no transfers (Wn), work assuming energy transfer within a segment (Ww) and work assuming energy transfer within and between segments (Wwb), as per Caldwell and Forrester (1992). Internal work increased with respect to exercise intensity, regardless of the method of calculation. At each exercise intensity, the Wn methodology derived the largest estimation of internal work and the Wwb methodology derived the smallest estimations. Skilled participants did more work per stroke than novice participants (Figures 5.1.-5.3)

5.3.1.1 Method of calculation

The method of calculation (Wn, Ww and WWb) derived different values for internal work per exercise intensity for novice participants. Internal work calculated by the Wn method gave the largest value and Wwb the smallest value for internal work, irrespective of the exercise intensity. Some data were not normally distributed (Appendix 3) hence a Friedman's ANOVA indicated statistical differences (X^2=24.0, p<0.05) between each method at 50 W. A post-hoc Wilcoxon signed rank test with an adjusted alpha level (0.05/3=0.017) to account for multiple comparison, showed statistical differences between methods of calculation, supported by large effect sizes (p<0.016, d = 0.81-1.61, Table 5.1). Additionally, statistical differences and large effect sizes were reported for 100 W (X^2=24.0, p<0.05, d = 1.31-2.34, Table 5.1) and 150 W (X^2=24.0, p<0.05, d = 1.24-2.76, Table 5.1). These results indicated important differences in estimates of internal work depending upon the method of calculation used.

As with the novice participants, the method of calculation (Wn, Ww and WWb) derived different values for internal work per exercise intensity for the skilled participants. In all conditions of intensity and method of calculation, the skilled participants did more internal work per stroke than novice participants. The data were normally distributed (Appendix 3) and subjected to a repeated measures ANOVA to examine the effect of the method of calculation on internal work estimates. At 50 W (Figure 5.1), Mauchly's test indicated violation of sphericity, ($X^2(2)=6.618$, $p<0.05$), so Greenhouse-Geisser correction was applied. ANOVA showed the calculation method affected the internal work done (*F* (1.3, 14.8) =342.2, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences for internal work at 50 W between all methods of calculation ($p<0.05$), supported by large effect size for all comparisons (*d* = 1.23-2.52, Table 5.2). At 100 W (Figure 5.2), a repeated measures ANOVA showed the calculation method affected the internal work done (F(2, 22)= 667.6, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences for internal work at 100 W between all methods of calculation ($p<0.05$), supported by large effect size for all comparisons (*d* = 0.80-1.69, Table 5.2). A repeated measures ANOVA showed the calculation method affected the internal work done at 150 W (Figure 5.3), *F*(2, 22)= 459.5, $p<0.05$. Bonferroni post hoc comparisons indicated statistical differences for internal work at 150 W between all methods of calculation ($p<0.05$) supported by large effect sizes (*d* = 0.82-1.72, Table 5.3). Large effect sizes for all comparisons indicated important differences in internal work done as a results of the method of calculation.

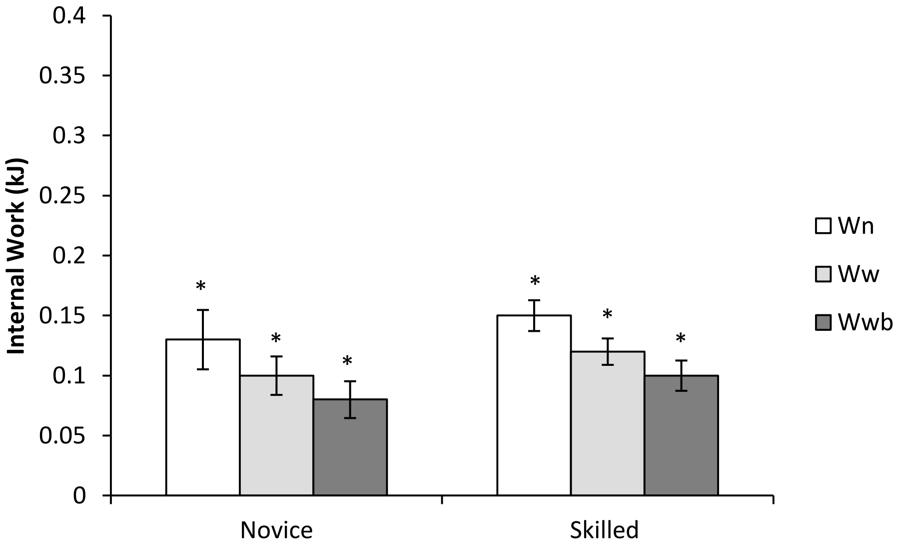

Figure 5.1 Mean (±95%CI) internal work at 50W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference $p<0.05$

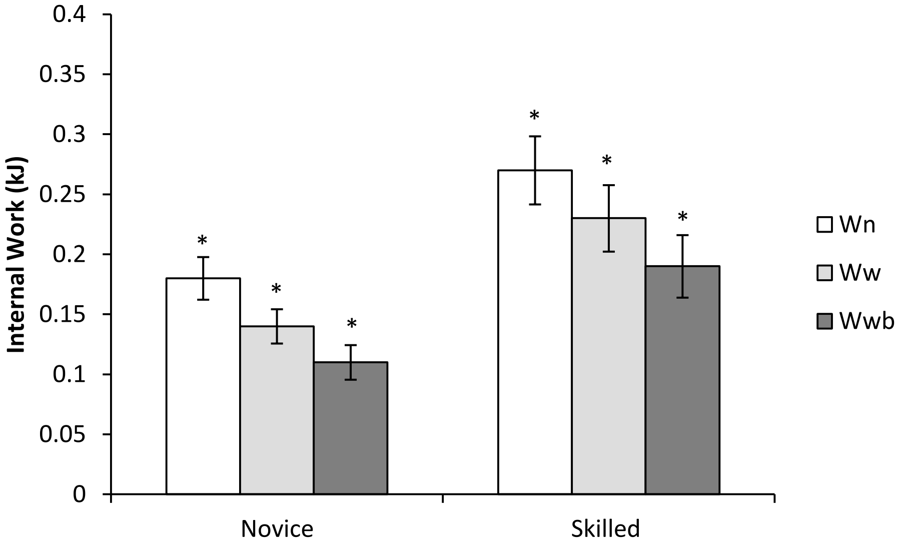

Figure 5.2 Mean (±95%CI) internal work at 100W for novice and skilled participants
* indicates statistical difference *p*<0.05

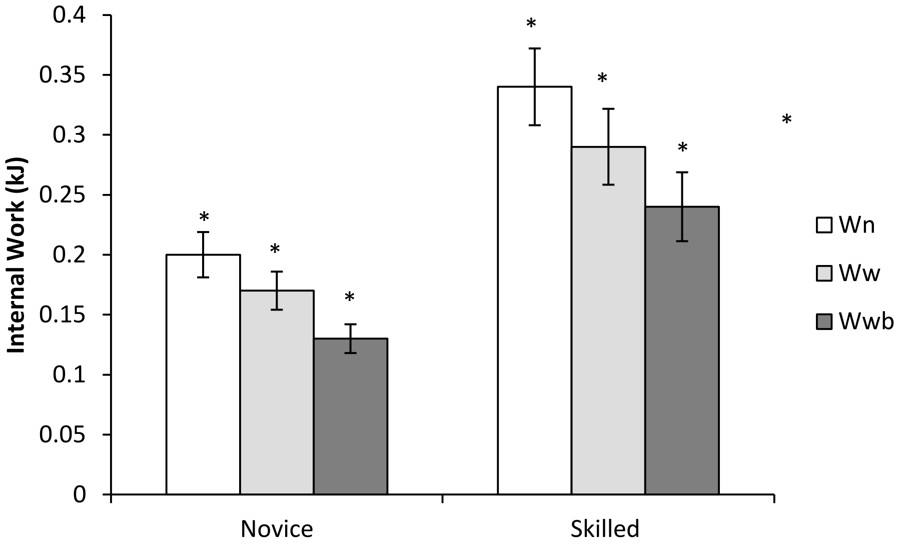

Figure 5.3 Mean (±95%CI) internal work at 150W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

Table 5.1 Post-hoc comparison and effect size for internal work by method of calculation for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Z	df	sig	Cohen's *d*
50	Wn vs Ww	-3.059	2	0.002*	0.81
50	Ww vs Wwb	-3.059	2	0.002*	1.04
50	Wn vs Wwb	-3.059	2	0.002*	1.61
100	Wn vs Ww	-3.059	2	0.002*	1.18
100	Ww vs Wwb	-3.059	2	0.002*	1.31
100	Wn vs Wwb	-3.059	2	0.002*	2.34
150	Wn vs Ww	-3.059	2	0.002*	1.24
150	Ww vs Wwb	-3.059	2	0.002*	1.56
150	Wn vs Wwb	-3.059	2	0.002*	2.76

* indicates statistical difference *p*<0.05

Table 5.2 Post-hoc comparison and effect size for Internal work by method of calculation for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Mean Difference	Std error	sig	Cohen's *d*
50	Wn vs Ww	30.89	1.524	0.000*	1.46
50	Ww vs Wwb	25.75	1.985	0.000*	1.23
50	Wn vs Wwb	56.66	2.798	0.000*	2.52
100	Wn vs Ww	39.87	1.734	0.000*	0.80
100	Ww vs Wwb	41.61	2.100	0.000*	0.87
100	Wn vs Wwb	81.33	2.729	0.000*	1.69
150	Wn vs Ww	46.10	1.93	0.000*	0.82
150	Ww vs Wwb	46.54	3.50	0.000*	0.87
150	Wn vs Wwb	92.64	3.48	0.000*	1.72

* indicates statistical difference *p*<0.05

5.3.1.2 Exercise Intensity

The results indicated an increased level of internal work with respect to intensity for the novice participants. Using the Wn method, a Freidman's ANOVA indicated statistical difference between the three exercise intensities. An adjusted alpha (p=0.017) Wilcoxon signed rank test indicated statistical differences between all intensities with large effect sizes (*p*<0.017, *d* = 0.87-1.78, Table 5.3). This pattern of results was repeated for the Ww (*p*<0.017, *d* = 0.89-2.16, Table 5.3) and Wwb (*p*<0.017, *d*=0.77-2.08, Table 5.3) conditions. This indicated important differences in internal work done between exercise intensities.

Similarly the levels of internal work increased with respect to exercise intensity when calculated within each method of calculation, for the skilled participants. Internal work calculated using the Wn method violated Mauchly's test of sphericity ($X^2(2)=15.0$, $p<0.05$). A Greenhouse-Geisser corrected repeated measures ANOVA showed the exercise intensity affected the internal work done ($F(1.1, 12.4)= 180.5$, $p<0.05$). Bonferroni post hoc comparisons showed statistical differences and large effect sizes between all exercise intensities ($p<0.05$, d = 1.18-4.25, Table 5.4). Internal work calculated via the Ww method violated Mauchly's test of sphericity ($X^2(2)=15.5$, $p<0.05$). A Greenhouse-Geisser corrected repeated measures ANOVA showed the exercise intensity affected the internal work done ($F(1.2, 12.3)= 180.5$, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences with large effect sizes between all exercise intensities ($p<0.05$, d = 2.99-4.01, Table 5.4). The Wwb method of calculating internal work violated Mauchly's test of sphericity ($X^2(2)=12.5$, $p<0.05$). A Greenhouse-Geisser corrected repeated measures ANOVA indicated the exercise intensity affected the internal work done, ($F(1.2, 12.8)= 180.5$, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences and large effect sizes between all exercise intensities ($p<0.05$, d = 2.65-3.76, Table 5.4). The large effect sizes in all comparisons indicated important differences in internal work done, as a result of increasing exercise intensities.

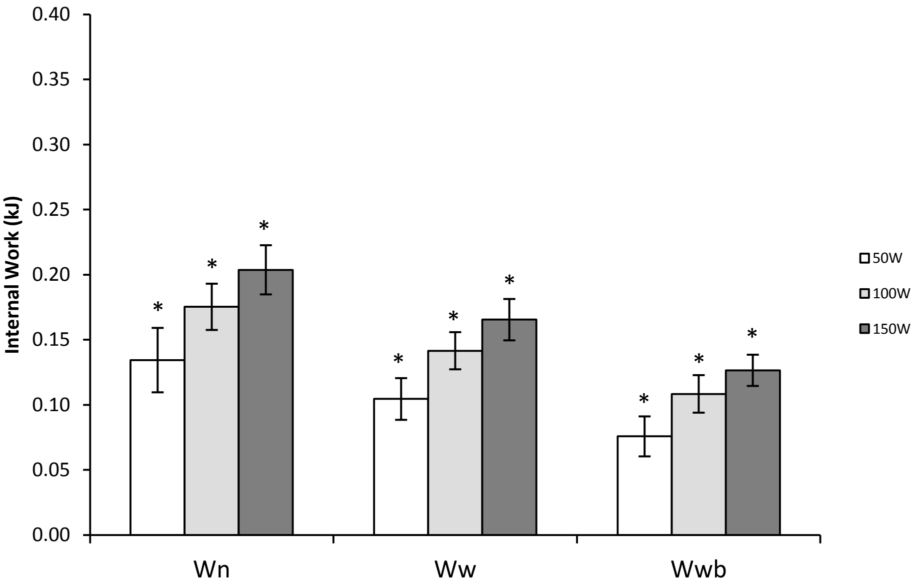

Figure 5.4 Mean (±95%CI) internal work for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference $p<0.05$

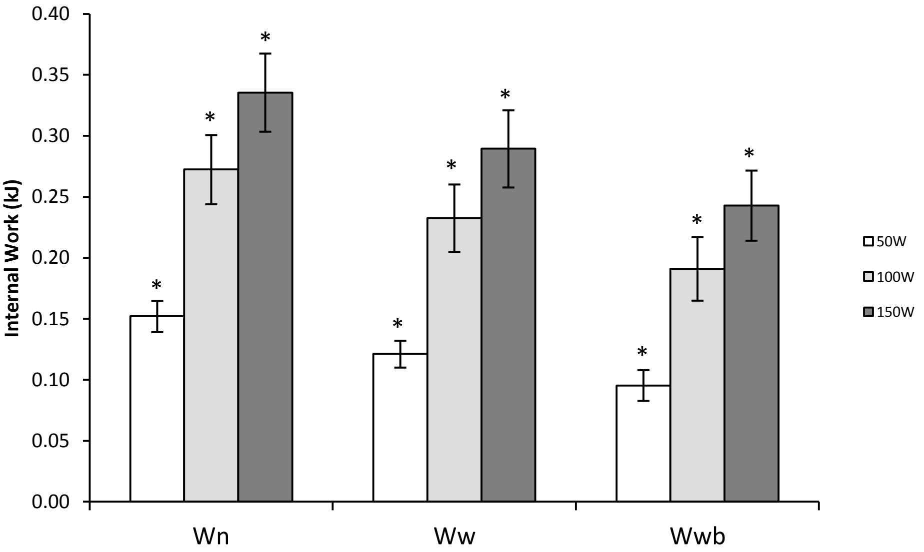

Figure 5.5 Mean (±95%CI) internal work for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

Table 5.3 Post-hoc comparison and effect size for internal work by exercise intensity for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Z	df	sig	Cohen's *d*
Wn	50W vs 100W	-2.981	2	0.003*	1.08
Wn	100Wvs 150W	-3.059	2	0.003*	0.87
Wn	50W vs 150W	-3.059	2	0.003*	1.78
Ww	50W vs 100W	n/a			1.38
Ww	100Wvs 150W	n/a			0.89
Ww	50W vs 150W	n/a			2.16
Wwb	50W vs 100W	-3.059	2	0.002*	1.24
Wwb	100Wvs 150W	-3.059	2	0.002*	0.77
Wwb	50W vs 150W	-3.059	2	0.002*	2.08

* indicates statistical difference *p*<0.05

Table 5.4 Post-hoc comparison and effect size for Internal work by exercise intensity for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Mean Difference	Std error	sig	Cohen's *d*
Wn	50W vs 100W	120.38	10.13	0.000*	3.09
Wn	100W vs 150W	120.38	4.47	0.000*	1.18
Wn	50W vs 150W	183.50	12.90	0.000*	4.25
Ww	50W vs 100W	111.34	10.07	0.000*	2.99
Ww	100W vs 150W	56.89	4.39	0.000*	1.08
Ww	50W vs 150W	168.29	12.86	0.000*	4.01
Wwb	50W vs 100W	95.68	8.48	0.000*	2.65
Wwb	100W vs 150W	51.82	4.17	0.000*	1.07
Wwb	50W vs 150W	147.50	10.90	0.000*	3.76

* indicates statistical difference $p<0.05$

At all intensities and methods of calculation, skilled participants did more internal work per stroke than novice participants. The method of calculation, which represents the energy transfer assumption, affected the calculated work done at each intensity level. The effect sizes for method of calculation were large, indicating that the assumptions made had an important effect on the resultant internal work values. Wn had the largest estimate and Wwb the smallest estimate of internal work for all intensities, for both cohorts. Within each method of calculation, internal work increased with respect to intensity. Within the skilled population, the method of calculation (Wn, Ww and Wwb) showed large effect sizes indicating meaningful differences in estimates of internal work at the same exercise intensity, suggesting the choice of method of calculation is important to the derived values.

Within the same method of calculation, large effect sizes indicated that the differences in exercise intensity made important differences to the estimates of internal work done. The differences between exercise intensity levels, irrespective of method of calculation and cohort, were all assessed as large (>0.7) using Cohen's *d*. The skilled participants showed larger absolute increased in internal work, than novice participants.

5.3.2 External work

External work (Table 5.5) was calculated as the difference in energy from the start of the movement to the end (i.e. the start and finish of the drive phase). Data are reported in J rather than kJ as the values were very small and lose clarity of interpretation if presented in kJ. Novice participants did more external work than skilled participants, at each exercise intensity. Both novice and skilled participants increased external work with respect to intensity. Small to moderate effect sizes were reported for novice participants (*d* = 50 v 100 W = 0.39; 100 v 150 W = 0.19; 50 v 150 W = 0.61) and large effect sizes were reported for skilled participants (*d*= 50 v 100 W = 0.92; 100 v 150 W = 0.79; 50 v 150 W = 1.41) between exercise intensities.

Table 5.5 Mean (± SD) External work (J) for novice and skilled participants

	50 W	100 W	150 W
Novice	1.25 (±1.26)	1.81(±1.63)	2.31(±1.60)
Skilled	0.11 (±0.05)	0.18(±0.11)	0.31(±0.20)

5.3.3 Total work

Total work was calculated as the sum of internal work for each method of calculation and intensity, and external work for each intensity (Table 5.6).

Table 5.6 Mean (± SD) total work (kJ) for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

	Intensity (W)	**Wn (kJ)**	**Ww (kJ)**	**Wwb (kJ)**
Novice	50 W	0.14(±0.04)	0.11(±0.03)	0.08(±0.03)
	100 W	0.18(±0.03)	0.14(±0.03)	0.11(±0.03)
	150 W	0.21(±0.03)	0.17(±0.03)	0.13(±0.02)
Skilled	50 W	0.15(±0.02)	0.12(±0.02)	0.10(±0.02)
	100 W	0.27(±0.05)	0.23(±0.05)	0.19(±0.05)
	150 W	0.34(±0.06)	0.29(±0.06)	0.24(±0.05)

5.3.4 Efficiency - method of calculation

Three versions of gross and net efficiency were calculated based on the energy transfer assumptions, hence the Wn, Ww and Wwb notation was used to highlight the different methods. As previously stated, the results were assessed for the effect of the method of calculation and the effect of exercise intensity on the estimates of efficiency. The novice and skilled participants were considered as separate groups.

5.3.4.1 Gross efficiency

Gross efficiency was estimated for Wn, Ww and Wwb methods at 50, 100 and 150 W, respectively, are represented for novice and skilled participants (Figure 5.6-5.8). Efficiency estimates based on using Wn as internal work derived the highest gross efficiency values, whereas results using Wwb as internal work derived the smallest values of gross efficiency.

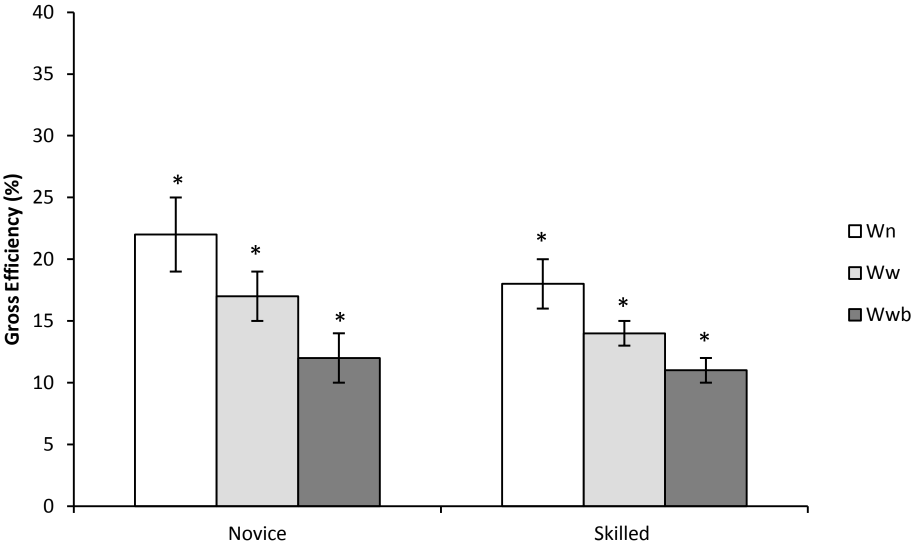

Figure 5.6 Mean (±95%CI) Gross efficiency at 50W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

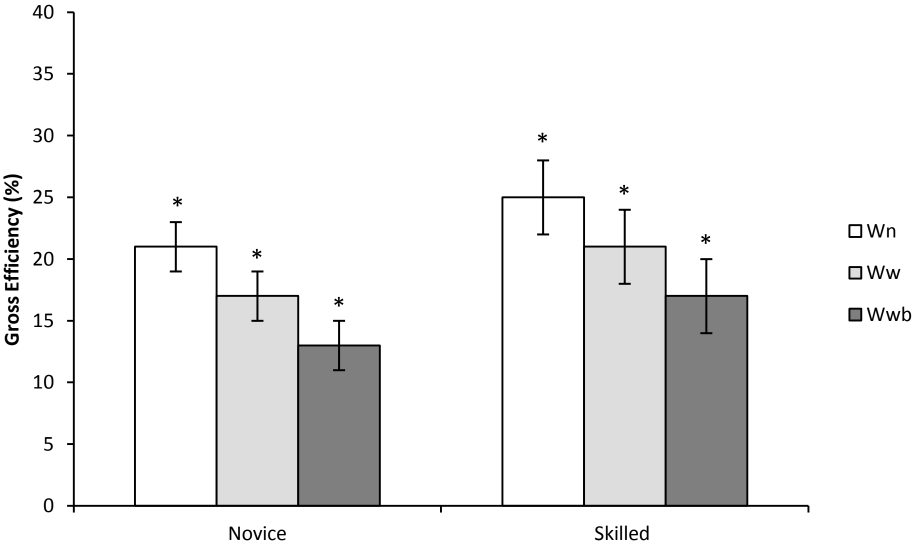

Figure 5.7 Mean (±95%CI) Gross efficiency at 100W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

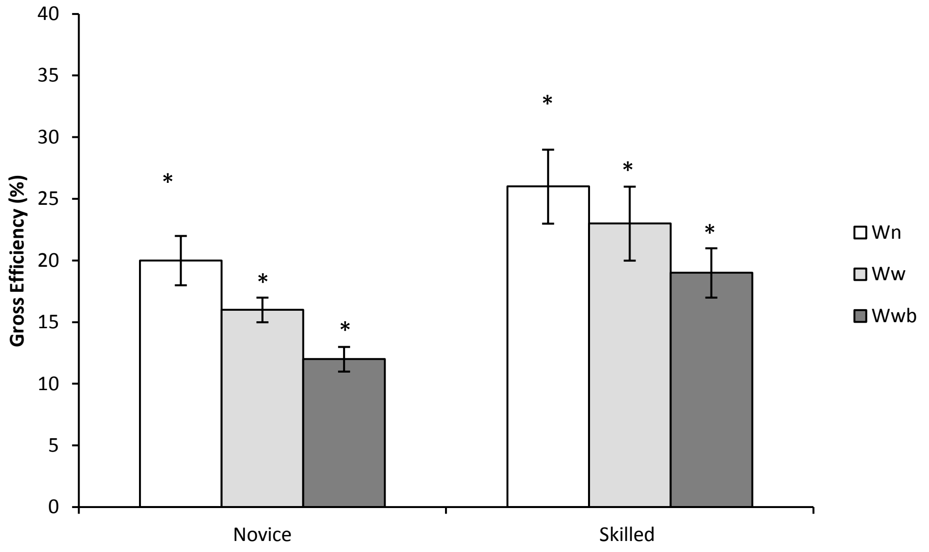

Figure 5.8 Mean (±95%CI) Gross efficiency at 150W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments) * indicates statistical difference *p*<0.05

Within the novice participants, gross efficiency differed by method of calculation where the Wn method estimated the highest efficiency (22 %) and Wwb the lowest efficiency (12 %) at 50 W. This pattern was repeated at 100 W and 150 W. Some gross efficiency results were not normally distributed (Appendix 3), hence non-parametric statistics were used. Statistical differences (X^2=24.0, *p*>0.05) were reported for gross efficiency at 50 W between calculation methods (Wn, Ww and Wwb). Post hoc Wilcoxon signed ranks tests indicated statistical differences (*p*<0.016, Table 5.7) between all three conditions, indicating the method of calculation affected the gross efficiency result. Large effect sizes supported the importance of these differences. Statistical differences with large effect sizes were also reported for 100 W (X^2=24.0, *p*>0.05, *d*=1.02-1.99, Table 5.7) and 150 W (X^2=24.0, *p*>0.05, *d*=1.30-2.85, Table 5.7). These results indicated that important differences in the estimates of gross efficiency were influenced by the method of calculating internal work.

The method of calculation (Wn, Ww and Wwb) affected the estimates of gross efficiency for the skilled participants. The Wn method was the largest estimate of gross efficiency and the Wwb method the smallest, for each exercise intensity. Comparing the methods of calculation for 50 W, a decrease in gross efficiency was observed. Mauchly's test indicated violation of sphericity ($X^2(2)$=15.95. *p*<0.05) so Greenhouse-

Geisser correction was applied. Repeated measures ANOVA indicated the calculation method affected gross efficiency at 50 W, (*F*(1.1, 12.2)= 231.3, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences between all exercise intensities ($p<0.05$). This was supported by large effect sizes (d=1.42-2.67, Table 5.8). Gross efficiency also decreased across the calculation methods at 100 W. Mauchly's test indicated violation of sphericity ($X^2(2)=10.51$. $p<0.05$). A Greenhouse-Geisser corrected repeated measures. ANOVA showed the calculation method affected gross efficiency at 100 W (*F*(1.2, 13.3)= 241.3, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences between all exercise intensities ($p<0.05$), with large effect sizes (d=0.77-1.62, Table 5.8). Similar to above, the gross efficiency at 150 W decreased across the methods of calculation. Repeated measures ANOVA indicated the calculation method affected gross efficiency at 150 W, (*F*(2, 22)= 426.7, $p<0.05$). Bonferroni post hoc comparisons indicated statistical differences between all exercise intensities ($p<0.05$) with large effect sizes (d= 0.80-1.64, Table 5.8). The results showed large effect sizes for all comparisons indicating the method of calculation derived important differences in the estimates of gross efficiency. Skilled participants displayed larger values of gross efficiency for 100 and 150 W, irrespective of the method of calculation. However, novice participants displayed higher efficiency at 50 W.

5.3.4.2 Net Efficiency

Net efficiency for novice participants decreased for each intensity when calculated by different methods (Wn, Ww and Wwb). At 50 W exercise intensity, net efficiency approximated 30 %, 24 % and 17 %, using the Wn, Ww and Wwb methods, respectively (Figure 5.9). Large effect sizes (d=0.89-1.82, Table 5.9) indicated important differences between calculation methods. Friedman's ANOVA ($X^2=24.0$, $p>0.05$) and post-hoc Wilcoxon signed ranks tests indicated statistical differences ($p<0.016$, Table 5.9) between all three conditions. At 100 W, net efficiency approximated 26 %, 21 % and 16 %, using the Wn, Ww and Wwb methods, respectively (Figure 5.10). Large effect sizes (d=0.94-1.87, Table 5.9) indicated importance differences. Friedman's ANOVA ($X^2=24.0$, $p>0.05$) and post hoc Wilcoxon signed ranks tests indicated statistical differences ($p<0.016$, table 5.9) between all three conditions. At 150 W net efficiency approximated 23 %, 19 % and 14 %, using the Wn, Ww and Wwb methods, respectively (Figure 5.11). Large effect sizes suggested (*d*=1.51-3.31, Table 5.9) important differences, between calculation methods. Friedman's ANOVA (X^2=24.0, *p*>0.05) and post-hoc Wilcoxon signed ranks tests indicated statistical differences (*p*<0.016, Table 5.9) between all three conditions. This indicated that the method of calculation used had an important effect on the estimates of net efficiency at a given exercise intensity.

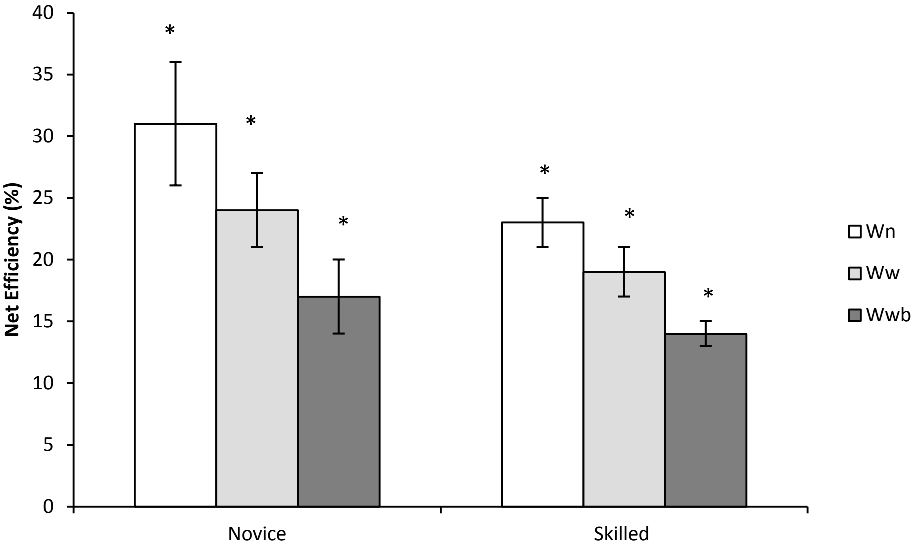

Figure 5.9 Mean (±95%CI) Gross and net efficiency at 50W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

* indicates statistical difference *p*<0.05

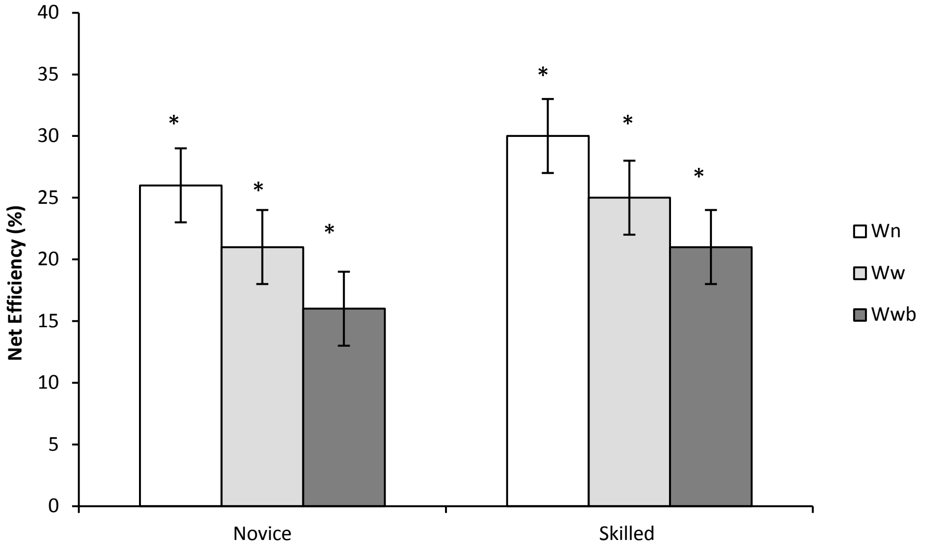

Figure 5.10 Mean (±95%CI) Gross and net efficiency at 100W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

* indicates statistical difference *p*<0.05

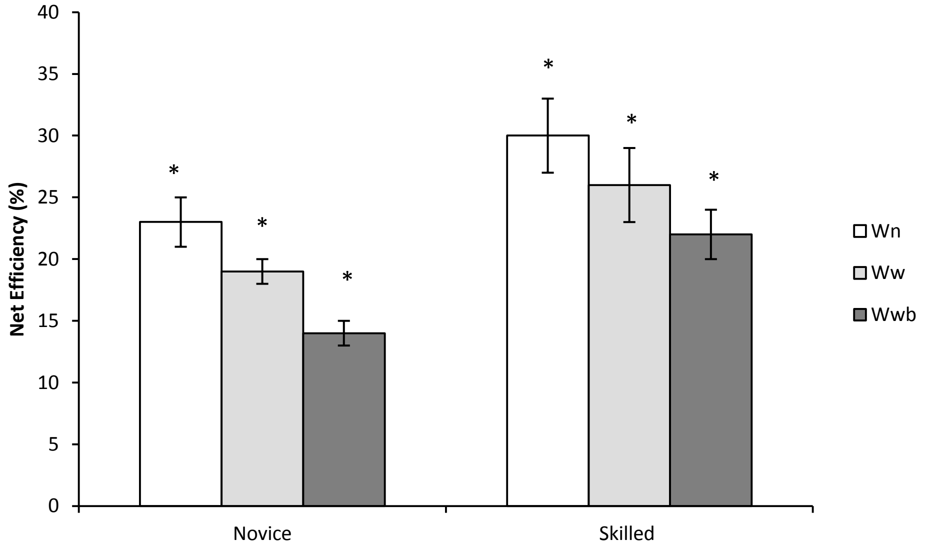

Figure 5.11 Mean (±95%CI) Gross and net efficiency at 150W for novice and skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

* indicates statistical difference *p*<0.05

Net efficiency for skilled participants increased with respect to intensity and was larger in magnitude than gross efficiency for all conditions. Differences between the methods of calculation (Wn, Ww and Wwb) for each intensity, were assessed using repeated measures ANOVA (table 5.10). At 50 W, Mauchly's test indicated violation of sphericity, ($X^2(2)=19.63$. $p<0.05$) so Greenhouse-Geisser correction was applied. ANOVA showed the calculation method affected net efficiency at 50 W, (*F*(1.1, 11.8)=108.5, $p<0.05$). Post hoc tests showed statistical differences between all exercise intensities ($p<0.05$). Large effect sizes were seen between all intensities (*d*=1.43-2.50, Table 5.10). At 100 W Mauchly's test indicated violation of sphericity, ($X^2(2)=12.8$. $p<0.05$). A Greenhouse-Geisser correction repeated measures ANOVA showed the calculation method affected net efficiency at 100 W, (*F*(1.2, 12.8)= 201.4, $p<0.05$). Post hoc tests showed statistical differences between all exercise intensities ($p<0.05$) supported by large effect sizes (*d*=0.82-1.73, Table 5.10). At 150 W a repeated measures ANOVA showed the calculation method affected net efficiency, (*F*(2, 22)= 396.9, $p<0.05$). Post hoc tests showed statistical differences between all exercise intensities ($p<0.05$) with large effect sizes (*d*= 0.87-1.80, Table 5.10). Overall, large effect sizes indicated that method of calculation had an important effect upon net efficiency estimated for skilled participants.

Table 5.7 Post-hoc comparison and effect size for gross efficiency (%) by method of calculation for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Z	df	Sig.	Cohen's *d*
50	Wn vs Ww	-3.088	2	0.002*	0.92
50	Ww vs Wwb	-3.097	2	0.002*	1.19
50	Wn vs Wwb	-3.068	2	0.002*	1.82
100	Wn vs Ww	-3.084	2	0.002*	1.02
100	Ww vs Wwb	-3.104	2	0.002*	1.12
100	Wn vs Wwb	-3.074	2	0.002*	1.99
150	Wn vs Ww	-3.134	2	0.002*	1.30
150	Ww vs Wwb	-3.088	2	0.002*	1.60
150	Wn vs Wwb	-3.084	2	0.002*	2.85

* indicates statistical difference $p<0.05$

Table 5.8 Post-hoc comparison and effect size for gross efficiency (%) by method of calculation for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Mean Difference	Std error	Sig.	Cohen's *d*
50	Wn vs Ww	0.037	0.003	0.000*	1.44
50	Ww vs Wwb	0.032	0.003	0.000*	1.42
50	Wn vs Wwb	0.068	0.005	0.000*	2.67
100	Wn vs Ww	0.036	0.003	0.000*	0.77
100	Ww vs Wwb	0.038	0.002	0.000*	0.86
100	Wn vs Wwb	0.073	0.004	0.000*	1.62
150	Wn vs Ww	0.039	0.003	0.000*	0.80
150	Ww vs Wwb	0.035	0.002	0.000*	0.83
150	Wn vs Wwb	0.074	0.003	0.000*	1.64

* indicates statistical difference $p<0.05$

Table 5.9 Post-hoc comparison and effect size for net efficiency (%) by method of calculation for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Z	df	Sig.	Cohen's *d*
50	Wn vs Ww	-3.059	2	0.002*	0.89
50	Ww vs Wwb	-3.061	2	0.002*	1.20
50	Wn vs Wwb	-3.059	2	0.002*	1.82
100	Wn vs Ww	-3.059	2	0.002*	0.94
100	Ww vs Wwb	-3.064	2	0.002*	1.06
100	Wn vs Wwb	-3.059	2	0.002*	1.87
150	Wn vs Ww	-3.063	2	0.002*	1.51
150	Ww vs Wwb	-3.061	2	0.002*	1.86
150	Wn vs Wwb	-3.061	2	0.002*	3.31

* indicates statistical difference $p<0.05$

Table 5.10 Post-hoc comparison and effect size for net efficiency (%) by method of calculation for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Intensity (W)	Comparison	Mean Difference	Std error	Sig.	Cohen's *d*
50	Wn vs Ww	0.050	0.005	0.000*	1.43
50	Ww vs Wwb	0.039	0.005	0.000*	1.43
50	Wn vs Wwb	0.089	0.009	0.000*	2.50
100	Wn vs Ww	0.046	0.004	0.000*	0.82
100	Ww vs Wwb	0.046	0.006	0.000*	0.92
100	Wn vs Wwb	0.092	0.003	0.000*	1.73
150	Wn vs Ww	0.042	0.003	0.000*	0.87
150	Ww vs Wwb	0.042	0.003	0.000*	0.91
150	Wn vs Wwb	0.082	0.003	0.000*	1.80

* indicates statistical difference $p<0.05$

5.3.5 Efficiency and exercise intensity

Three versions of gross and net efficiency were compared for novice and skilled participants, for each exercise intensity (50, 100 and 150 W) and compared to assess the differences in efficicency estimates using all three methods of calculation. The novice and skilled participants were considered as separate groups.

5.3.5.1 Gross efficiency

Gross efficiency did not appear to vary in response to increasing exercise intensities when calculated for the same method of calculation (Wn, Ww or Wwb) for novice participants (Figure 5.12). Gross efficiency of novice participants approximated 21 % for 50, 100 and 150 W when calculated with the Wn method of internal work. No statistical difference in gross efficiency was reported between 50, 100 and 150 W (X^2=2.167, p>0.05). Small effect sizes (d = 50 vs 100 W = 0.10, 100 vs 150 W = 0.29, 50 vs 150 W = 0.33), suggested small differences in gross efficiency when calculated using Wn method. Using the Ww method the gross efficiency for novice participants approximated 17 % for all intensities. No statistical differences were reported between 50, 100 and 15 0W (X^2=1.167, p>0.05) and small effect sizes were calculated (d = 50 vs 100W = 0.05, 100 vs 150 W = 0.22, 50 vs 150 W = 0.18) suggesting small differences in gross efficiency, using Ww method. Gross efficiency approximated 13 % calculated using the Wwb method. No statistical difference and small effect sizes were reported between 50, 100 and 150 W calculated (X^2=0.894, p>0.05, d = 50 vs 100 W = 0.24, 100 vs 150W = 0.21, 50 vs 150 W = 0.08), suggesting small differences in gross efficiency when calculated using Wwb. The results indicated that no differences in gross efficiency were seen as a result of increasing exercise intensities.

Within each method of calculation (Wn, Ww and Wwb) gross efficiency increased with respect to exercise intensity for the skilled participants (Figure 5.13). Using the Wn method, gross efficiency approximated 18 %, 25 % and 26 % for 50, 100 and 150 W, respectively. A repeated measures ANOVA showed statistical differences (F(2, 22)=78.1, p<0.05) between intensities and Bonferroni post hoc test showed statistical differences, with large effect sizes, between 50 and 100 W (p<0.05, d = 1.82) and 50 and 150 W (p<0.05, d = 2.3). There was no statistical difference between 100 and 150 W (p>0.05) and a small effect size (d = 0.29). Gross efficiency approximated 16 %, 21 % and 23 % for 50, 100 and 150 W, respectively, using the Ww method. A repeated measures ANOVA showed statistical difference (*F*(2, 22) = 90.2, *p*<0.05) between intensities and Bonferroni post hoc test showed statistical differences with large effect sizes were reported between 50 and 100 W (*p*<0.05, *d* = 2.00) and 50 and 150 W (*p*<0.05, *d* = 2.5, Table 5.12). There was no statistical difference between 100 and 150 W (*p*>0.05, *d* = 0.32). Gross efficiency approximated 10 %, 17 % and 20 % for 50, 100 and 150 W, respectively, using the Wwb. A repeated measures ANOVA showed statistical difference (*F*(2, 22) = 108.9, *p*<0.05) between intensities and Bonferroni post hoc test showed statistical differences with large effect sizes between 50 and 100 W (*p*<0.05, *d* = 1.95) and 50 and 150 W (*p*<0.05, *d* = 2.46, Table 5.10). A statistical difference between 100 and 150 W (*p*>0.05, *d* = 0.39) was reported with a moderate effect size. The results indicated that the estimate of gross efficiency increased with respect to exercise intensity.

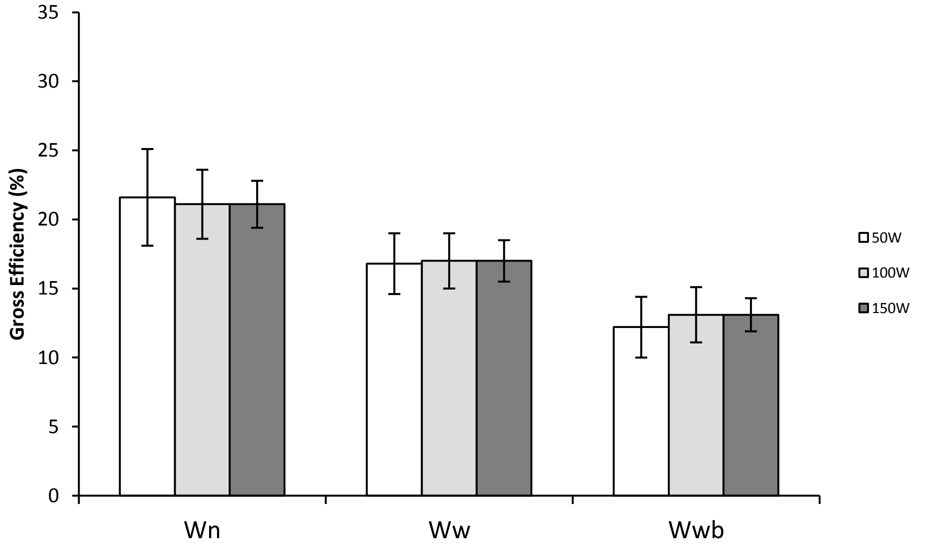

Figure 5.12 Mean (±95%CI) gross efficiency (%) for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

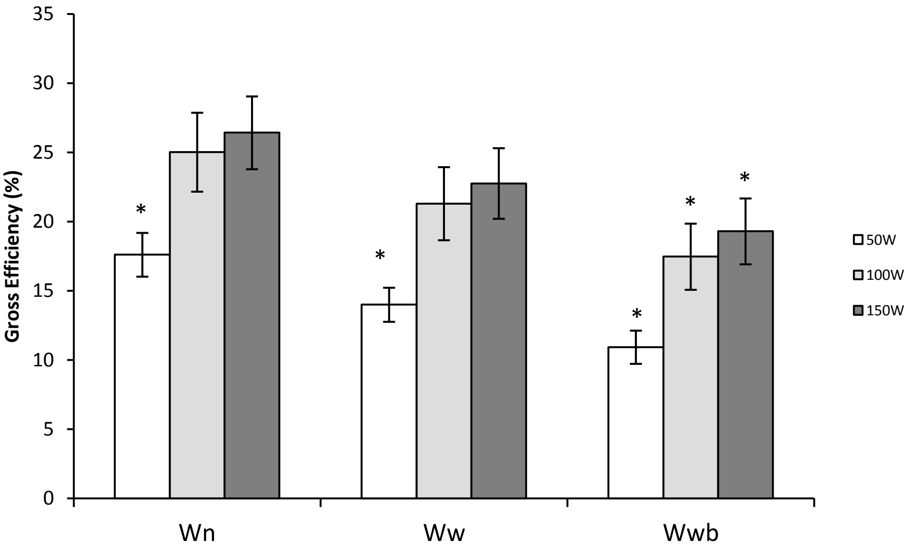

Figure 5.13 Mean (±95%CI) gross efficiency (%) for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

Table 5.11 Post-hoc comparison and effect size for gross efficiency for novice participants(Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Z	df	sig	Cohen's *d*
Wn	50W vs 100W	n/a			0.10
Wn	100W vs 150W	n/a			0.29
Wn	50W vs 150W	n/a			0.33
Ww	50W vs 100W	n/a			0.05
Ww	100W vs 150W	n/a			0.22
Ww	50W vs 150W	n/a			0.18
Wwb	50W vs 100W	n/a			0.24
Wwb	100W vs 150W	n/a			0.21
Wwb	50W vs 150W	n/a			0.08

* indicates statistical difference *p*<0.05

Table 5.12 Post-hoc comparison and effect size for gross efficiency (%) by exercise intensity for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Mean Difference	Std error	sig	Cohen's *d*
Wn	50W vs 100W	0.073	0.007	0.000*	1.82
Wn	100W vs 150W	0.016	0.007	0.104	0.29
Wn	50W vs 150W	0.088	0.009	0.000*	1.82
Ww	50W vs 100W	0.073	0.008	0.000*	2.00
Ww	100W vs 150W	0.012	0.005	0.096	0.32
Ww	50W vs 150W	0.086	0.009	0.000*	2.50
Wwb	50W vs 100W	0.068	0.007	0.000*	1.95
Wwb	100W vs 150W	0.015	0.005	0.021*	0.39
Wwb	50W vs 150W	0.082	0.008	0.000*	2.46

* indicates statistical difference *p*<0.05

Large differences in gross efficiency estimates for a given exercise intensity were linked to the assumptions of energy transfers (Wn, Ww and Wwb). At each exercise intensity gross efficiency was largest using the Wn method and smallest using the Wwb method, for both novice and skilled participants. This indicated that the method of calculation can has an important effect on gross efficiency estimates. Exercise intensity did not display any differences in gross efficiency estimates as a function of exercise intensity. However, gross efficiency increased with respect to exercise intensity for skilled participants. The data suggested that irrespective of the method of calculation, novice participants were more efficient than skilled participants at 50 W. However at 100 and 150 W, irrespective of the method of calculation, skilled participants were more efficient than novice.

5.3.5.2 Net efficiency

Net efficiency decreased with respect to exercise intensity when calculated by Wn, Ww and Wwb methodologies for the novice participants (Figure 5.14) and were larger in magnitude than gross efficiency in all conditions. Statistical differences ($X^2 = 13.167$, $p>0.05$) were reported for net efficiency using the Wn calculation method. An alpha adjusted post hoc Wilcoxon Signed rank test indicated statistical differences between 50 W and 100 W ($p<0.016$) with a moderate effect size ($d = 0.61$) and 50 W and 150 W ($p<0.016$) with a large effect size ($d = 1.14$, Table 5.13). No statistical difference was reported between 100 W and 150 W ($p>0.016$) however, a moderate effect size was reported ($d = 0.64$). Net efficiency when calculated using the Ww method reported statistical differences ($X^2=9.5$, $p>0.05$) from a Friedman's ANOVA. An alpha adjusted post hoc Wilcoxon Signed rank test indicated statistical differences between all exercise intensities ($p<0.016$), with moderate to large effect sizes (Table 5.13). No statistical differences ($X^2= 9.5$, $p<0.05$) were reported for net efficiency using the Wwb calculation method. Effect sizes ranged from small to large (Table 5.13). The results indicated net efficiency decreased with respect to exercise intensity. Moderate to large differences were reported for the Wn and Ww method, and small to moderate differences for the Wwb method.

Net efficiency approximated 23 %, 29 % and 31 % for 50, 100 and 150 W, respectively, using the Wn method for the skilled participants (Figure 5.15). Repeated measures

ANOVA indicated statistical differences (F(2, 22)=28.9, *p*<0.05) between intensities. Post hoc tests shows statistical differences with large effect sizes between 50 and 100 W (*p*<0.05, *d* = 1.23) and 50 and 150 W (*p*<0.05, *d* = 1.42, Table 5.14). There was no statistical difference with a trivial effect size between 100 and 150 W (*p*>0.05, *d* = 0.06). Net efficiency approximated 19 %, 25 % and 26 % for 50, 100 and 150 W, respectively, using the Ww method. Statistical differences (F(2, 22)=39.5, *p*<0.05) with large effect sizes were reported between 50 and 100 W (*p*<0.05*, d* = 1.55) and 50 and 150 W (*p*<0.05, *d* = 1.81, Table 5.14). There was no statistical difference and trivial effect sizes between 100 and 150 W (*p*>0.05, *d* = 0.12). Net efficiency approximated 14 %, 21 % and 22 % for 50, 100 and 150 W, respectively, using the Wn method. Statistical differences (F(2, 22)=55.8, *p*<0.05) with large effect sizes were reported between 50 and 100 W (*p*<0.05, *d* = 1.67) and 50 and 150 W (*p*<0.05, *d* = 2.02). There was no statistical difference between 100 and 150 W (*p*>0.05, *d* = 0.22, Table 5.14)

In summary, net efficiency estimates increased with respect to exercise intensity. Important differences were seen between 50 W compared to 100 and 150 W. Trivial effect sizes suggested no differences between the net efficiency estimates at 100 and 150 W. Net efficiency was affected by the method of calculation employed and estimates were largest using the Wn method and smallest using the Wwb method. This indicted that the method of calculation can have important effects on the estimates of net efficiency for both novice and skilled participants. Net efficiency decreased with respect to exercise intensity for the novice participants, where as net efficiency increase with respect to intensity for the skilled participants. The increase in net efficiency between 100 and 150 W for the skilled participants was small. Similarly to gross efficiency, the data suggested that irrespective of the method of calculation, novice participants were more efficient that skilled participants at 50 W. However, at 100 and 150 W, irrespective of the method of calculation, skilled participants had larger net efficiency values.

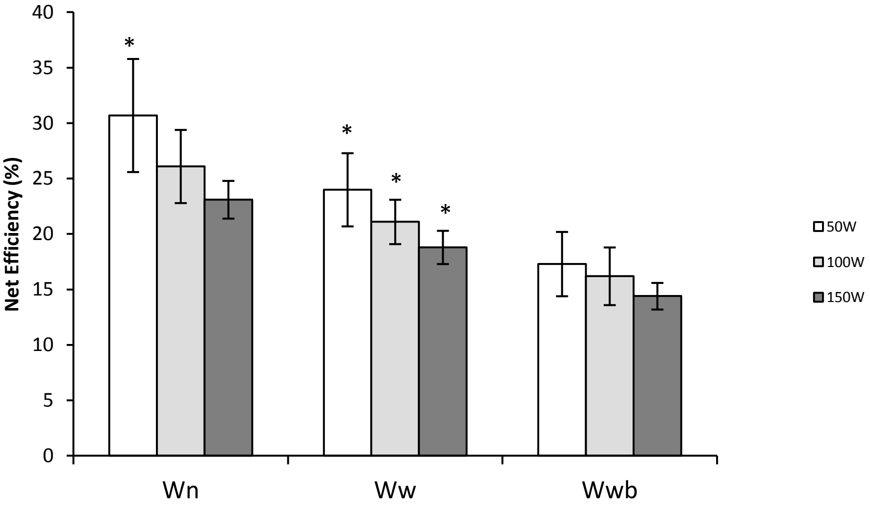

Figure 5.14 Mean (±95%CI) Net efficiency (%) for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

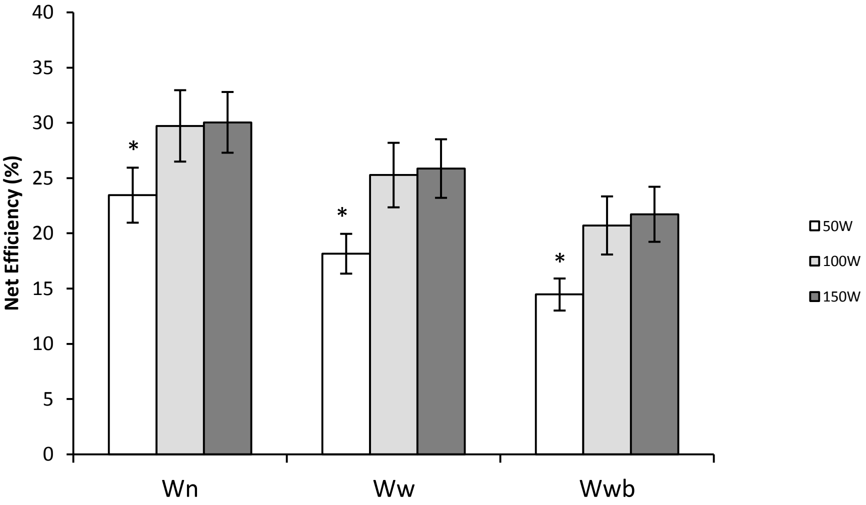

Figure 5.15 Mean (±95%CI) Net efficiency (%) for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)
* indicates statistical difference *p*<0.05

Table 5.13 Post-hoc comparison and effect size for net efficiency for novice participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Z	df	sig	Cohen's *d*
Wn	50W vs 100W	-3.061	2	0.002*	0.61
Wn	100W vs 150W	-1.844	2	0.065	0.64
Wn	50W vs 150W	-2.824	2	0.005*	1.14
Ww	50W vs 100W	-2.667	2	0.008*	0.55
Ww	100W vs 150W	-1.883	2	0.006*	0.62
Ww	50W vs 150W	-2.589	2	0.010*	1.16
Wwb	50W vs 100W	n/a			0.23
Wwb	100W vs 150W	n/a			0.52
Wwb	50W vs 150W	n/a			0.74

* indicates statistical difference $p<0.05$

Table 5.14 Post-hoc comparison and effect size for net efficiency (%) by exercise intensity for skilled participants (Wn= no energy transfers, Ww = energy transfer within segments, Wwb = Energy transfers within and between segments)

Method	Comparison	Mean Difference	Std error	sig	Cohen's *d*
Wn	50W vs 100W	0.063	0.009	0.000*	1.23
Wn	100W vs 150W	0.002	0.008	1.000	0.06
Wn	50W vs 150W	0.065	0.012	0.000*	1.42
Ww	50W vs 100W	0.067	0.009	0.000*	1.55
Ww	100W vs 150W	0.006	0.007	1.000	0.12
Ww	50W vs 150W	0.073	0.011	0.000*	1.81
Wwb	50W vs 100W	0.060	0.008	0.000*	1.67
Wwb	100W vs 150W	0.012	0.006	0.186	0.22
Wwb	50W vs 150W	0.072	0.009	0.000*	2.02

* indicates statistical difference $p<0.05$

5.3.6 Energy transfer

Energy transfer was calculated by the methods of Norman and Komi (1987). The amount of energy transferred increased with intensity for both groups. Skilled participants transferred more energy at 100 and 150 W for all transfers (Tw, Tb and Twb, Figure 5.17). Novice participants transferred more energy at 50 W for all transfer methods (Figure 5.16). This is supported by statistical differences and large effect sizes (Table 5.15) except in the 50 W conditions and 150 W condition.

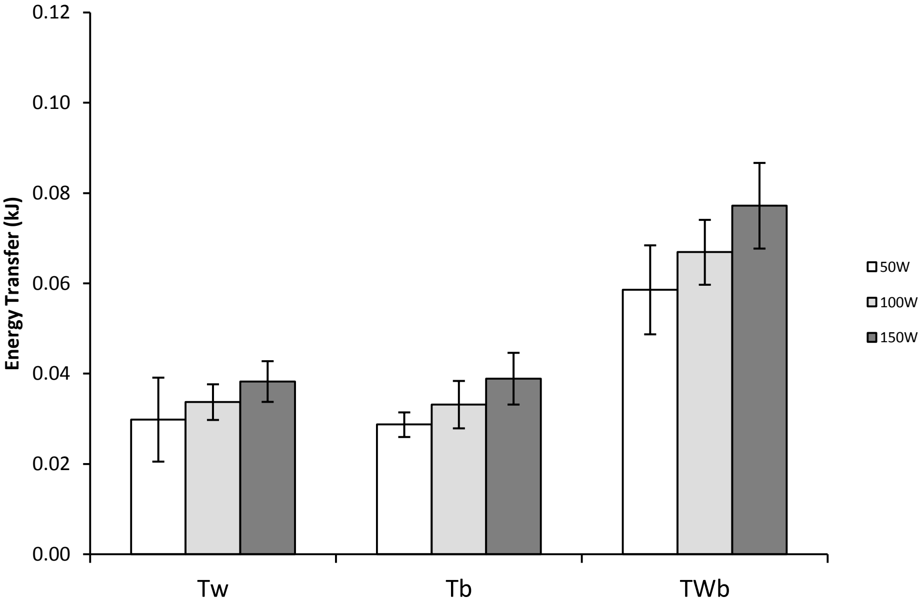

Figure 5.16 Mean (±95%CI) Energy transfer (kJ) for novice participants (Tw= transfers within segments, Tb = transfer between segments, TWb = transfers within and between segments)
* indicates statistical difference *p*<0.05

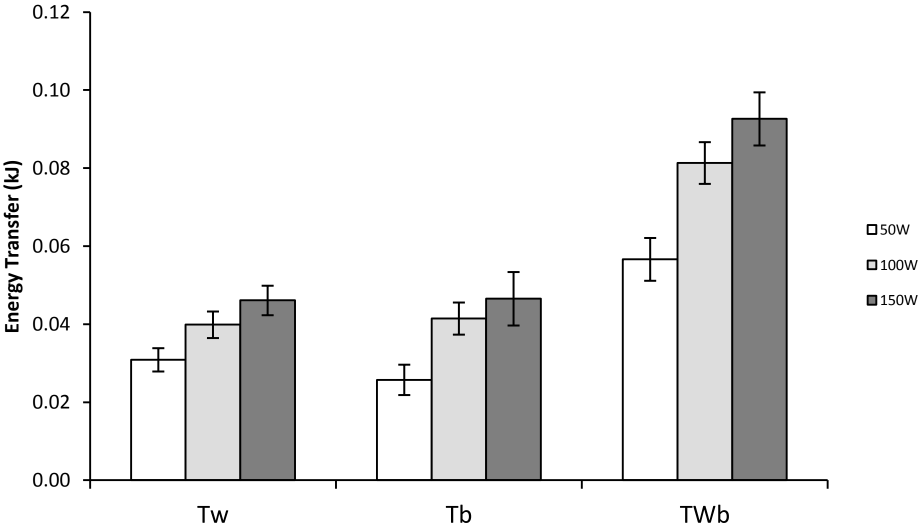

Figure 5.17 Mean (±95%CI) Energy transfer (kJ) for skilled participants (Tw= transfers within segments, Tb = transfer between segments, TWb = transfers within and between segments)
* indicates statistical difference *p*<0.05

Table 5.15 Independent samples difference test effect size for energy transfer between novice and skilled participants. (Tw= transfers within segments, Tb = transfer between segments, TWb = transfers within and between segments)

Intensity (W)	Transfer	t	df	sig	Cohen's *d*
50	Tb	1.233	22	0.231	0.50
100	Tw	-2.310	22	0.023*	0.94
100	Tb	-2.434	22	0.021*	0.99
100	Twb	-3.156	22	0.005*	1.29
150	Tw	-2.603	22	0.016*	1.06
150	Tb	-1.670	22	0.109	0.68
150	Twb	-2.589	22	0.017*	1.06

* indicates statistical difference *p*<0.05

Table 5.16 Independent samples difference test effect size for energy transfer between novice and skilled participants. (Tw= transfers within segments, Tb = transfer between segments, TWb = transfers within and between segments)

Method	Comparison	U	Z	sig	Cohen's *d*
50	Tw	46.0	1.501	0.133	0.08
50	Twb	69.0	0.173	0.862	0.14

* indicates statistical difference *p*<0.05

5.4 Discussion

The aims of this chapter were to model internal work to reflect three assumptions of energy transfer within and between segments and to examine the changes to efficiency. Three levels of energy transfer were used (Caldwell and Forrester, 1992), firstly, representing the work done assuming no energy transfers (Wn); secondly, the work done assuming transfers within the segments (Ww) and thirdly, work done assuming energy transfer within and between segments (Wwb). Gross and net efficiency were calculated based on each on the models of energy transfer (Wn, Ww and Wwb). The data in this chapter were based on the data collected in Chapter 4 and reworked to reflect the methods of Caldwell and Forrester (1992). Results indicated that the assumptions of energy transfer had an important impact of the calculated value of work done, in turn affecting the estimation of gross and net efficiency. In the previous chapter the efficiency of novice participants was greater than that of skilled participants. The results in this chapter partially reverse this result. This section will consider the impact firstly on internal work, followed by efficiency.

5.4.1 Internal work

The methods of calculation (Wn Ww and Wwb), representing the assumption of energy transfer, showed important differences in efficiency estimates for each exercise intensity, within each participant group. The results indicated that when comparing a single exercise intensity (i.e. 50 W), large differences (d>0.71) were seen for efficiency estimates based on Wn, Ww and Wwb. This applied to all exercise intensities and both groups of participants. There are clear differences in efficiency estimates based on the assumption of energy transfer.

A number of movement patterns have previously reported similar results to the present study in walking (Caldwell and Forrester, 1992), running (Williams and Cavanagh, 1983; Slavin *et al*., 1993) and cross-country skiing (Norman *et al*., 1985; Norman and Komi, 1987). To the author’s knowledge, only one study has examined these movement patterns in ergometer rowing (Martindale and Robertson, 1984). The results of this study showed a similarity in values for work done and patterns of change, despite differences in gender, number of participants, ergometers used, exercise intensities and using analysis of a single stroke (catch to catch) to the results of this Chapter. Furthermore, the present study employed a multi-segment trunk model and used the body segment inertial data set of de Leva, as it was considered to be more representative of the participants (Bechard *et al.*, 2009). Additionally, as metabolic data had been collected, it was possible to estimate efficiency per method of calculation, which Martindale and Robertson (1984) did not do. The results supported the contention that the method of calculation will affect both the mechanical work done and estimates of efficiency, but in doing so, may make more mechanically and physiologically appropriate estimates of these variables.

5.4.2 Changes in work

The first aim of this chapter was to examine the differences in internal work done dependent upon the assumption of energy transfer for the given movement pattern. The three methods of calculation used (Wn, Ww, Wwb) are the most commonly used methods within the literature and reflect the assumption of the degree of energy transfer. The derived values for internal work showed large effect sizes between the three models employed at three exercise intensities, for both cohorts. As with previous studies, Wn produced the largest values of internal work and Wwb the smallest (Martindale and Robertson, 1984; Norman and Komi, 1987; Caldwell and Forrester, 1992). The results suggested that the method of calculation used to determine internal work, specifically the assumptions of energy transfer has an important influence upon the derived values for work done. This indicated that the choice of assumptions, need careful consideration and that comparison to studies with different assumptions needs to be considered with care.

The work done for all methods of calculations increased with respect to exercise intensity, in both cohorts. This follows the pattern of increased Wwb with an increase in incline of cross-country skiers (Norman and Komi, 1987). Additionally, the values at 150 W were larger than those at 100 W, in line with previous research (Saibene and Minetti, 2003; Ettema and Loras, 2009). There is limited research with which to make direct comparisons due to differences in modality (running, cross country skiing) and when rowing has been used, there were differences in methodology, such as the calculation of internal work (Hofmijster *et al*., 2009). The values of internal work obtained in the present study were smaller than the values for Wwb reported for four rowers on an ergometer at three self-selected increasing intensities (i.e. 315 and 396 J) for the lowest and highest intensities (Martindale and Robertson, 1984). However, this was calculated for the entire (catch-to-catch) stroke. If the drive phase was estimated at 50 % of stroke time, the values would be somewhat closer, but these could not be matched for intensity, differences in the BSIP data used, or the use of a multi-segmented trunk. The internal work values are also within the previously explained peaks of Bechard *et al*., (2009) and Slawinski *et al*., (2010). Hence, these results indicated some similarities to previous results. The percentage change in work between Wn and Ww was approximately 15 %, similar to the changes reported by Slavin *et al*. (1993). The change between Wn and Wwb was larger (≈30 %), following a similar trend in Slavin *et al*. (1993). This indicated that the model followed similar patterns of results compared to previous literature.

Whilst it is argued that the Wwb method is the most mechanically and physiologically appropriate method of calculating work (Winter, 1979; Martindale and Robertson, 1984) and by extrapolation efficiency, there is not universal agreement on the use of Wwb as originally suggested by Winter (1979). The issue of allowing transfers amongst all segments is not universally accepted and researchers have modified the Wwb protocol to only allow energy transfer between specific segments considered as mechanically and physiologically appropriate. Frost *et al*. (1997, 2002) allowed transfers between contiguous segments of the legs only, however did not compare the results to an unrestricted transfer model. Slavin *et al*. (1993) examined the total transfer and restricted transfer of energy of heel strike and forefoot strike showing different values for work done depending on the assumptions and restrictions of between segment energy transfer, based on the methods of Williams and Cavanagh (1983). The approach of restricting transfer makes comparison of studies difficult as different assumptions will be made, hence limited research has used this method, opting more commonly for an unrestricted method as proposed by Winter (1979). Most of the research studies pertaining to energy transfer and work estimates have examined walking or running, often considering the upper body as a single unit

(Williams and Cavanagh, 1983; Slavin *et al.*, 1993). Total body movements such as rowing (Martindale and Robertson, 1984) and cross-country skiing (Norman *et al.*, 1985; Norman and Komi, 1987) have used the Wwb model with unrestricted transfers. In these modalities the total body is used for producing motion. Specifically in rowing, the motion and force generation starts and the feet, moves to the trunk and finishes at the hands (Soper and Hume, 2004), therefore marking transfers across the body more realistic than might be argued for running and walking. Hence, the reason the Wwb model of Winter (1979) was used, as in Martindale and Robertson (1984). This additionally allowed for comparison of results. Changes in energy of the arm segments were shown to increase jump performance suggesting that when the total body is being used, also suggested the assumption of all transfers may be more valid (Lees *et al.*, 2004).

Skilled participants did more internal work, at all intensities, using all calculation methods. This may indicate that skilled or trained participants attempt to maximise the work done as suggested by Purkiss and Robertson (2003). Internal work (Wn) done was similar at 50 W intensity (0.13 kJ vs 0.15 kJ) between novice and skilled participants, respectively, irrespective of method of calculation. The differences were more pronounced for 100 W and 150 W. Whilst the drive duration was longer for the skilled participants, they did more work per stroke than novices; this would increase the value of the numerator of an efficiency equation. The large effect sizes indicated that the methods of calculation of internal work, hence the assumption of energy transfer, can make a meaningful impact on the resultant levels of internal work. Increased internal work with respect to exercise intensity was seen in the previous chapter, but comparisons are more difficult to make as internal work in this Chapter included potential energy, whereas in the previous chapter it was within external work. It would be more appropriate to compare total work.

5.4.3 Efficiency

Gross efficiency for novice participants was very similar for each of the exercise intensities, whereas skilled participants showed an increasing gross efficiency. Net efficiency for novice participants decreased with respect to exercise intensity, where as the skilled participants increased with respect to intensity, although the final increase was small. The results for the novice participants differ from the results in the previous chapter, particularly in terms of the changes in efficiency related to exercise intensity. These will be discussed later.

In the previous chapter, the novice participants were considered to be more efficient than skilled participants. The results of this chapter suggested that whilst the novice participants were still more efficient at 50 W for both gross and net efficiency, at 100 and 150W the skilled participants were more efficient. As the energy expenditure data were the same as the previous chapter, the changes in work done due to the different assumptions of energy transfer have affected these results.

Large effect sizes suggested important differences in gross and net efficiency during the drive phase of ergometer rowing with 12 novice and 12 skilled male participants at three intensities as a results of the assumptions of energy transfer included in the calculations. Gross and net efficiency were calculated for each version of internal work (Wn, Ww and Wwb) using the energy expenditure data provided in the previous Chapter.

Gross efficiency for novice participants approximated 21 % for 50, 100 and 150 W using the Wn methodology, 17 % using the Ww methodology and 13 % using the Wwb methodology. Unlike the previous Chapter which saw increasing efficiency across the intensities, gross efficiency effectively plateaued for all intensities. Although total work increased across the intensities, the rise in metabolic cost was proportional. The plateauing nature of efficiency has been reported in cycling (Marsh *et al*., 2000; Moseley *et al*., 2004) and rowing (Hofmijster *et al*., 2009), although there were differences in methodologies. The results of this chapter for gross efficiency using the Wn method to the 20% reported gross efficiency for elite female rowers and are within the range of gross efficiency from the previous of 20-27 % for novice and 16-25 % for skilled participants. Ettema and Loras (2009) indicated that gross efficiency increased with respect to exercise intensity. However this was based on ergometry based data. As the work done was calculated from motion capture data and did not include external work from an ergometer, it may indicate a different relationship based on protocol. Net efficiency for novice participants showed a decrease in efficiency with respect to intensity, irrespective of the method of calculation. Net efficiency was larger than gross efficiency at all intensities and methods of calculation. Similar to gross efficiency, there were statistical differences with large effect sizes ($p<0.05$, d = 0.89-3.31) between each exercise intensity and the method of calculation, suggesting the importance of the assumptions of energy transfer in subsequent calculations of efficiency. The decrease in efficiency is different to the previous chapter where net efficiency plateaued. Net efficiency has been suggested as more appropriate to investigate changes in intensity (Ettema and Loras, 2009) or skill levels (Sidiossis *et al*., 1992), and has displayed results that differ from previously reported net efficiency studies. There is a dearth of research on net efficiency using a total body model. However, net efficiency of 20 % and 24 % values reported for two participants rowing on the water at 2 $m.s^{-1}$ and 4 $m.s^{-1}$, respectively (Nozaki *et al*., 1993) were smaller in magnitude than the results of the novice participants in the present study, but, were similar to the skilled participants values. Mohri and Yamamoto (1985) reported net efficiency of 10-11 % for female rowers, differing considerably to the results in this or the previous chapter.

Skilled participants showed increasing gross efficiency across all intensities and all methodologies, approximating 17-26 % for Wn, 14-23 % for Ww and 11-20 % for Wwb. Large effect sizes suggested that the method of calculation had a significant effect on resulting efficiency estimates. These values are similar to those reported in the literature (Hofmijster *et al*., 2009), and to the results of the previous chapter. Furthermore, gross efficiency increased with respect to exercise intensity, as suggested by Ettema and Loras (2009). Net efficiency for skilled participants was larger in magnitude than gross efficiency and the value of net efficiency increased with intensity but was smaller with each version of internal work. 50 W efficiency values showed large effect size differences compared to 100 and 150 W. Small to moderate effect sizes were seen between 100 and 150 W at all three methods of calculation. Net efficiency was larger than gross efficiency at all intensities and methods and was around the 20-24 % which was similar to the values reported by Nozaki *et al*. (1993) and the results from the previous chapter. Net efficiency showed large increases between 50 and 100 W, irrespective of method of calculation. However, the net efficiency was similar between 100 and 150 W for all methods of calculation. This may indicate a plateau of efficiency with respect to exercise intensity as suggested by Dean and Kuo (2009). As with gross efficiency, the skilled participants were more efficient except at 50 W compared to novice participants, in contrast to the results from the previous chapter. This was postulated to be linked to the calculation of external work and potential energy as discussed above.

In the previous chapter at each intensity level, the novice participants had higher gross and net efficiency than the skilled participants, which may appear unusual as training tends to enhance efficiency (Lay *et al*., 2002). Within this chapter at 50 W, the novice participants were more efficient than the skilled, irrespective of the method of calculation, similar to the previous chapter. However, as intensity increased the skilled performers increased their efficiency above that of the plateauing novices, suggesting at 100 W or more skilled participants were more efficient. These results seem to fit with the existing literature; that skilled participants are more efficient than novices (Norman and Komi, 1987; Lay *et al*., 2002; Sandbakk *et al*., 2013). This goes some way to supporting the anecdotal reports from the skilled participants of the challenge of the rowing at 50 W. In the previous chapter, internal work was calculated as rotational and translation kinetic energy, and summed to external work. The same data were used for energy expenditure. In this chapter, the method of calculating total work did not use the ergometer for external work and potential energy. This allowed for specific changes of potential energy to be accounted for, rather than being part of the mean contribution from external work. Whilst it has been suggested that an ergometer is an appropriate method of obtaining external work (Ettema and Loras, 2009), this may not be true of a rowing ergometer due to the active and relatively passive components of the rowing cycle.

The efficiency results gave three different estimates per intensity examined, but did not indicate which was the most appropriate method to use. The Wn has consistently reported the highest estimates of work done in the literature over a range of activities

(Williams and Cavanagh, 1983) and that result was repeated within this data. As this approach gives the largest numerator figure for work done, the efficiency estimate is the largest. However, the weight of arguments suggest that Wn is not an appropriate method for estimating work done as it does not allow for energy exchange between PE, TKE and RKE within a segment nor energy exchange between segments and, is neither mechanically or physiologically representative (Williams and Cavanagh, 1983, Martindale and Robertson, 1984; Caldwell and Forrester, 1992). Williams and Cavanagh (1983) specifically suggested that the use of Wn, with no transfers of energy, cannot be recommended and this is agreed by other researchers (Norman and Komi, 1987; Norman *et al*., 1985). The inability for the Wn method to allow for transfer of energy would overestimate the work done, affecting efficiency estimations (Williams and Cavanagh, 1983). If, as suggested by Norman and Komi (1987), the transfer is an important part of skilled performance, the efficiency estimates based on Wn would not be sensitive to such analysis.

The efficiency estimates using Ww appear to be more theoretically sound as they allow for transfers within a segment (Williams and Cavanagh, 1983; Slavin *et al*., 1993). There appears to be little counterargument to within-segment transfer methods of internal work and hence efficiency. However, the noted shortcoming is that it does not include between segment transfers. Whilst, theoretically it appears to be an improvement upon a Wn based model, in effect, it creates another method of calculating efficiency, one which does not clarify or improve any estimates or correlates of performance.

The Wwb method of calculating efficiency used the smallest calculated values of work done in the numerator, hence deriving the lowest value for gross efficiency. Whilst the Wwb method of estimating work is used by researchers, few have used it in the calculation of efficiency, and none, to the author’s knowledge, specifically to rowing performance. Although no metabolic data were collected an estimate of level terrain cross-country skiers was postulated to be 38 % using Wwb as the measure of mechanical work done (Norman and Komi, 1987). However, this estimate of efficiency is almost double the values reported recently by Sandbakk *et al*. (2012, 2013). Some authors (Winter, 1979) have argued that this method attempts to be the most complete method by assessing both within and between exchanges of energy and as such if a common denominator could be agreed on could become the most appropriate method to assess efficiency. Using the different models has a limitation as it is not possible to suggest which of them is best or correct one to use. Winter (1979) indicated that all contributions to internal work need to be considered, including the positive and negative work done by the muscle. Others have gone further in an attempt to consider elastic contributions from the stretch shortening cycle (Williams, 1985).

5.4.4 External work

The calculations of total mechanical work were based on Caldwell and Forrester (1992), where the contribution of external work was not included, hence work was, in effect internal work. Winter (1979) indicated that all sources of work, including external work should be accounted for and as external work was included, a rowing specific method to account for external work was adopted from Martindale and Robertson (1984) where the mechanical energy at the catch and the finish of the stroke was considered external work. Within this study, the catch and finish energies were calculated for the start and the end of the drive phase, differing from Martindale and Robertson's (1984) catch-to-catch protocol. As their participants were in effect in the same position they considered this value a constant. This chapter's results showed very small changes in external work for all participants, less than 3 J. This can be explained by the low velocity at the catch and finish of the stroke. At the catch the rower was likely stationary or at a very low velocity as they would have been changing direction from the recovery phase. At the finish the body would be approaching zero velocity before changing direction and returning to the beginning of the stroke. Hence, any differences would have come from the change in body position from the start of the drive to the end of the drive phase. Whilst the centres of mass of the thighs and shanks would have been lower in height, reducing the PE due to position, this would have been somewhat counteracted by the raising of the upper and for arm segments. The difference between the start and finish of the drive phase would be due to the difference in position and the greater proportion of mass of the legs compared to the arms. Overall, very small differences were observed, which to a degree support the methods of Caldwell and Forrester (1992) that external work, when using a segmental approach that included potential energy, can be ignored.

In the previous chapter, external work had a larger contribution to total work than in this chapter. External work was determined from the ergometer (Ettema and Loras, 2009) and included potential energy within its values. If internal work was calculated including potential energy, as above, then the output of the ergometer cannot be used as potential energy would be calculated twice (Ettema and Loras, 2009). The inclusion of potential energy in the previous chapter's calculation of external work explains the large difference compared to the values within this chapter. Additionally, this may suggest why internal work is larger in this chapter. The change in methodology for this Chapter was due to a need to know the instantaneous potential energy, as well as translational and rotational kinetic energy, for the various methods of calculation of work and transfer. However, the calculated values for external work had negligible effects upon the results.

The novice participants had a larger magnitude of external work at each intensity level than skilled participants, however the standard deviation was much larger suggesting greater variation in external work done. Due to smaller variation the skilled participants had large effect sizes between intensities, but smaller values of external work. Tanaka *et al*. (2007) and Pollock *et al*. (2009) indicated that skilled rowers minimise the motion of the trunk in order to stabilise and transfer force. The data could support this as the main contributor to external work in rowing would be the trunk segments, due to their proportional size. It has been suggested that greater movement efficiency is obtained by minimising the movement of the centre of mass (Minetti, 2004). External work is considered as the work to move the centre of mass relative to the environment. Although skilled participants had longer drive length, the external work done was less than the novice participants and should contribute to greater efficiency.

5.4.5 Total Work

Total work was considered the sum of internal and external work. Statistical differences were observed between the three methods at each intensity level and were supported by large effect sizes, indicating meaningful differences between the methods of calculation. The sizes of differences would therefore affect any efficiency calculations based upon the results (Williams and Cavanagh, 1983). Mechanical work rate was greater in more successful elite skiers at two different intensities (Norman and Komi, 1897) suggesting mechanical differences may be an important performance variable. In this chapter, as with the preceding chapter, total work done was larger for the skilled participants than the novice participants, agreeing that skilled performer attempt to maximise work done, which could be used as a discriminating tool for skill levels (Purkiss and Robertson, 2003; Slawinski *et al.*, 2010). Due to differences in calculation between this chapter and the previous chapter, it has not been possible to compare internal or external work. However total work can be compared using the Wn data at 50, 100 and 150 W, as the assumption of no transfer was made in the previous chapter. Novice participants showed slightly increased total work values of 0.14, 0.18 and 0.21 kJ compared to 0.13, 0.15 and 0.17 kJ from the previous chapter. Whilst there was some similarity at 50 W there were larger differences at higher intensities in the current Chapter (0.15, 0.27 and 0.34 vs 0.14, 0.16 and 0.19) with in the skilled participants.

5.4.6 Transfer of energy

Whilst the debate of appropriate transfers between non contiguous segments has been considered (Williams and Cavanagh, 1983; Norman *et al.*, 1985; Frost *et al.*, 1997; Frost *et al.*, 2002), one other use of energy transfer methods of calculation is to quantify the amount of energy transferred (Norman *et al.*, 1985; Norman and Komi, 1987). It is suggested by Norman and Komi (1987) that skilled participants should transfer the most energy, reducing the cost of internal work. The pattern of percentage energy transfers (Tw, Tb and TWb) in the present study were similar to studies of cross country skiing where Twb was the largest percentage transfer (Norman *et al.*, 1985; Norman and Komi, 1987). In addition, Tw and Tb showed some similarity to the rowing specific data of Martindale and Robertson (1984), where differences could be due to methodological and intensity factors. The scope of transfer is important, as are individuals who can effectively transfer energy, as it will create more work for a comparatively lower metabolic cost. In comparison between expert and recreational skiers, experts were shown to have larger within segment (Tw) transfers and this was linked to performance (Norman and Komi, 1987). The skilled participants in this Chapter transferred greater amounts of energy than the novice participants, at all intensities, by all methods of calculation (Tw, Tb and Twb). It is important to consider that not all energy transfers between segments are caused by increased metabolic energy usage, as transfer can be achieved through pendulum, whip and tendon transfer (Caldwell and Forrester, 1992; Norman and Komi, 1987) hence the criticism of the use of methods that use Wn (no transfer) as a measure of internal work. The Wn and Wwb appear to account for the assumption of the Wn method, but it was difficult to argue for the correctness of the transfer assumptions. However, there were differences in total work between the skilled and novice participants and the quantification of transfer that offers some explanation for those differences.

The metabolic cost of negative work was less than positive work and has led to some authors correcting work values assuming a 3:1 ratio for negative: positive efficiency ratio during running and walking in children (Frost *et al*, 1997; Frost *et al*., 2002). One difficulty is to assess when and where negative and positive work are occurring. This issue has led to the cost of positive and negative work being ignored (Martin *et al*., 1993) or assumed to be the same (Winter, 1979). In its simplest terms, positive work can be considered concentric muscle action and is associated with an increase in energy whereas negative work can be considered eccentric muscle actions which reduce energy (Williams, 1995). Many of the previous studies examined activities such as running where in one stride, both positive and negative work was occurring. During the drive phase of the rowing stroke, there is little eccentric muscle action within the legs as the extension of the hip, knee and ankle occurs through the concentric action of the gluteal, anterior thigh and posterior shank muscles (Soper and Hume, 2004). This is also true in the extension of the spine and flexion of the arms. As the data in this Chapter only examined the drive phase, an assumption has been made that all work was positive. Martindale and Robertson (1984) suggested that during the rowing stroke negative work is minimised through the coaching process, and is likely only to be present at the end of the stroke to arrest motion before returning to the start of the stroke (Hase *et al.,* 1996). Should the entire stroke be examined (catch to catch) then a more compelling argument for the inclusion of positive and negative work could be made.

Additionally the role of transfer of energy from elastic sources has been considered (Williams, 1985). In activities such as running and jumping there would be reason to attempt to correct for this issue. However, in a rowing stroke, the change in direction of the motion of the rower, whilst preceded by flexion of the knees before an extension of the knees, at low intensities would have mimimum contribution from elastic stored energy. Martindale and Robertson (1984) concurred that the relatively slow movement of a rowing stoke was unlikely to make significant changes to the energy and as such has not been considered to contribute within the present study.

5.5 Summary

As suggested by Williams and Cavanagh (1983), the method of calculating work affected the estimation of efficiency in the present study. An efficiency model for total body action was modified to account for transfers of energy within and between segments, during the drive phase of the rowing action.

Internal work was affected by the assumption of energy transfer used, which in turn modified gross and net efficiency measurements, for skilled and novice participants. In the previous chapter novice rowers were reported as more efficient than skilled rowers. The modifications of protocols and calculation methods changed the results indicating, with the exception of 50 W exercise intensity, skilled participants were more efficient than novice participants. At 50 W it was suggested that the low level of the target work rate caused low efficiency in the skilled participants. Efficiency estimates were within the values reported in the literature. Skilled participants additionally showed a greater amount of energy transferred, and higher levels of internal and total work, and despite the higher energy expenditure, they were more efficient than novice participants.

CHAPTER SIX THESIS SUMMARY

6.1 Introduction

The aim of this thesis was to develop and evaluate a model of total body efficiency during a rowing motion, that included internal work, considered issues of energy transfer and was applied to a skilled and unskilled population, addressing the lack of research in this area. Previous literature reported estimates of mechanical efficiency focussed on cycling, running and walking and to a lesser extent arm-cranking and wheelchair propulsion. There is a dearth of efficiency estimates for activities that use the total body for locomotion which is usually limited to cross-country skiing and to a lesser extent, rowing. Due to different protocols, methods and cohorts, a wide range of efficiency estimates have been reported but comparison between studies is difficult. Comparisons of experienced and inexperienced performers, particularly in cycling (Moseley *et al*., 2004) have resulted in equivocal results, where the impact of training on efficiency is unclear (Hopker, 2012).

Methodological shortcomings such as not including internal work (Kram, 2011), not accounting for energy transfers (Martindale and Robertson, 1984) or appropriateness of the body segment parameters used (Bechard *et al*., 2009) questioned the biomechanical and physiological appropriateness of reported efficiency estimates. In response, this thesis developed a model of mechanical efficiency during the drive phase of ergometer rowing which included internal work, external work and energy expenditure. This was applied to novice and skilled participants, across a range of exercise intensities. The efficiency model was further developed by including energy transfers within and between body segments, addressing the limitations of previous research. The effect of these modifications to the modelling process changed the estimates of efficiency.

6.2 Original Contribution to Knowledge

6.2.1 Development of total body internal work model

A model for the determination of internal work of a total body action, ergometer rowing, was developed based on kinematics from three-dimensional motion capture and body segment inertial parameters, without the need for measures of force. In Chapter Three, based upon healthy but untrained individuals using the body segment parameters of Winter (2005), internal work for the drive phase of the rowing stroke was shown to be highly reliable (ICC range 0.71-0.91) and within expected values (Bechard *et al*., 2009; Slawinski *et al*., 2010). Chapter Four also reported highly reliable (ICC range 0.938-0.960) data for internal work of novice and skilled participants, where the de Leva's (1996) body segment parameter data was applied in preferences to Winter (2005). Furthermore, drive duration for novices (Chapter Three) and drive duration and drive length for novice and skilled participants (Chapter Four) was also shown to be highly reliable (ICC range 0.8-0.992), indicating a consistent rowing performance can be achieved, even when using unskilled participants.

6.2.2 Total body efficiency estimates

The results presented in this thesis reported the gross efficiency for ergometer rowing from 17 to 25% for novice participants (Chapter Three), and for novice and skilled performers (Chapter Four) range16 % to 27 % over a range on submaximal exercise intensities to be consistent with the current literature (Hofmijster et al., 2009).

Net efficiency ranged of 24 % and 30 % for novice participants (Chapter Three), and for novice and skilled performers (Chapter Four) range 21 % to 31 %. Net efficiency has not been previously reported for ergometer rowing so these results give an indication of the net efficiency during ergometer rowing. This is broadly in line with the on-water net efficiency values, 20-24% reported by (Nozaki et al., 1993).

The gross efficiency for novice participants (Chapter Three) and for novice and skilled participants (Chapter Four) increased with respect to intensity as previous suggested. Net efficiency rose with respect to exercise intensity for skilled participants (Chapter Four) but showed a trend towards plateau for novice participant (Chapters Three and Four). There does not appear to be any comparative data for net efficiency during ergometer rowing.

6.2.3 Energy transfer

Previously reported efficiency estimates have commonly assumed that work done occurred without any transfer of energy within and between segments of the body.

Chapters Three and Four were developed on the assumption of no energy transfers. However, unexpectedly the results of Chapter Four, indicated the gross and net efficiency estimates were higher for the novice participants, than skilled participants. Large effect sizes (*d*= 0.73-1.04) suggested that skilled participants did more total work than novice participants, but that energy expenditure (*d*= 0.93-1.24) was larger for skilled participants despite lower heart rate and R-values. Within Chapter Five, the same data was recalculated to account for energy transfers within and between the body segments. The inclusion of within segment (Ww) and within and between segment (Wwb) energy transfers changed both the efficiency estimates and the pattern of the data. When energy transfer was included skilled participants reported greater gross and net efficiency than novice participants at 100 and 150 W. However the novice participants were still more efficient at 50W. This was attributed to the low exercise intensity, which trained rowers were not familiar with (Bateman *et al.*, 2006). This indicated that assumptions of energy transfer need to be carefully considered as they can influence the results. This additionally suggested that efficiency estimates may be the most appropriate method to compare different groups (i.e. novice and skilled) and need to be carefully considered when used to assess sporting performance.

The results showed that at 100 and 150W the skilled participants were more efficient than the novice participants, irrespective of the method of internal work calculation used. Gross and net efficiency increased with respect to intensity for the skilled participants. In the net efficiency calculations there was little difference, indicated by small effect sizes between net efficiency at 100 and 150 W, possibly indicating a plateau and again indicating the different result between gross and net efficiency calculations (Sidossis *et al.,* 1992). Novice participants showed a plateau of gross efficiency with respect to exercise intensity, irrespective of the method of calculation, contrary to the suggestions of Ettema and Loras, (2009). Net efficiency decreased with respect to exercise intensity, irrespective of the method of calculation of internal work.

Within the efficiency literature, the concept of energy transfer has received little attention. Martindale and Robertson (1984) assessed the differences in internal work done during a rowing stroke, using 4 trained rowers. This showed important differences due to the assumptions of energy transfer, but they did not assess efficiency. Similarly Norman et al. (1985) and Norman and Komi (1987) examined the differences in internal work based energy transfer estimations but did not estimate efficiency. This thesis has both examined the changes in internal work with respect to assumptions of energy transfer and estimated gross and net efficiency. This reworking of efficiency estimates based on the energy assumption transferred, not only altered the efficiency estimates but changed the pattern of efficiency estimates between the groups.

6.2.4 Body segment parameters and multi-segmented trunk

Inverse dynamics calculations are dependent on motion data and an appropriate, representative body segment parameter data set. The data of Winter (2005) is commonly used, but has been criticised as not appropriate to current athletes due to the age of the data and the small sample size (Bartlett and Bussey, 2011).The role of the trunk to transfer force from the lower to the upper body has been identified (Shephard, 1998), but has been considered a single segment (Caplan and Gardner, 2007; Cerne *et al*., 2013). This has been suggested as a limitation in previous research

(Cerne *et al*., 2013). The results within Chapter Four and Five were developed using a multi-segmented trunk based on the body segment parameter data set of de Leva (1996). This thesis appears to be the only study that has applied a multi-segmented trunk analysis for the estimation of internal work and efficiency during ergometer rowing.

6.3 Limitations

6.3.1 Drive phase only

Internal work was estimated for the drive phase of the rowing stroke only. Whilst this allowed a simplification to the model, that all work was considered positive and no negative work occurred, it therefore does not address the work done in the recovery phase of the rowing stroke. This may limit the comparison with other studies that analyse the total stroke.

6.3.2 Symmetry of movement

An assumption of symmetry of the movement of this limbs were made, simplifying the calculations of internal work. The use of this assumption has been supported within the literature (Consiglieri and Pires, 2009; Hofmijster *et al*., 2009; Cerne *et al*., 2013), but limits the generalisability of the results to ergometer rowing. This assumption may be less appropriate if applied to on-water rowing as there may be differences in segmental movement patterns due to the oar providing resistance to the side of the rower, rather than in front during ergometer rowing. This may limit the generalisability of the results to performance enhancement for on-water rowing.

Associated with the assumption of symmetry, motion capture data was only examined in two-dimensions and all motion was considered to occur in the sagittal plane. Whilst this may have been acceptable for ergometer rowing (Hofmijster *et al*., 2009), the transverse plane motion of on water rowing, may undermine the use of a two-dimensional approach and necessitate a three-dimensional approach as indicated by Bechard *et al*. (2009).

6.3.3 Application to on-water rowing

The rowing action was on an ergometer, which has limited application to on-water rowing. The efficiency of on-water rowing performance is the interaction of the boat, the water, the oar and the rower (Kleshnev, 2011). It is the combination of these factors that will determine true rowing efficiency and has been describe as an efficiency cascade (Minetti, 2004). However, to determine rowing efficiency by this definition is a complex undertaking. Part of which would be to determine the contribution or efficiency of the rower. Whilst the study could be considered to be limited to the efficiency of the rower (Affeld *et al.*, 1993), this has made a contribution to developing a more complex model of the rowing efficiency. The use of the ergometer has allowed the rowing action to be simplified so in this study the focus is upon the biomechanics and physiology of the rower.

6.4 Future directions

6.4.1 Positive and negative work estimations

Winter (1979) suggested that all sources of work need to be considered. One simplification made within the thesis was the contributions of positive and negative work. This is linked to energy expenditure as it is suggested that the cost of positive work is greater than the cost of negative work, thus influencing the efficiency values derived (Frost *et al.*,2002).

6.4.2 Development of three-dimensional analysis

The data and results presented in the thesis, simplified the movement to two-dimensional sagittal plane motion. Specifically, an on-water rowing action, does not only occur in a sagittal plane, but has a rotational component. Further research could attempt to collect three-dimensional data during on-water rowing, to establish the relationship of efficiency and work in a more ecologically valid environment. The methods of analysis could be applied to other actions to assess the efficacy of training programmes from high level sport to sit-to-stand action in a therapy setting, for instance.

6.4.3 Rowing specific exercise intensities

Heart rate data suggested that skilled rowers found the exercise intensities comfortably within their physical capacity. As such, their efficiency at race paces were not assessed which may derive information valuable to development of training programmes and coaching. Data collection at race paces would provide greater information for performance orientated research, and potentially expand the research to examine changes in efficiency when participants are fatigued. Previous research examining efficiency in cycling has produced equivocal results as the affect of training on efficiency (Hopker, 2012). Currently, no such data appears to have been published for rowing. Training induced changes in physiology and technique improvements could be monitored over time, deriving useful training feedback for athletes, with the goal to enhance performance.

6.5 Practical applications

Periodic assessments using a similar protocol as used throughout this thesis would provide athletes and coaches with useful feedback as to fitness and technique, which has the potential to enhance training programmes. The exercise intensities could be matched to race paces to provide more appropriate data.

The methodology within the thesis could be adapted for a two-dimensional video based protocol, which would is less expensive in equipment and could be set-up at an indoor training venue. Energy expenditure could be estimated from heart rate monitors (Keytel *et al.*, 2005). This would allow for efficiency, work done and energy expenditure to me monitored outside of the laboratory.

The amount of work done by a segment or group of segments can be monitored as a function of training skill or fatigue. For example, the data in Chapter Four showed that skilled rowers had lower levels of internal work in the trunk, than novice participants.

Techniques that minimise the trunk internal work could be coached and monitored using the methods outlined (Hase *et al*., 2002)

The amount of energy transferred may be indicative of the skill level of the individual, and potentially may be used to monitor improvements in skilled performance (Norman and Komi, 1987; Purkiss and Robertson, 2003).The amount of energy transferred may be indicative of the skill level of the individual, and potentially may be used to monitor improvements in skilled performance.

6.6 Conclusion

The aim of this thesis was to develop a model of total body efficiency during a rowing motion. This addressed the lack of studies that have considered the total body as a complete locomotive unit. This differed from previous research by including internal work for the limbs and trunk, developing internal work model by changing the BSP data set, modelling a multi-segmented trunk and accounting for energy transfers within and between segments. Energy expenditure data were used to calculate gross and net efficiency for skilled and novice rowers across an increasing exercise intensities suggesting the methods of calculation affect the estimates of efficiency.

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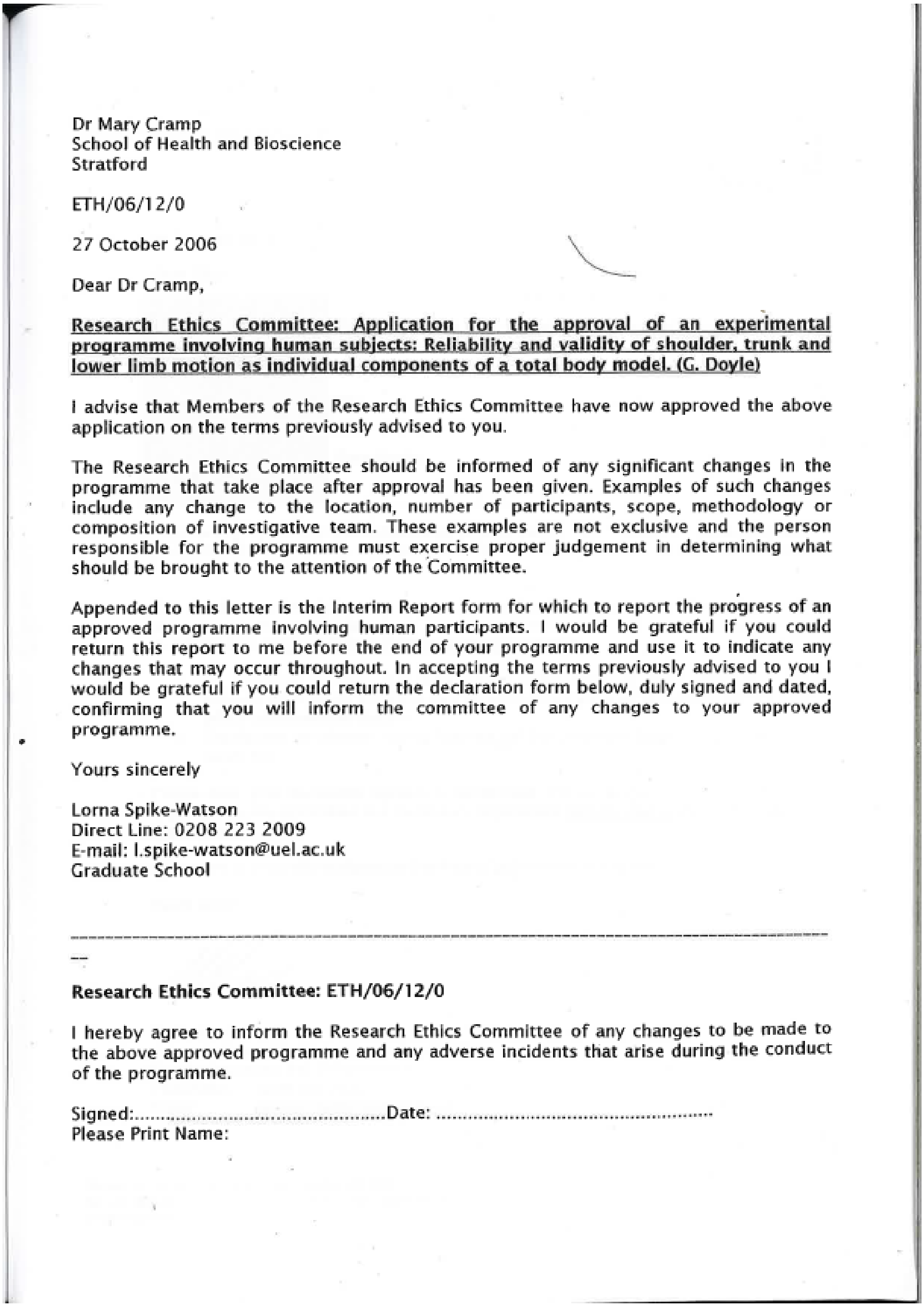
Appendix 1: Ethical Approval



Dr Mary Cramp
School of Health and Bioscience
Stratford

ETH/06/12/0

27 October 2006

Dear Dr Cramp,

Research Ethics Committee: Application for the approval of an experimental programme involving human subjects: Reliability and validity of shoulder, trunk and lower limb motion as individual components of a total body model. (G. Doyle)

I advise that Members of the Research Ethics Committee have now approved the above application on the terms previously advised to you.

The Research Ethics Committee should be informed of any significant changes in the programme that take place after approval has been given. Examples of such changes include any change to the location, number of participants, scope, methodology or composition of investigative team. These examples are not exclusive and the person responsible for the programme must exercise proper judgement in determining what should be brought to the attention of the Committee.

Appended to this letter is the Interim Report form for which to report the progress of an approved programme involving human participants. I would be grateful if you could return this report to me before the end of your programme and use it to indicate any changes that may occur throughout. In accepting the terms previously advised to you I would be grateful if you could return the declaration form below, duly signed and dated, confirming that you will inform the committee of any changes to your approved programme.

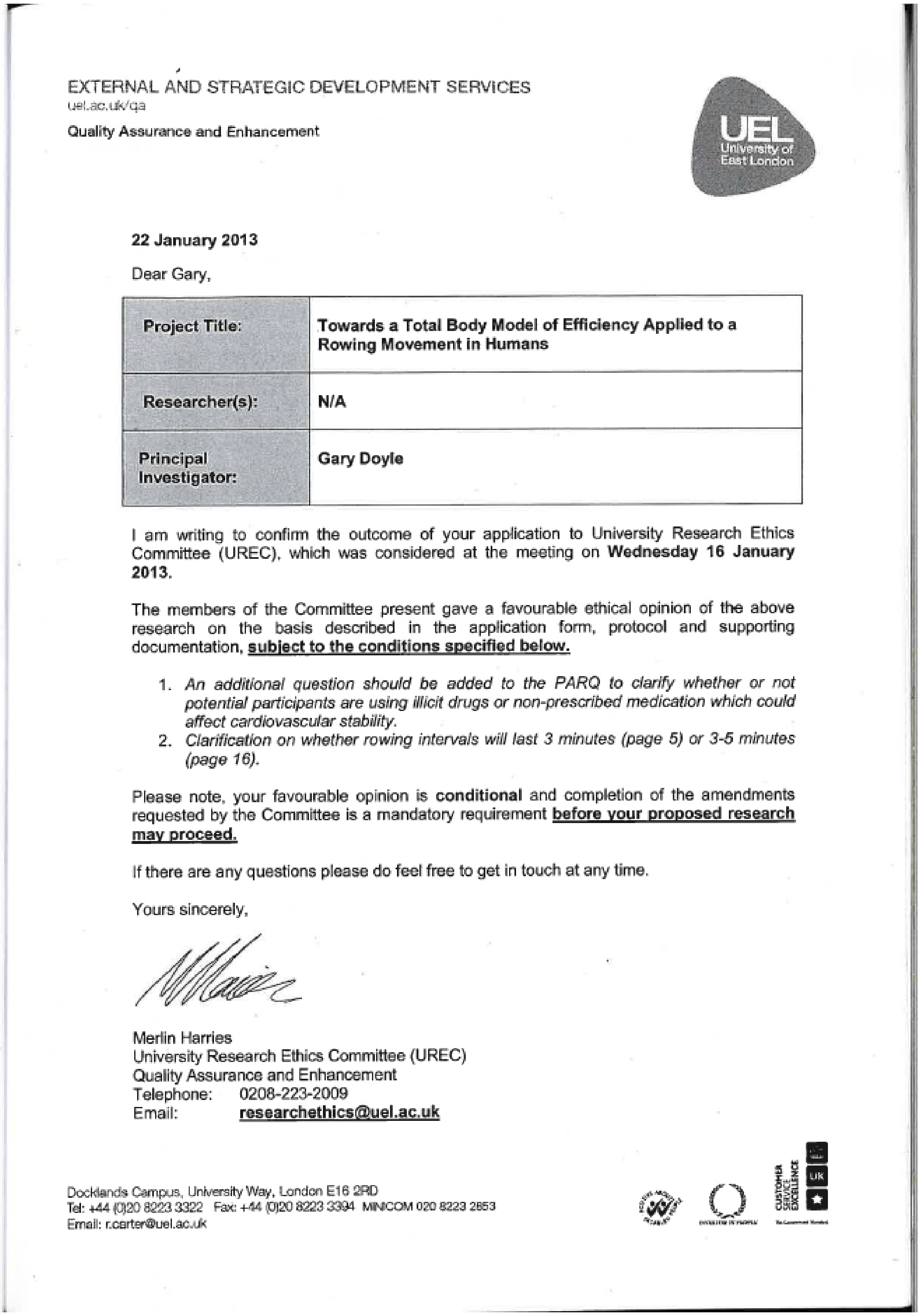
Yours sincerely

Lorna Spike-Watson
Direct Line: 0208 223 2009
E-mail: l.spike-watson@uel.ac.uk
Graduate School

Research Ethics Committee: ETH/06/12/0

I hereby agree to inform the Research Ethics Committee of any changes to be made to the above approved programme and any adverse incidents that arise during the conduct of the programme.

Signed:..Date: ....
Please Print Name:



EXTERNAL AND STRATEGIC DEVELOPMENT SERVICES
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Quality Assurance and Enhancement

22 January 2013

Dear Gary,

Project Title:	**Towards a Total Body Model of Efficiency Applied to a Rowing Movement in Humans**
Researcher(s):	**N/A**
Principal Investigator:	**Gary Doyle**

I am writing to confirm the outcome of your application to University Research Ethics Committee (UREC), which was considered at the meeting on **Wednesday 16 January 2013.**

The members of the Committee present gave a favourable ethical opinion of the above research on the basis described in the application form, protocol and supporting documentation, **subject to the conditions specified below.**

1. *An additional question should be added to the PARQ to clarify whether or not potential participants are using illicit drugs or non-prescribed medication which could affect cardiovascular stability.*
2. *Clarification on whether rowing intervals will last 3 minutes (page 5) or 3-5 minutes (page 16).*

Please note, your favourable opinion is **conditional** and completion of the amendments requested by the Committee is a mandatory requirement **before your proposed research may proceed.**

If there are any questions please do feel free to get in touch at any time.

Yours sincerely,

Merlin Harries
University Research Ethics Committee (UREC)
Quality Assurance and Enhancement
Telephone: 0208-223-2009
Email: **researchethics@uel.ac.uk**

Docklands Campus, University Way, London E16 2RD
Tel: +44 (0)20 8223 3322 Fax: +44 (0)20 8223 3394 MINICOM 020 8223 2853
Email: r.carter@uel.ac.uk

Appendix 2: Information and Consent forms

University of East London

School of Health and Bioscience
Stratford Campus
Water Lane
London
E15 4LZ

University Research Ethics Committee

If you have any queries regarding the conduct of the programme in which you are being asked to participate, please contact the Secretary of the University Research Ethics Committee, Ms Debbie Dada, Admissions and Ethics Officer, Graduate School, University of East London, Docklands Campus, London E16 2RD (Tel 020 8223 2976, Email: d.dada@uel.ac.uk)

The Principal Investigator(s)

Gary Doyle

School of Health and Bioscience, Water Lane, London, E15 4LZ

0208 223 2404

Consent to Participate in a Research Study

The purpose of this letter is to provide you with the information that you need to consider in deciding whether to participate in this study.

Determination of a total body model of efficiency applied to a rowing movement in humans

Project Description

This project aims to assess the level of efficiency achieved during a rowing action. To achieve this, the movement of the body's segments and the energy used needs to be assessed. To record the movement of the body's segments a three-dimensional motion analysis system will record the position of reflective markers placed upon the body and reconstruct the movement. The energy expended will be calculated by assessing the amount of oxygen and carbon dioxide breathed out during these activities.

Your written and informed consent would be sought before any testing began. Additionally, standard screening questionnaire (ParQ and you) would be completed to ensure you are in a good state of health to participate.

Firstly, a number of physical measures would need to be recorded. These include your height and weight, as well as hand, wrist, elbow, shoulder, hip, knee and ankle width. The project would require you to have number of small spherical markers attached to specific parts of your trunk, upper and lower body. You would be required to stand still for 1 second within the view of 10 infrared cameras, which records the position of the reflective markers only. These are not video cameras and do not record any image.

To collect the energy expended during the testing session, it is necessary to analyse the levels of oxygen and carbon dioxide used during the activity. Hence, you will be asked to sit on the rowing machine and a facemask which covers your nose and mouth will be placed on your face and secured with head straps. The air you breathe out be analysed via wires attached to the facemask. After you have become used to wearing the face mask, you will be asked to remain in a seated and still position for 3 minutes so a resting measure of energy expenditure can be assessed.

You will then be asked to start row at a specific stroke rate or power output as indicated on the rowing machine’s display panel. This level will not be greater than your capacity, hence may be demanding but not exhaustive. The length of time you row for will depend upon how quickly your body accommodates the intensity required, but the rowing trial is not expected to take longer than 10 minutes. The motion analysis system will record the position of the markers during this time but will not interfere with the protocol.

You may be asked to participate in an extended protocol. This is allows as assessment of the procedure against other research data. You will be asked to complete two additional trials that involves cycling and arm cranking, whilst wearing the face mask. The cycling trial would consist of sitting upon a standard cycle ergometer and pedalling at the desired intensity for a period of upto 10 minutes. The arm-crank would involve sitting on a chair at a height adjustable arm-crank ergo meter and working at the desired intensity for upto 10 minutes.

As with any testing procedure there is a minor risk of accident or injury. These will be minimised by the use of a familiarisation session, screening, warm-ups and supervision of testing. You may find the protocols tiring or they may become uncomfortable. At any time you may stop, for any reason. Any discomfort due to the exertion of the rowing activity, should pass within 5-minutes of you stopping.

It is possible, but unlikely, that you may experience some mild muscle soreness for upto 48 hours after the test. This would be as a result of being unaccustomed to the rowing action. This will naturally diminish within 48 hours.

Confidentiality of the Data

All data that is collected will be recorded will be kept in accordance with the Data Protection Act. To keep your confidential you will be identified by a number, with no personal data identifiable by name. Collected data may be used for future publication but will reported anonymously. All paper-based data will be stored in locked filling cabinets in locked office of the investigator. All electronically stored data will protected by passwords. Data will be held for a period of 10 years. Any paper based information will be shredded and electronic data will be deleted by the investigator.

Location

Testing will take place in the Motion Analysis Laboratory (room UH203) at the Stratford Campus of the University of East London.

Disclaimer

You are not obliged to take part in this study, and are free to withdraw at any time during tests. Should you choose to withdraw from the programme you may do so without disadvantage to yourself and without any obligation to give a reason.

Annexe 2

UNIVERSITY OF EAST LONDON

Consent to Participate in an Experimental Programme Involving the Use of Human Participants

Determination of a total body model of efficiency applied to a rowing movement in humans

I have the read the information leaflet relating to the above programme of research in which I have been asked to participate and have been given a copy to keep. The nature and purposes of the research have been explained to me, and I have had the opportunity to discuss the details and ask questions about this information. I understand what it being proposed and the procedures in which I will be involved have been explained to me.

I understand that my involvement in this study, and particular data from this research, will remain strictly confidential. Only the researchers involved in the study will have access to the data. It has been explained to me what will happen once the experimental programme has been completed.

I hereby freely and fully consent to participate in the study which has been fully explained to me.

Having given this consent I understand that I have the right to withdraw from the programme at any time without disadvantage to myself and without being obliged to give any reason.

Participant's Name (BLOCK CAPITALS)
……………………………………………………………………

Participant's Signature
………………………………………………………………………………………..

Investigator's Name (BLOCK CAPITALS)
…………………………………………………………………..

Investigator's Signature
……………………………………………………………………………………….

Date: ………………………….

PARTICIPANT INFORMATION SHEET

University of East London

School of Health, Sport and Bioscience
Stratford Campus
Water Lane
London
E15 4LZ

Project title: Determination of a total body model of efficiency

University Research Ethics Committee

If you have any queries regarding the conduct of the investigators, researchers or any other aspedt of this research project in which you are being asked to participate, please contact researchethics@uel.ac.uk

The Principal Investigator(s)

Gary Doyle

School of Health, Sport and Bioscience, Water Lane, London, E15 4LZ

0208 223 2404

Consent to Participate in a Research Study

The purpose of this letter is to provide you with the information that you need to consider in deciding whether to participate in this research study.

Determination of a total body model of efficiency applied to a rowing movement in humans

Project Description

This project aims to assess the level of efficiency achieved during a rowing action. To achieve this, the movement of the body's segments and the energy used needs to be assessed. To record the movement of the body's segments a three-dimensional motion analysis system will record the position of reflective markers placed upon the body and reconstruct the movement. The energy expended will be calculated by assessing the amount of oxygen and carbon dioxide breathed out during these activities.

Your written and informed consent would be sought before any testing began. Additionally, standard screening questionnaire (ParQ and you) would be completed to ensure you are in a good state of health to participate. This research has received formal approval from the University Research Ethics Committee. If you are a student within the University, your participation or non-participation will be without prejudice and will not affect assessment or service.

Firstly, a number of physical measures would need to be recorded. These include your height and weight, as well as hand, wrist, elbow, shoulder, hip, knee and ankle width. The project would require you to have number of small spherical markers attached to specific parts of your trunk, upper and lower body. You would be required to stand still for 1 second within the view of 10 infrared cameras, which records the position of the reflective markers only. These are not video cameras and do not record any image.

To collect the energy expended during the testing session, it is necessary to analyse the levels of oxygen and carbon dioxide used during the activity. Hence, you will be asked to sit on the rowing machine and a facemask which covers your nose and mouth will be placed on your face and secured with head straps. The air you breathe out be analysed via wires attached to the facemask. After you have become used to wearing the face mask, you will be asked to remain in a seated and still position for 3 minutes so a resting measure of energy expenditure can be assessed.

You will then be asked to start rowing at a specific stroke rate or power output as indicated on the rowing machine's display panel. This level will not be greater than your capacity, hence may be demanding but not exhaustive. Each rowing intensity will last for 3 minutes, followed by a 30 second rest, before the next, increased intensity, for a maximum of 5 intensities. The length of time you row for will depend upon how quickly your body accommodates the intensity required, but the rowing trial is not expected to take longer than 15 minutes. The motion analysis system will record the position of the markers during this time but will not interfere with the protocol.

As with any testing procedure there is a minor risk of accident or injury. These will be minimised by the use of a familiarisation session, screening, warm-ups and supervision of testing. You may find the protocols tiring or they may become uncomfortable. At any time you may stop, for any reason. Any discomfort due to the exertion of the rowing activity, should pass within 5-minutes of you stopping.

It is possible, but unlikely, that you may experience some mild muscle soreness for upto 48 hours after the test. This would be as a result of being unaccustomed to the rowing action. This will naturally diminish within 48 hours.

Confidentiality of the Data

All data that is collected will be recorded will be kept in accordance with the Data Protection Act. To keep your confidential, you will be identified by a number, with no personal data identifiable by name. Collected data may be used for future publication but will reported anonymously. All paper-based data will be stored in locked filling cabinets in locked office of the investigator. All electronically stored data will protected by passwords. Data will be held for a period of 10 years. Any paper based information will be shredded and electronic data will be deleted by the investigator.

Location

Testing will take place in the Motion Analysis Laboratory (room UH203) at the Stratford Campus of the University of East London.

isclaimer

You are not obliged to take part in this study, and are free to withdraw at any time during tests. Should you choose to withdraw from the programme you may do so without disadvantage to yourself and without any obligation to give a reason.

CONSENT FORM

UNIVERSITY OF EAST LONDON

School of Health, Sport and Bioscience

Consent to Participate in an Experimental Research Involving the Use of Human Participants

Determination of a total body model of efficiency applied to a rowing movement in humans

I have the read the information leaflet relating to the above programme of research in which I have been asked to participate and have been given a copy to keep. The nature and purposes of the research have been explained to me, and I have had the opportunity to discuss the details and ask questions about this information. I understand what it being proposed and the procedures in which I will be involved have been explained to me.

I understand that my involvement in this study, and particular data from this research, will remain strictly confidential. Only the researchers involved in the study will have access to the data. It has been explained to me what will happen once the experimental programme has been completed. I understand that the data collected could be reported in scientific journal, conferences or other similar publication and that any data will be annonymised.

I hereby freely and fully consent to voluntarily participating in this study which has been fully explained to me.

Having given this consent I understand that I have the right to withdraw from the programme at any time without disadvantage to myself and without being obliged to give any reason.

Participant's Name (BLOCK CAPITALS)
……………………………………………………………………….

Participant's Signature
……………………………………………………………………………………………..

Investigator's Name (BLOCK CAPITALS)
………………………………………………………………………..

Investigator's Signature
……………………………………………………………………………………………

Date: ………………………….

Physical Activity and Readiness Questionnaire

PAR-Q and YOU

Please read the following questions carefully and tick the appropriate box for each question. If you have any doubts or queries please ask.

Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes • **No •**

Do you feel pain in your chest when you do physical activity?

Yes • **No •**

In the past month, have you had chest pain when you were not doing physical activity?

Yes • **No •**

Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes • **No •**

Do you have a bone or joint problem that could be made worse by a change in your physical activity?

Yes • **No •**

Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

Yes • **No •**

Do you know of any other reason why you should not do physical activity?

Yes • **No •**

If you answered NO to all questions

> If you answered Par-Q honestly, you have reasonable assurance of your present suitability for:

- **A graduated exercise programme**. A gradual increase in proper exercise promotes good fitness development while minimising or eliminating discomfort
- **A fitness appraisal**. Simple or more complex test of fitness

If you answer YES to one or more questions

If you have not recently done so, consult your doctor BEFORE increasing your physical activity or BEFORE a fitness appraisal

Name_____________________________ Date______________

Signature__________________________

Appendix 3: Normality tests for Chapter 3, 4 and 5

Chapter 3

Table A3.1. Shapiro-Wilk test for internal work

	Shapiro-Wilk		
Condition	Statistic	df	Sig.
Rowing at 50 W (J)	0.957	10	0.756
Rowing at 100 W (J)	0.831	10	0.035*
Rowing at 150 W (J)	0.952	10	0.696
Cycling at 50 W (J)	0.990	10	0.997
Cycling at 100 W (J)	0.857	10	0.070
Cycling at 150 W (J)	0.961	10	0.801
Arm cranking at 40W (J)	0.887	10	0.157
Arm cranking at 60 W (J)	0.924	10	0.396
Arm cranking at 80 W (J)	0.935	10	0.503

* indicates statistical difference $p<0.05$

Table A3.2. Shapiro-Wilk test for normality of gross efficiency

	Shapiro-Wilk		
	Statistic	df	Sig.
GE rowing at 50 W (%)	0.892	10	0.185
GE rowing 100 W (%)	0.884	10	0.145
GE rowing 150 W (%)	0.924	10	0.394
NE rowing 50 W (%)	0.728	10	0.002*
NE rowing 100 W (%)	0.782	10	0.009*
NE rowing 150 W (%)	0.918	10	0.639
GE Cycling at 50 W (%)	0.904	10	0.242
GE Cycling at 100 W (%)	0.888	10	0.160
GE Cycling at 150 W (%)	0.977	10	0.945
GE Arm Cranking at 40 W (%)	0.946	10	0.617
GE Arm Cranking at 60 W (%)	0.957	10	0.748
GE Arm Cranking at 80 W (%)	0.976	10	0.937

* indicates statistical difference $p<0.05$

Table A3.3. Shapiro-Wilk test for total work done

	Shapiro-Wilk		
Condition	Statistic	df	Sig.
Rowing at 50 W (J)	0.909	10	0.272
Rowing at 100 W (J)	0.880	10	0.130
Rowing at 150 W (J)	0.988	10	0.993
Cycling at 50 W (J)	0.990	10	0.996
Cycling at 100 W (J)	0.858	10	0.072
Cycling at 150 W (J)	0.961	10	0.796
Arm cranking at 40W (J)	0.885	10	0.148
Arm cranking at 60 W (J)	0.924	10	0.394
Arm cranking at 80 W (J)	0.934	10	0.468

Table A3.4. Shapiro-Wilk test for normality of energy expenditure (n=10).

	Shapiro-Wilk		
	Statistic	df	Sig.
GEE rowing at 50 W (kJ.min^{-1})	0.898	10	0.208
GEE rowing at 100 W (kJ.min^{-1})	0.883	10	0.142
GEE rowing at 150 W (kJ.min^{-1})	0.963	10	0.821
NEE rowing at 50 W (kJ.min^{-1})	0.844	10	0.049*
NEE rowing at 100 W (kJ.min^{-1})	0.819	10	0.025*
NEE rowing at 150 W (kJ.min^{-1})	0.964	10	0.832
GEE Cycling at 50 W (kJ.min^{-1})	0.967	10	0.862
GEE Cycling at 100 W (kJ.min^{-1})	0.853	10	0.703
GEE Cycling at 150 W (kJ.min^{-1})	0.965	10	0.843
GEE arm cranking at 40 W (kJ.min^{-1})	0.913	10	0.305
GEE arm cranking at 60 W (kJ.min^{-1})	0.956	10	0.745
GEE arm cranking at 80 W (kJ.min^{-1})	0.936	10	0.507

* indicates statistical difference *p*<0.05

Table A3.5 Shapiro-Wilk test for Drive duration during rowing (n=10).

	Shapiro-Wilk		
	Statistic	df	Sig.
Drive duration at 50 W (s)	0.980	10	0.966
Drive duration at 100 W (s)	0.892	10	0.176
Drive duration at 150 W (s)	0.902	10	0.229

* indicates statistical difference *p*<0.05

CHAPTER 4

Table A3.6 Shapiro-Wilk test for Novice participant anthropometrics (n=12).

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Age (Years)	Novice	0.874	12	0.073
Mass (Kg)	Novice	0.821	12	0.016*
Stature(m)	Novice	0.897	12	0.146
BMI	Novice	0.889	12	0.114
Age (Years)	Skilled	0.935	12	0.441
Mass (Kg)	Skilled	0.931	12	0.391
Stature(m)	Skilled	0.915	12	0.245
BMI	Skilled	0.956	12	0.724

* indicates statistical difference *p*<0.05

Table A3.7 Shapiro-Wilk test for normality of drive length for novice participants (n=12).

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Drive length at 50 W (m)	Novice	0.962	12	0.813
Drive length at 75 W (m)	Novice	0.955	12	0.705
Drive length at 100 W (m)	Novice	0.959	12	0.769
Drive length at 125 W (m)	Novice	0.948	12	0.601
Drive length at 150 W (m)	Novice	0.927	12	0.345
Drive length at 50 W (m)	Skilled	0.740	12	0.002*
Drive length at 75 W (m)	Skilled	0.787	12	0.007*
Drive length at 100 W (m)	Skilled	0.778	12	0.005*
Drive length at 125 W (m)	Skilled	0.777	12	0.005*
Drive length at 150 W (m)	Skilled	0.765	12	0.004*

* indicates statistical difference *p*<0.05

Table A3.8 Shapiro-Wilk test for normality of drive duration for novice participants (n=12)

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Drive duration at 50 W (s)	Novice	0.930	12	0.380
Drive duration at 75 W (s)	Novice	0.960	12	0.788
Drive duration at 100 W (s)	Novice	0.942	12	0.526
Drive duration at 125 W (s)	Novice	0.941	12	0.516
Drive duration at 150 W (s)	Novice	0.924	12	0.324
Drive duration at 50w (s)	Skilled	0.945	12	0.559
Drive duration at 75W (s)	Skilled	0.942	12	0.530
Drive duration at 100W (s)	Skilled	0.925	12	0.332
Drive duration at 125W (s)	Skilled	0.917	12	0.262
Drive duration at 150W (s)	Skilled	0.894	12	0.131

* indicates statistical difference *p*<0.05

Table A3.9 Shapiro-Wilk test for normality of internal work for novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Internal work at 50 W (kJ)	Novice	0.891	12	0.121
Internal work at 75 W (kJ)	Novice	0.912	12	0.228
Internal work at 100 W (kJ)	Novice	0.841	12	0.028*
Internal work at 125 W (kJ)	Novice	0.834	12	0.023*
Internal work at 150 W (kJ)	Novice	0.950	12	0.630
Internal work at 50 W (kJ)	Skilled	0.944	12	0.547
Internal work at 75 W (kJ)	Skilled	0.946	12	0.575
Internal work at 100 W (kJ)	Skilled	0.933	12	0.407
Internal work at 125 W (kJ)	Skilled	0.908	12	0.199
Internal work at 150 W (kJ)	Skilled	0.953	12	0.681

* indicates statistical difference *p*<0.05

Table A3.10 Shapiro-Wilk test for normality of total work for Novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Total work at 50 W (kJ)	Novice	0.951	12	0.657
Total work at 75 W (kJ)	Novice	0.953	12	0.680
Total work at 100 W (kJ)	Novice	0.883	12	0.096
Total work at 125 W (kJ)	Novice	0.976	12	0.961
Total work at 150 W (kJ)	Novice	0.931	12	0.390
Total work at 50 W (kJ)	Skilled	0.948	12	0.606
Total work at 75 W (kJ)	Skilled	0.970	12	0.906
Total work at 100 W (kJ)	Skilled	0.958	12	0.757
Total work at 125 W (kJ)	Skilled	0.921	12	0.296
Total work at 150 W (kJ)	Skilled	0.968	12	0.890

* indicates statistical difference *p*<0.05

Table A3.11 Shapiro-Wilk test for normality for gross energy expenditure (GEE) for novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
GEE at 50 W (kJ.min^{-1})	Novice	0.954	12	0.698
GEE at 75 W (kJ.min^{-1})	Novice	0.833	12	0.023*
GEE at 100 W (kJ.min^{-1})	Novice	0.928	12	0.358
GEE at 125 W (kJ.min^{-1})	Novice	0.972	12	0.927
GEE at 150 W (kJ.min^{-1})	Novice	0.965	12	0.835
GEE at 50 W (kJ.min^{-1})	Skilled	0.955	12	0.705
GEE at 75 W (kJ.min^{-1})	Skilled	0.923	12	0.312
GEE at 100 W (kJ.min^{-1})	Skilled	0.884	12	0.098
GEE at 125 W (kJ.min^{-1})	Skilled	0.929	12	0.367
GEE at 150 W (kJ.min^{-1})	Skilled	0.901	12	0.163

* indicates statistical difference *p*<0.05

Table A3.12 Shapiro-Wilk test for normality for net energy expenditure (NEE) for novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
Rest (kJ.min^{-1})	Novice	0.962	12	0.344
NEE at 50 W (kJ.min^{-1})	Novice	0.888	12	0.112
NEE at 75 W (kJ.min^{-1})	Novice	0.921	12	0.295
NEE at 100 W (kJ.min^{-1})	Novice	0.918	12	0.272
NEE at 125 W (kJ.min^{-1})	Novice	0.939	12	0.491
NEE at 150 W (kJ.min^{-1})	Novice	0.982	12	0.989
Rest (kJ.min^{-1})	Skilled	0.956	12	0.733
NEE at 50 W (kJ.min^{-1})	Skilled	0.938	12	0.469
NEE at 75 W (kJ.min^{-1})	Skilled	0.940	12	0.497
NEE at 100 W (kJ.min^{-1})	Skilled	0.959	12	0.772
NEE at 125 W (kJ.min^{-1})	Skilled	0.983	12	0.994
NEE at 150 W (kJ.min^{-1})	Skilled	0.958	12	0.750

* indicates statistical difference *p*<0.05

Table A3.13 Shapiro-Wilk test for normality of gross efficiency (%) for Novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
GE at 50 W (%)	Novice	0.900	12	0.158
GE at 75 W (%)	Novice	0.874	12	0.074
GE at 100 W (%)	Novice	0.934	12	0.423
GE at 125 W (%)	Novice	0.955	12	0.718
GE at 150 W (%)	Novice	0.955	12	0.705
GE at 50 W (%)	Skilled	0.935	12	0.435
GE at 75 W (%)	Skilled	0.940	12	0.502
GE at 100 W (%)	Skilled	0.964	12	0.843
GE at 125 W (%)	Skilled	0.939	12	0.438
GE at 150 W (%)	Skilled	0.925	12	0.335

* indicates statistical difference *p*<0.05

Table A3.14 Shapiro-Wilk test for normality of net efficiency (%) for Novice participants

		Shapiro-Wilk		
Variable	Group	Statistic	df	Sig.
NE at 50 W (%)	Novice	0.766	12	0.004*
NE at 75 W (%)	Novice	0.908	12	0.200
NE at 100 W (%)	Novice	0.902	12	0.168
NE at 125 W (%)	Novice	0.940	12	0.502
NE at 150 W (%)	Novice	0.961	12	0.798
NE at 50 W (%)	Skilled	0.901	12	0.161
NE at 75 W (%)	Skilled	0.903	12	0.172
NE at 100 W (%)	Skilled	0.934	12	0.424
NE at 125 W (%)	Skilled	0.914	12	0.239
NE at 150 W (%)	Skilled	0.883	12	0.097

* indicates statistical difference *p*<0.05

Chapter 5

Table A3.15 Shapiro-Wilk test for normality of internal work for novice participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.848	12	0.035*
50	Ww	0.935	12	0.434
50	Wwb	0.863	12	0.054
100	Wn	0.848	12	0.035*
100	Ww	0.935	12	0.434
100	Wwb	0.863	12	0.054
150	Wn	0.889	12	0.114
150	Ww	0.910	12	0.212
150	Wwb	0.851	12	0.038*

* indicates statistical difference *p*<0.05

Table A3.16 Shapiro-Wilk test for normality of internal work for Skilled participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.972	12	0.932
50	Ww	0.948	12	0.614
50	Wwb	0.944	12	0.546
100	Wn	0.972	12	0.932
100	Ww	0.948	12	0.614
100	Wwb	0.944	12	0.546
150	Wn	0.959	12	0.769
150	Ww	0.961	12	0.804
150	Wwb	0.980	12	0.984

* indicates statistical difference *p*<0.05

Table A3.17 Shapiro-Wilk test for normality of gross efficiency for novice participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.810	12	0.012*
50	Ww	0.872	12	0.068
50	Wwb	0.833	12	0.023*
100	Wn	0.884	12	0.098
100	Ww	0.877	12	0.080
100	Wwb	0.748	12	0.003*
150	Wn	0.910	12	0.211
150	Ww	0.936	12	0.451
150	Wwb	0.897	12	0.144

* indicates statistical difference *p*<0.05

Table A3.18 Shapiro-Wilk test for normality of gross efficiency for skilled participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.885	12	0.103
50	Ww	0.903	12	0.173
50	Wwb	0.924	12	0.322
100	Wn	0.926	12	0.342
100	Ww	0.906	12	0.187
100	Wwb	0.894	12	0.132
150	Wn	0.942	12	0.525
150	Ww	0.912	12	0.224
150	Wwb	0.926	12	0.340

* indicates statistical difference *p*<0.05

Table A3.19 Shapiro-Wilk test for normality of net efficiency for novice participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.860	12	0.048*
50	Ww	0.899	12	0.153
50	Wwb	0.836	12	0.025*
100	Wn	0.878	12	0.082
100	Ww	0.867	12	0.059
100	Wwb	0.800	12	0.009*
150	Wn	0.904	12	0.180
150	Ww	0.942	12	0.519
150	Wwb	0.945	12	0.569

* indicates statistical difference *p*<0.05

Table A3.20 Shapiro-Wilk test for normality of net efficiency for skilled participants (n=12).

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Wn	0.932	12	0.396
50	Ww	0.938	12	0.474
50	Wwb	0.951	12	0.651
100	Wn	0.888	12	0.111
100	Ww	0.910	12	0.215
100	Wwb	0.874	12	0.073
150	Wn	0.920	12	0.287
150	Ww	0.883	12	0.095
150	Wwb	0.908	12	0.203

* indicates statistical difference *p*<0.05

Table A3.21 Shapiro-Wilk test for normality of transfer for novice participants.

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Tw	0.970	12	0.000*
50	Tb	0.930	12	0.380
50	Twb	0.836	12	0.025*
100	Tw	0.928	12	0.357
100	Tb	0.973	12	0.939
100	Twb	0.931	12	0.396
150	Tw	0.900	12	0.689
150	Tb	0.938	12	0.096
150	Twb	0.949	12	0.397

* indicates statistical difference $p<0.05$

Table A3.22 Shapiro-Wilk test for normality of transfer for skilled participants.

		Shapiro-Wilk		
Intensity (W)	Condition	Statistic	df	Sig.
50	Tw	0.955	12	0.717
50	Tb	0.984	12	0.132
50	Twb	0.935	12	0.440
100	Tw	0.888	12	0.110
100	Tb	0.941	12	0.512
100	Twb	0.965	12	0.857
150	Tw	0.954	12	0.689
150	Tb	0.883	12	0.096
150	Twb	0.932	12	0.379

* indicates statistical difference $p<0.05$

Appendix 4: Efficiency values with and without internal work from Chapter 3.

Background

Previous research has not always included internal work when calculating efficiency, instead only using external work as work done. The data in this thesis has included internal work. To allow for easier comparison, the gross efficiency for rowing, cycling and arm cranking from Chapter Three are presented below, calculated with internal work (Wtot) or without internal work (Wext).

Rowing Efficiency

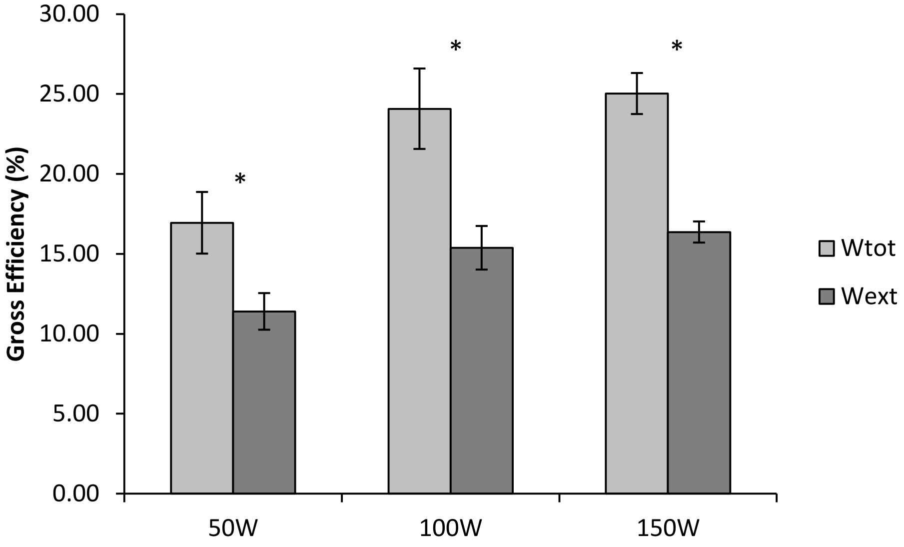

Figure A4.1 Gross efficiency with and without the inclusion of internal work
* indicates statistical difference *p*<0.05

Table A4.1 Shapiro-Wilk test for normality of gross efficiency during rowing (n=10).

	Statistic	df	Sig.
Wtot 50w	0.893	10	0.185
Wext 50W	0.835	10	0.039*
Wtot 100w	0.884	10	0.145
Wext100W	0.767	10	0.006*
Wtot 150w	0.924	10	0.394
Wext 150W	0.979	10	0.960

* indicates statistical difference *p*<0.05

The data for Wext at 100 and 150W were not normally distributed, hence a Wilcoxon Signed Rank tests showed statistical differences between efficiency calculated with and without the inclusion of internal work (*Z*=-2.803, *p*<0.05). Large effect sizes were displayed at 50 W (*d*=5.47), at 100 W (*d*=8.57) and 150 W (*d*=8.86), suggesting that the inclusion of internal work made important effects on the subsequent calculation of gross efficiency. The mean difference in gross efficiency was ≈ 6, 9 and 9% with respect to exercise intensity.

Cycling efficiency

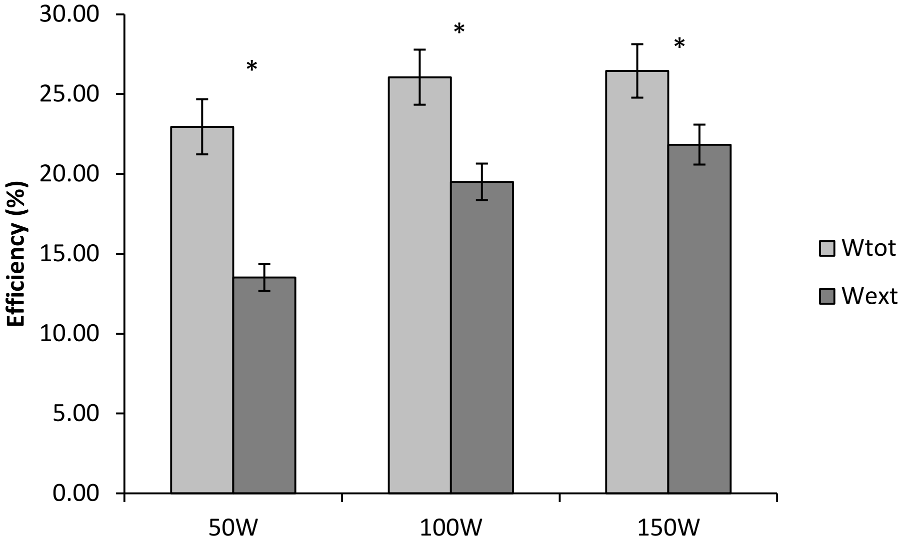

Figure A4.2 Gross efficiency with and without the inclusion of internal work
* indicates statistical difference *p*<0.05

Table A4.2 Shapiro-Wilk test for normality of gross efficiency during cycling (n=10).

	Statistic	df	Sig.
Wtot 50w	0.904	10	0.242
Wext 50W	0.960	10	0.160
Wtot 100w	0.888	10	0.145
Wext100W	0.912	10	0.295
Wtot 150w	0.977	10	0.945
Wext 150W	0.961	10	0.295

* indicates statistical difference *p*<0.05

The data was normally distributed, and paired samples T-tests showed statistical differences with large effect sizes between estimates of gross efficiency in cycling dependant on the inclusion (Wtot) or exclusion (Wext) of internal work (50W t = 17.1, *p*<0.05, *d* = 9.43; 100W *t* =17.9, *p*<0.05, *d* =7.0; 150 W *t* =16.6, *p*<0.05, *d* = 4.61). This suggested the inclusion of internal work made important effects on the subsequent calculation of gross efficiency. The mean difference in gross efficiency was ≈ 9, 7 and 4% with respect to exercise intensity.

Arm Cranking Efficiency

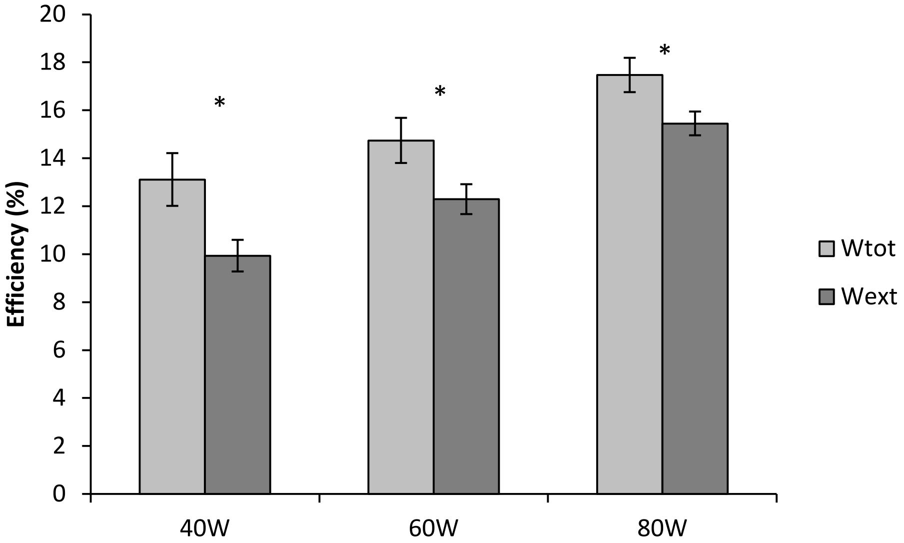

Figure A4.3 Gross efficiency with and without the inclusion of internal work
* indicates statistical difference *p*<0.05

Table A4.3 Shapiro-Wilk test for normality of gross efficiency during arm cranking (n=10).

	Statistic	df	Sig.
Wtot 40w	0.946	10	0.617
Wext 40W	0.869	10	0.097
Wtot 60w	0.957	10	0.748
Wext60W	0.963	10	0.816
Wtot 80w	0.976	10	0.937
Wext 80W	0.934	10	0.487

* indicates statistical difference *p*<0.05

The data was normally distributed, and paired samples T-tests showed statistical differences with large effect sizes between estimates of gross efficiency in arm cranking dependant on the inclusion (Wtot) or exclusion (Wext) of internal work (40W t = 10.2, *p*<0.05, *d* = 2.17; 60W *t* =11.2, *p*<0.05, *d* =1.89; 80 W *t* =13.4 *p*<0.05, *d* = 2.03). This suggested the inclusion of internal work made important effects on the subsequent calculation of gross efficiency. The mean difference in gross efficiency was ≈ 3, 2 and 2% with respect to exercise intensity.

Appendix 5: Internal work and efficiency for Chapter 3 rowing data using Winter (2005) and de Leva (1996) BSP data sets.

The following examined the effect of the body segment data set on the calculation of internal work and gross efficiency. The data was from the rowing trials presented in Chapter 3 and was used to calculate the internal work for the same trials, but with different BSP.

Internal work was calculated for the same trials using both the data sets of Winter (2005) and de Leva (1996) over 3 exercise intensities (i.e. 50, 100 and 150 W). Gross efficiency was calculated .....

Internal work

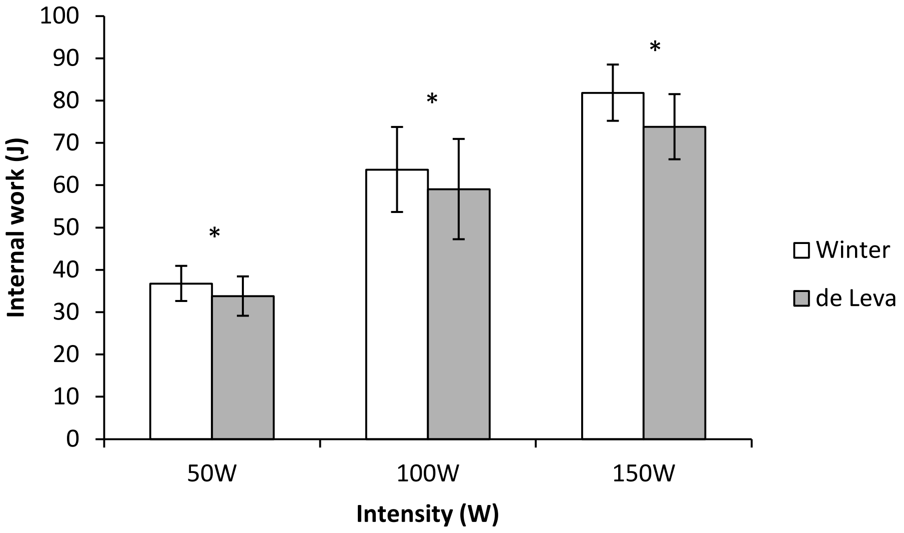

Figure A5.1 Internal work using BSP of Winter and de Leva for rowing
* indicates statistical difference *p*<0.05

At each exercise intensity internal work calculated using the Winter data set derived larger levels of internal work. Except for the Winter condition at 100W the data were normally distributed. Paired samples T-test showed statistical difference with a moderate effect size at 50W (*t*=(9) -6.332, *p*<0.05, *d*=0.49) and a large effect size at 150W (*t*=(9)-8.560, *p*<0.05, *d*=0.80). A Wilcoxon signed rank test indicated statistical differences and a small effect size at 100W (*z*=-2.803, *p*<0.05, *d*=0.30). This indicated that the choice of BSP data set will have an effect upon the calculated level of internal work.

Table A5.1 Shapiro-Wilk test for Internal work during rowing(n=10).

		Shapiro-Wilk		
Condition	Intensity	Statistic	df	Sig.
Winter	50W	0.958	10	0.763
de Leva	50W	0.955	10	0.729
Winter	100W	0.831	10	0.035*
de Leva	100W	0.877	10	0.122
Winter	150W	0.952	10	0.696
de Leva	150W	0.977	10	0.948

*= P.0.05

Table A5.2 Mean, SD, ICC and SEMfor Internal work during rowing(n=10).

	Mean (J)	SD	ICC2,1	SEM
de Leva 50W	33.8	5.81	0.78	2.721
Dempster 50W	36.8	6.44	0.80	2.909
de Leva 100W	59.1	14.01	0.92	4.086
Dempster 100W	63.7	16.56	0.91	5.104
de Leva 150W	73.8	9.32	0.70	5.069
Dempster 150W	81.8	10.74	0.71	5.835

Gross Efficiency

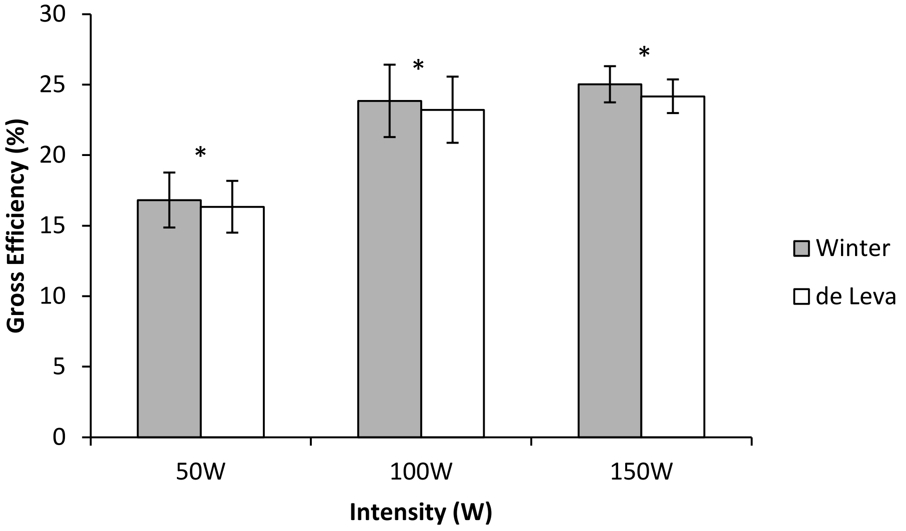

Figure A5.1 Gross efficiency using BSP of Winter and de Leva for rowing

* indicates statistical difference *p*<0.05

At each exercise intensity gross efficiency calculated using the Winter data set derived larger gross efficiency estimates. The data were normally distributed and Paired samples T-tests showed statistical differences with a moderate effect size at 50W (*t*=(9) 4.530, *p*<0.05, *d*=0.48) and 100W (*t*=(9)4.402, *p*<0.05, *d*=0.63) and a large effect size at 150W (*t*=(9)9.179, *p*<0.05, *d*=0.84). The results indicated that the choice of BSP would affect the internal work calculation which in term would have important effects on the efficiency estimates even though the mean difference was small (50=0.48%, 100W=0.63%, 150W=0.84).

Table A5.3 Shapiro-Wilk test for gross efficiency during rowing (n=10).

		Shapiro-Wilk		
Condition	Intensity	Statistic	df	Sig.
Winter	50W	0.893	10	0.185
de Leva	50W	0.908	10	0.265
Winter	100W	0.884	10	0.145
de Leva	100W	0.884	10	0.146
Winter	150W	0.924	10	0.394
de Leva	150W	0.924	10	0.393

*= P.0.05